HAZARDOUS GEOMORPHIC PROCESSES IN THE EXTRATROPICAL ANDES WITH A FOCUS ON GLACIAL LAKE OUTBURST FLOODS

By

Pablo Iribarren Anacona

A thesis

submitted to the Victoria University of Wellington
in fulfilment of the
requirements for the degree of
Doctor of Philosophy
in Physical Geography

Victoria University of Wellington

2016

Abstract

This study examines hazardous processes and events originating from glacier and permafrost areas in the extratropical Andes (Andes of Chile and Argentina) in order to document their frequency, magnitude, dynamics and their geomorphic and societal impacts. Ice-avalanches and rock-falls from permafrost areas, lahars from ice-capped volcanoes and glacial lake outburst floods (GLOFs) have occurred in the extratropical Andes causing ~200 human deaths in the Twentieth Century. However, data about these events is scarce and has not been studied systematically. Thus, a better knowledge of glacier and permafrost hazards in the extratropical Andes is required to better prepare for threats emerging from a rapidly evolving cryosphere.

I carried out a regional-scale review of hazardous processes and events originating in glacier and permafrost areas in the extratropical Andes. This review, developed by means of a bibliographic analysis and the interpretation of satellite images, shows that multi-phase mass movements involving glaciers and permafrost and lahars have caused damage to communities in the extratropical Andes. However, it is noted that GLOFs are one the most common and far reaching hazards and that GLOFs in this region include some of the most voluminous GLOFs in historical time on Earth. Furthermore, GLOF hazard is likely to increase in the future in response to glacier retreat and lake development. To gain insight into the dynamics of GLOFs I create a regional-scale inventory of glacier lakes and associated hazards in the Baker Basin, a 20500 km^2 glaciated basin in the Chilean Patagonia. I also simulate and reconstruct moraine- and ice- dammed lake failures in the extratropical Andes using numerical and empirical models.

More than 100 GLOFs have occurred in the extratropical Andes since the Eighteenth Century and at least 16 moraine-dammed lakes have produced GLOFs. In the extratropical Andes most of the failed moraine-dammed lakes were in contact with retreating glaciers and had moderate (> 8°) to steep (>15°) outlet slopes. Ice-dammed lakes also produced GLOFs in the extratropical Andes, damaging communities and highlighting the need for a better understanding of the GLOF dynamics and hazards. Thus, I reconstruct and model GLOFs that occurred in

maritime western Patagonia (Engaño Valley) and the high-arid Andes (Manflas Valley) to characterise the GLOF dynamics in these contrasting environments.

Hydraulic modelling and geomorphologic analysis shows that the Engaño River GLOF (46º S) behaved as a Newtonian flow and incorporated tree trunks, from the gently sloping and heavily-forested valley, which increased the GLOF damaging capacity. In contrast, the Manflas GLOF (28º S) descended from a steep valley behaving as a sediment-laden flow, which was capable of moving boulder-size rocks dozens of kilometres from the GLOF source. In both events lack of awareness of the GLOF hazard and a lack of territorial planning accentuated the GLOF damage. These GLOF reconstructions highlight both the difficulties in modelling sediment-laden flows over long distances, and the utility of empirical debris-flow models for regional-scale hazard analysis.

This thesis synthesises and increases our knowledge about the distribution, frequency, magnitude and dynamics of hazardous processes that have occurred in glacier and permafrost areas in the extratropical Andes. This knowledge forms a basis for future assessments of glacier and permafrost related hazards in the Chilean and Argentinean Andes and helps inform strategies and policies to face hazardous geomorphologic and hydrological processes emerging from a rapidly evolving cryosphere.

Acknowledgements

My supervisors Andrew Mackintosh and Kevin Norton are greatly thanked for providing timely and constructive criticism which helped to improve this thesis. Their outstanding editorial skills helped to clarify ideas and both, patiently, introduced me to the craft of scientific writing. Both diligently helped me with paperwork when needed. I also wish to thank Andrew and Kevin for providing funds to cover publication costs and conference fees. Finally, I thank Andrew for inviting me to field work in New Zealand which were always a good opportunity to learn.

Special thanks goes to my father who helped me to interview flood victims in Patagonia. I also wish to thank Hales López, my loyal field companion, who has been always willing to invest his time and resources in assiting me in the field. I thank Fernando Escobar and Simon Allen for providing feedback on the Manflas GLOF study. I also thank Becas Chile for funding my PhD studies.

I would like to thank my wife Valeria for her constant support and energy which made our time in New Zealand "enjoyable" in every circumstance. I also thank my daughter Aitana for constantly distracting me from the thesis to do more exciting activities. The support and love of my parents María and Rodrigo, siblings Paz and Jorge and parents in law Mercedes and Humberto was always a good incentive to finish this work and go back home.

Finally, I would like to thank my Latin friends in New Zealand; Daniela, Adrián and Nancy who constantly helped us in every possible way. Guillermo and Carlos are also thanked for inviting me to the Sunday football games which were always the highlight of the week. Carlos is also thanked for giving the opportunity to work with him and learn some painting skills. Fei and her familiy are thanked for their friendship. My office mates Alyssa, Tapuwa, Marie and Francesco are also thanked for the good times we shared.

This thesis is dedicated to the memory of my grandparents Nora and Fermín.

Table of contents

List of figures

List of tables

1 Introduction

1.1 Glacier and permafrost related hazards in mountain environments

Glacier and permafrost dynamics can cause hazardous processes such as glacier lake outburst floods, lahars, rock-slope failures and ice-avalanches. These events can mobilise millions of cubic metres of water, ice and debris, dozens of kilometres from their source, endangering inhabited areas (e.g. Kääb et al., 2005). Indeed, damages caused by these events have been documented over centuries in glaciated areas worldwide (Lliboutry et al., 1977; Hewitt 1982; Grove 1987; Figure 1.1). Glacier advance during the Little Ice Age (LIA) caused severe flooding in Europe when rivers were blocked by glaciers and suddenly released the impounded water (Grove 1987). After the maximum LIA expansion, however, the number of damaging events linked with glacier and permafrost dynamics has increased because of glacier retreat, permafrost degradation and the human occupation of high mountain areas (Evans and Clague 1994; Richardson and Reynolds 2000).

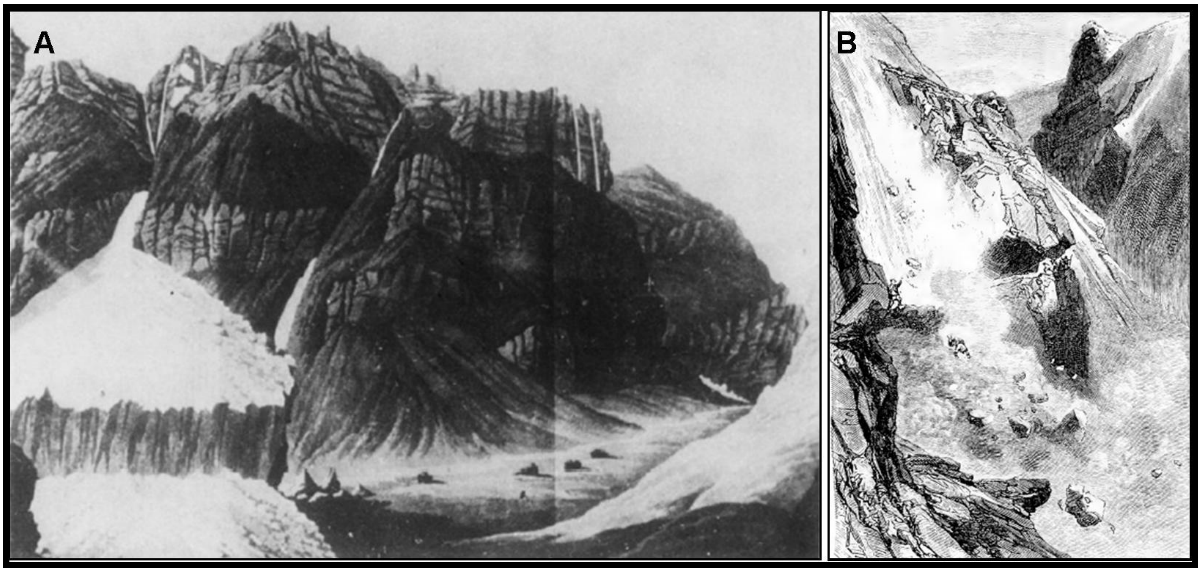

Figure 1.1 Hazards posed by ice-dammed lakes and ice avalanches depicted by nineteenth century authors in Europe. The advance of the Giétro Glacier (left side in A) formed a lake which drained catastrophically in 1818 causing dozens of fatalities. A slab ice avalanche affecting climbers is shown in B. Source: Bridel (1818) and Davenport (1880).

Glacier retreat and thinning has conditioned slope instabilities in deglaciating valleys due to changes in slope geometry and the redistribution of stresses within rock masses (Ballantyne 2000; McColl 2012). Permafrost degradation also has been linked with slopes failures due to the decrease in the adhesion of ice-cemented rocks and the acceleration and collapse of rock glaciers (Gruber and Haeberli 2007; Bodin et al., 2012). Slope failures in glacial and periglacial environments generally affect unpopulated valleys, however they can endanger distant areas after evolving into complex sediment-laden flows due to the entrainment of water, snow and ice in their paths (Petrakov et al., 2008). In the Peruvian Andes, for example, ice and snow collapses have caused debris flows with devastating impacts on populated areas located dozens of kilometres downstream. These phenomena have been extensively studied from human and physical perspectives (Oliver-Smith 1979; Carey 2005; Evans et al., 2009).

Glacier retreat also has enhanced the development of moraine and ice dammed lakes which have been the source of catastrophic GLOFs. As glaciers retreat, new lakes develop or existing lakes expand or deepen, increasing the hydrostatic pressure over dams making them more susceptible to failure (Richardson and Reynolds 2000). Furthermore, glacier thinning reduces thresholds for the initiation of catastrophic ice-dammed lake drainages (Clague and Evans 1997). The characteristics of unstable dams and the geomorphologic and social impacts of GLOFs have been widely studied in the Himalayas (Richardson and Reynolds 2000; Worni et al., 2012), Europe (Haeberli 1983; Vincent et al., 2010) and the tropical Andes (Carey 2005; Schneider et al., 2014). In these mountain ranges, GLOF modelling has also been carried out in order to unravel the GLOF's dynamics and assess the GLOF hazard (Wang et al., 2015).

Mass movement and GLOF studies in the Himalayas, Europe and the Tropical Andes have helped to improve our knowledge of the frequency, magnitude and dynamics of hazardous events, to identify the conditioning and triggering mechanisms of these phenomena and to map glacier and permafrost related hazards in these regions. This knowledge, however, is incomplete in the extratropical Andes, where hazards associated with glaciers and permafrost have been understudied (Figure 1.2), even though glaciers cover more than 23,000 km^2 in this region (Naruse 2006). Local studies of glacier and permafrost related hazards have been carried out in the extratropical Andes and the number of studies has increased the last five years (e.g. Hauser 2002; Worni et al 2012; Figure 1.3). However, this research has not been systematic. Furthermore, the inter-regional differences of glacier and permafrost hazards within the extratropical Andes have not been examined. Moreover, the dynamics of several past GLOF events is unknown, even though the reconstruction of past events can aid to understand, anticipate and mitigate damage from future events.

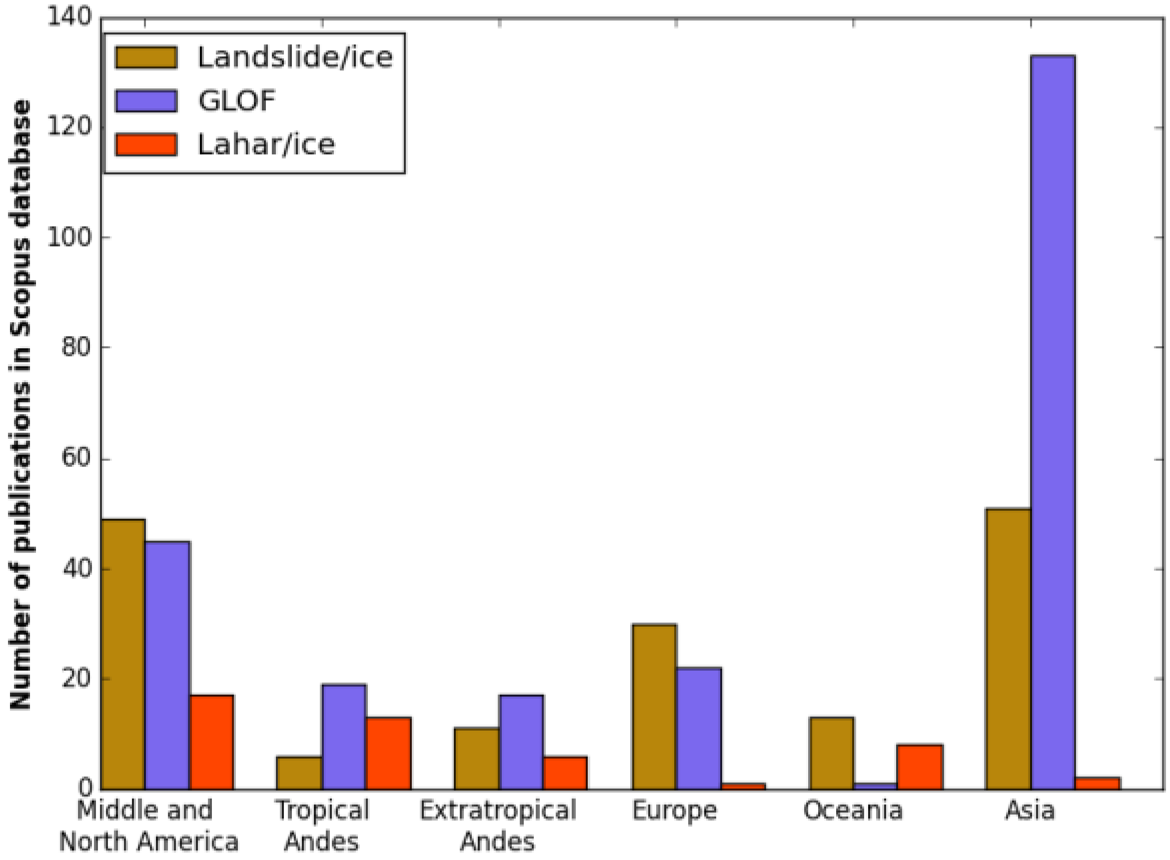

Figure 1.2. Publications in the scientific database Scopus featuring the terms landslide and ice, lahar and ice, and glacial lake outburst flood in the abstract, title and/or the key words. Publications also contained the name of glaciated ranges and countries listed in Ohmura (2009) grouped by (sub-) continents. The extratropical Andes are one of the glacierised areas with the fewest studies of glacier and permafrost related hazards. Scopus database accessed the 10 of December 2015.

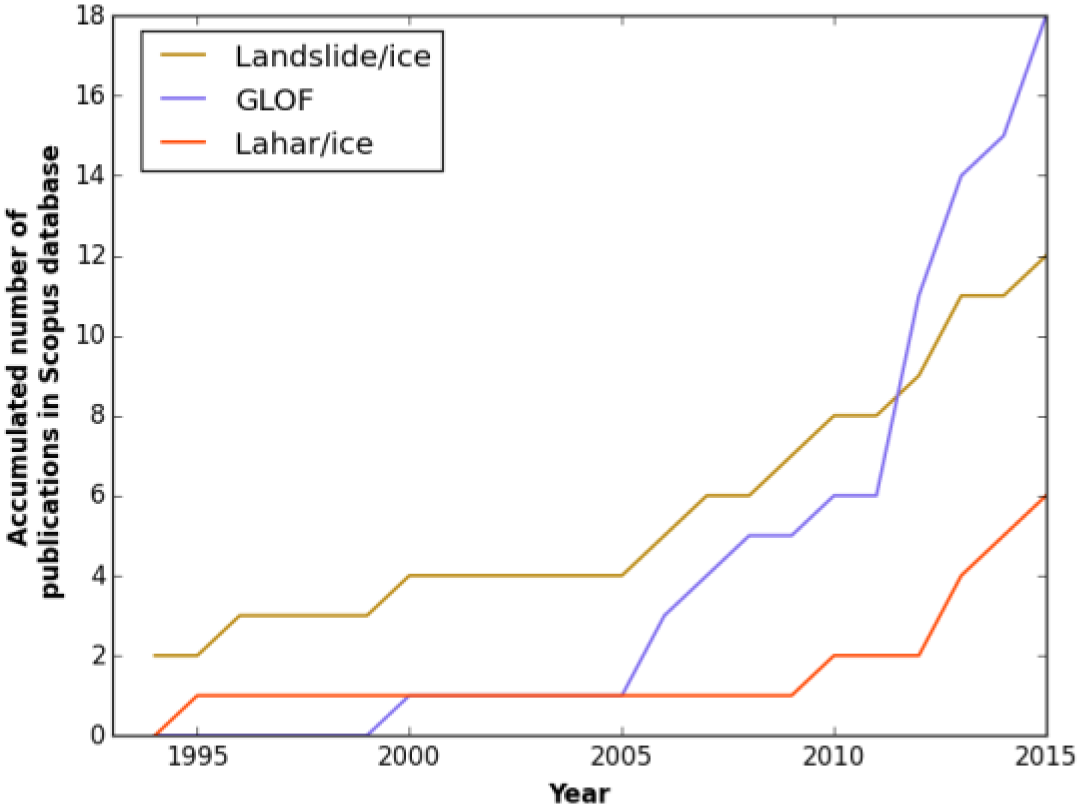

Figure 1.3 Studies of glacier and permafrost related hazards in the extratropical Andes featured in Scopus database. The terms landslide and ice, lahar and ice and glacial lake outburst flood were contained in publications abstract, title and/or key words. Publications also contained the words Chile, Argentina and/or extratropical Andes. An increase in the number of publications is observed from 2010 onwards. Scopus database accessed the 14 of December 2015.

1.2 Objectives of this thesis

Considering the above mentioned knowledge gaps and that a better understanding of the hazardous processes originating in glacier and permafrost areas can help reduce damage produced by these events, the overall aim of this study is to unravel the dynamics, frequency and magnitude of hazardous processes originating in glacial and permafrost areas in the extratropical Andes. As GLOFs are one the most common and hazardous processes affecting glaciated areas in the extratropical Andes, special emphasis is placed on understanding and assessing the GLOF dynamics and hazard. The following objectives are addressed in this study.

Objective 1: Provide a synthesis of the geomorphic and hydrologic processes and hazards originating in glacial and permafrost areas in the extratropical Andes in historic time.

A synthesis of mass movements that affected glacier and permafrost areas, damaging lahars originated in ice-capped volcanoes, GLOFs and other hazardous processes occurred in high-mountain areas can shed light on the frequency and magnitude of these events as well as helping clarify their interregional differences in the extratropical Andes. A review of these events also can help to identify knowledge gaps to address in future research.

Fulfilling this objective will help to answer: What are the distribution, frequency and magnitude of hazardous processes linked with glaciers and permafrost in the extratropical Andes and what are their interregional differences?

Objective 2: Characterise and create an inventory of failed glacial lakes and their surroundings in the extratropical Andes, in order to develop a method to assess the outburst flood susceptibility of glacial lakes in this region.

A description of moraine and ice dammed lakes that drained catastrophically can help to identify common characteristics of hazardous lakes and their surroundings in the extratropical Andes. Indeed, knowledge of features associated with failed lakes in the Tropical Andes and Himalaya has been used to develop methods to assess the outburst flood susceptibility of glacial lakes. These methods, however, are adapted to the climatic and tectonic settings of these ranges.

Objective 2 aims to answer the following questions: What are the characteristics of failed glacial lakes (and thus of hazardous glacial lakes) in Patagonia? What features associated to failed lakes can be used in regional GLOF hazard assessments? How common are hazardous glacial lakes in Patagonian basins?

Objective 3: To unravel GLOF dynamics in geographically contrasting environments and test empirical and physical flow models of these events.

Unravelling the conditioning and triggering factors of GLOFs are crucial steps towards reliable GLOF hazard assessments, which should be based on a sound understanding of the GLOF dynamics. Indeed, a good understanding of GLOF dynamics (e.g. flood progression and flood intensity) may help anticipating future GLOF behaviour. GLOF dynamics vary according to the lake and dam characteristics and according to the geography of downstream areas. Thus, in this study the conditioning and potential triggering factors of GLOFs in the Arid Andes and the wet western Patagonia are analysed. GLOFs are reconstructed and modelled in order to characterise the GLOF dynamics in steep-arid valleys as well as in more gently sloping forested areas.

Objective three aims to answer the following questions: What are the main differences in GLOFs in the high-arid Andes and in maritime western Patagonia? What are the advantages and drawbacks of physical and empirical flow models in simulating GLOFs in these environments?

1.3 Thesis structure

The first chapter of the thesis introduces the topic of glacier and permafrost hazards. The subsequent four chapters of the thesis are written as standalone research papers. Chapter 2, 3 and 4 are already published in *Earth Surface Process and Landforms*, *Natural Hazards and Earth System Sciences* and in *Science of the Total Environment* respectively. Chapter 5 will be submitted to *Natural Hazards*. In Chapter 6 I provide a thesis summary which discusses the conclusions reached in chapters 2 to 5 in the broader context of climate change and the hazards emerging from an evolving cryosphere. At the end of the thesis there is an Appendix with the transcript of the interviews used in chapter 4.

1.4 Chapter's outline

In chapter 2 I provide an overview of the hazardous process and events from glacier and permafrost areas that have occurred in the Chilean and Argentinean Andes in historical time, in order to unravel the conditioning and triggering factors of these events and their inter-regional differences. This is the first comprehensive review of glacier and permafrost hazards in the extratropical Andes. Data were collected through a bibliographic analysis and the multi-temporal study of satellite images. This review helped to identify gaps in our knowledge and suggest future research directions. Major knowledge gaps were identified concerning GLOF's frequency and the conditioning and triggering mechanisms of moraine-dammed lake failures. A lack of knowledge about the GLOF dynamics, their inter-regional differences, and associated hazards was also identified.

In chapter 3 the characteristics of failed moraine-dammed lakes in Patagonia are analysed in order to identify features associated with unstable lakes. These data were used to develop a method to identify glacier lakes susceptible to failure in Patagonia. Data were extracted using remote sensing techniques (to semi-automatically create inventories of glaciers, lakes and vegetation) and flow routine algorithms (to map the flow path of ice-avalanches, mass movements and outburst floods). Data were analysed using the Analytical Hierarchy Process (AHP). This method was used to assess the outburst susceptibility of hundreds of glacier lakes in the Baker Basin, Chilean Patagonia. This scheme could be used in other regions to provide regional-scale GLOF susceptibility assessments.

In Chapter 4 the flow dynamics and social consequences of an outburst flood from a moraine-dammed lake failure in Chilean Patagonia are analysed. The outburst was modelled using HEC-RAS 5 Beta which allows two dimensional modelling of Newtonian flows. The modelling was contrasted with data of flood extent, obtained from satellite images, and flood depth and duration stated by eyewitnesses. Eyewitnesses were interviewed and provided data about the damaging consequences of the event which included the village’s relocation. This case study helps to point out the utility of a recently developed 2D model in GLOF hazard assessments. Furthermore, it shows how the lack of territorial planning and the omission of GLOF hazard assessments can have negative socioeconomic consequences.

Finally, in Chapter 5 I analysed an outburst flood originating from the failure of a sub-glacial lake in the arid Andes of Chile. The outburst flood was reconstructed using empirical and physical models representing the dynamics of highly sediment-charged flows. The RAMMS, LAHARZ and MSF models were used to map the flow extent and derive flow velocity and depth. This case study expands our knowledge of the hazards emerging from high-altitude cold-based glaciers. This GLOF also exemplifies that large floods not only produce changes in the fluvial geomorphology but also in the vegetation cover.

1.5 References

Ballantyne CK (2002) Paraglacial geomorphology. *Quat. Sci. Rev*. 21:1935–2017

Bodin X, Krysiecki JM, Iribarren Anacona P (2012). Recent collapse of rock glaciers. Two study cases in the Alps and in the Andes. *Interpraevent* EA-48.

Carey M (2005) Living and dying with glaciers: People's historical vulnerability to avalanches and outburst floods in Peru. *Global and Planetary Change* 47:122–124.

Evans SG, Clague JJ(1994) Recent climatic change and catastrophic geomorphic processes in mountain environments. *Geomorphology* 10: 107–128.

Grove M (1987) Glacier fluctuations and hazards. *Geographical Journal* 153(3), 351-369.

Haeberli W (1983) Frequency and characteristics of glacier floods in the Swiss Alps. *Annals of Glaciology* 4: 85–90.

Hewitt K (1982) Natural dams and outburst floods in the Karakorum Himalaya. In Hydrological aspects of alpine and high-mountain areas. Edited by J.W. Glen. *International Association of Hydrological Sciences* (IAHS) 138: 259–269.

Holm K, Bovis M, Jakob M (2004) The landslide response of alpine basins to post-Little Ice Age glacial thinning and retreat in southwestern British Columbia. *Geomorphology* 57: 201–216.

Kääb A, Reynolds, JM, Haeberli W (2005) Glacier and permafrost hazards in high mountains. In: Huber, U.M., Bugmann, H.K.M., Reasoner, M.A. (Editors): Global change and mountain regions - a state of knowledge overview. Springer, Dordrecht, 225-234.

Lliboutry L, Arnao BM, Pautre A, Schneider B (1977) Glaciological problems set by the control of dangerous lakes in Cordillera Blanca, Peru. I. Historical failures of morainic dams, their causes and prevention. *Journal of Glaciology* 18(79): 239-254

Naruse R (2006) The response of glaciers in South America to environmental change. In: Knight, P. (Ed.), In Glaciers and Earth's Changing Environment. Blackwell, Oxford, UK, pp. 231-238.

2 Hazardous processes and events from glacier and permafrost areas: lessons from the Chilean and Argentinean Andes

2.1 Abstract

Glacier and permafrost hazards such as glacial-lake outburst floods and rock-ice avalanches cause significant socioeconomic damages worldwide, and these processes may increase in frequency and magnitude if the atmospheric temperature rises. In the extratropical Andes nearly two hundred human deaths were linked to these processes during the Twentieth Century. We analyzed bibliographical sources and satellite images to document the glacier and permafrost dynamics that have caused socioeconomic damages in this region in historic time (including glacial lake outburst floods, ice and rock-ice avalanches and lahars) to unravel their causes and geomorphological impacts. In the extratropical Andes, at least 15 ice-dammed lakes and 16 moraine-dammed lakes have failed since the Eighteenth Century AD, causing dozens of floods. Some floods rank amongst the largest events ever recorded ($5000x10^6$ m^3 and $229x10^6$ m^3 respectively). Outburst flood frequency has increased in the last three decades, partially as a consequence of long-term (decades to centuries) climatic changes, glaciers shrinkage, and lake growth. Short-term (days to weeks) meteorological conditions (i.e. intense and/or prolonged rainfall and high temperature that increased meltwater production) have also triggered outburst floods and mass movements. Enormous mass failures of glaciers and permafrost (>$10x10^6$ m^3) have impacted lakes, glaciers, and snow-covered valleys, initiating chain reactions that have ultimately resulted in lake tsunamis and far-reaching (>50 km) flows. The eruption of ice-covered volcanoes has also caused dozens of damaging lahars with volumes up to $45x10^6 m^3$.Despite the importance of these events, basic information about their occurrence (e.g. date, causes, and geomorphological impact), which is well established in other mountain ranges, is absent in the extratropical Andes. A better knowledge of the processes involved can help to forecast and mitigate these events.

2.2 Introduction

Global warming since the Little Ice Age (LIA) has resulted in transformations of geomorphic systems in mountain areas worldwide, and has accelerated certain catastrophic processes. These processes are closely linked with the recession and thinning of glaciers (Evans & Clague, 1994) and permafrost thawing (Haeberli 2013) and effects include;

- the destabilisation of alpine slopes due to stress redistribution after glacier shrinkage (Holm et al., 2004).
- the generation of outburst floods and debris flows as a result of the formation and failure of ice and moraine dammed lakes (Costa & Schuster, 1991)
- the genesis of mass movements as a consequence of permafrost degradation (Gruber & Haeberli, 2007).

These phenomena, together with glacier-volcano interactions and other glacier and permafrost related hazards (*sensu* Kääb et al*.,* 2005a), act quickly and can place thousands of lives at risk (Lliboutry et al., 1977; Carey 2005). They can affect areas located hundreds of kilometres from their origin, and cost 10^8 EURO annually worldwide (Kääb et al*.,* 2005b).

Research on glacier and permafrost hazards was developed in Europe and North America where infrastructure located in/or near glacial and periglacial environments has been impacted by glacier floods (Haeberli, 1983; Clague & Evans, 2000), rock-ice avalanches (Salzmann et al., 2004), lahars (Björnsson, 2002) or a combination of these processes. In the European Alps there are records of damaging glacial lake outburst floods dating as far back as 1595 (Grove, 1987), and casualties linked with ice avalanches were recorded in 1597 (Hambrey & Alean 1992). Disasters associated with glaciers in regions such as the Himalayas and Tropical Andes also have a long-standing history. The earliest records of severe damages and casualties related with glacier floods in these mountains date from 1533 and 1702 respectively (Hewitt 1982; Reynolds et al., 1998). In the last few decades, catastrophic events such as the mass flows of Nevado Huascarán in Perú in 1962 and 1970, which caused together nearly 7000 deaths (Evans et al., 2009), and the Kolka-Karmadon rock/ice slide and debris flow, in the Russian Caucasus in 2002 (Haeberli et al., 2004), amongst others, have aroused public and scientific attention about glacier hazards in these less-studied mountain ranges.

Glaciers in the extratropical Andes of South America (~17°-55° S) cover more than 23,000 km², in a wide range of geographical and climatological conditions. Overall, these glaciers are in retreat, and in Patagonia, an accelerated down-wasting trend is evident (Naruse, 2006; Masiokas et al., 2009; Davies & Glasser, 2012). Glacier retreat has destabilized bedrock and drift-covered slopes promoting mass movement, and has generated numerous glacial lakes (Harrison et al., 2006; Warren & Aniya, 1999). This situation together with the presence of ice-capped volcanoes, many of them active, steep hanging-glaciers and surge-type glaciers, makes the Chilean and Argentinean Andes a region prone to glacier- and permafrost-related hazards (Espizúa & Bengochea, 1990; Carrión, 2007 and Figure 2.1). The increasing use of glacial and periglacial belts by the mining industry, hydropower installations and tourism facilities, as well as the occurrence of numerous damaging glacier floods in the last thirty years (see e.g. Dusaillant et al., 2009) has stimulated interest in understanding the dynamics, magnitude and frequency of these phenomena. The aims of this paper are to a) document historic geomorphic and hydrologic processes and related hazards originating in glacial and periglacial areas in the Chilean and Argentinean Andes b) examine their temporal and spatial distribution c) provide insight into the preconditioning and triggering factors of these phenomena, and d) identify gaps in our knowledge and suggest future research directions.

In order to address these objectives we conducted a literature review and analyzed medium resolution (15-30 m of spatial resolution) satellite images of the entire region from the 1980s onward. Because few academic studies have been carried out, documenting the geomorphic and hydrologic processes and related hazards associated with glaciers and permafrost in the extratropical Andes requires a thorough investigation of a wide range of bibliographic sources such as technical reports and newspapers. The works of Gonzalez-Ferrán (1995); Carrión (2007) and Masiokas et al., (2009) serve as guides for the significant events in the region. We focus on analyzing processes of large magnitude (area, volume or run-out) registered in historical times (no older than 16th century). Due to the large number of eruptions of ice-capped volcanoes and the consequent generation of tens of lahars (see e.g. González-Ferrán., 1995) only the most damaging of these events are presented here. This bibliographical review is complemented with multi temporal analysis of Landsat TM/ETM+ images to estimate the timing of previously unnoticed, moraine and ice dammed lakes outburst, and to measure flow paths, glacier, mass movement and glacial lake morphometry. To facilitate the analysis, the regionalization of Lliboutry (1998) modified by Masiokas et al., (2009) is utilized which subdivides the extratropical Andes into the following regions; Desert Andes (17°-31°S), Andes of Central Chile and Argentina (31°-36°S), North Patagonian Andes (36°-45°S) and South Patagonian Andes (south of 45°). This is the first comprehensive review of hazardous processes related to glaciers and permafrost that have affected the extratropical Andes.

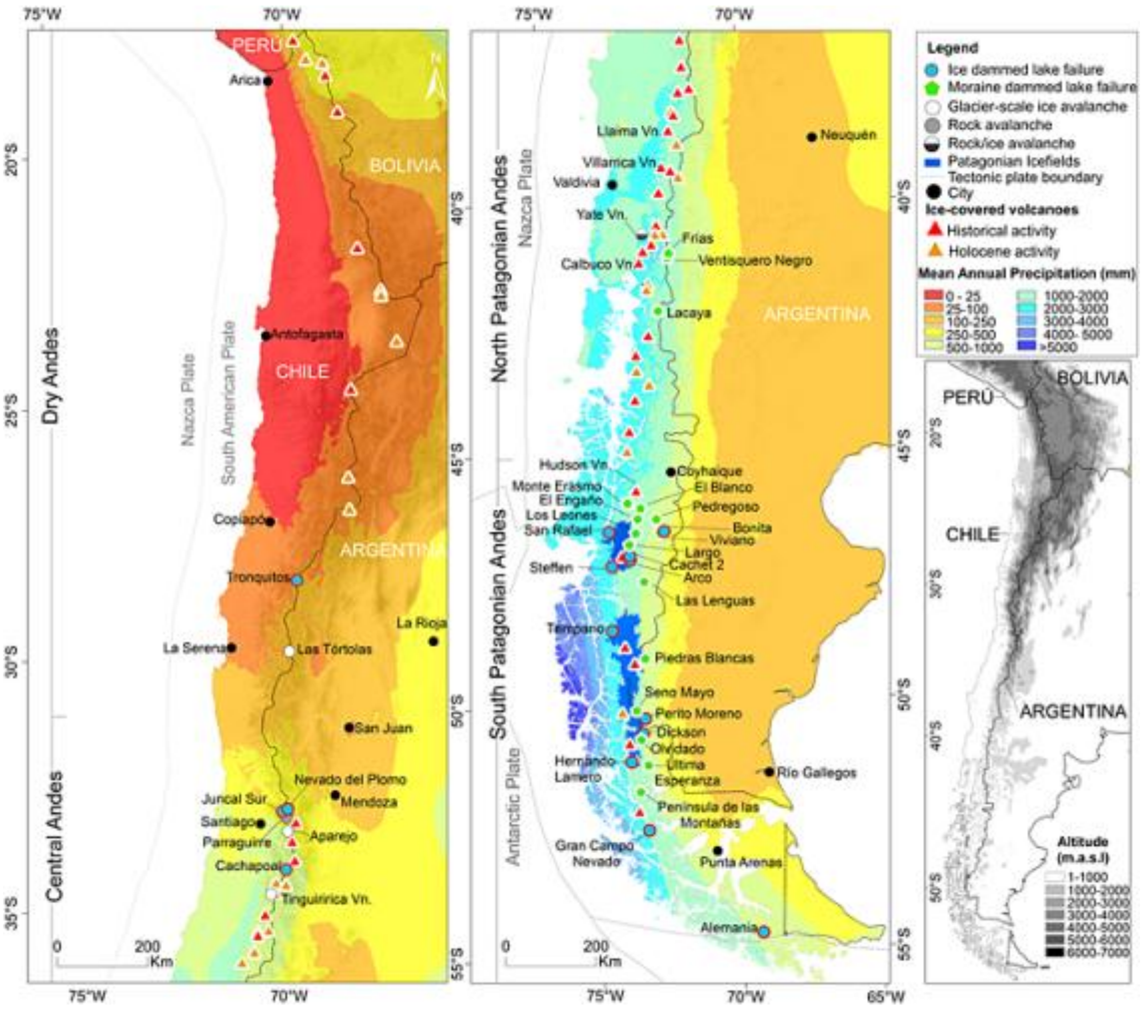

Figure 2.1. Hazardous events from glacier and permafrost areas in the extratropical Andes.Note the cluster of moraine dammed lake failures on the east side of the North Patagonian Icefield.Volcanoes in the Dry Andes are covered mainly by creeping ice-rich permafrost (rock glaciers).Ice-covered volcanoes were mapped according to Siebert and Simkin(2002), Chilean glacier inventories and satellite images. Rainfall data are based on Hijmans et al.,(2005).

2.3 Geographic setting

The Chilean and Argentinean Andes present a wide range of topographic and climatic conditions. The highest peaks of the Andes decrease in altitude southward from ~7000 m.a.s.l, in the dry Subtropical and Temperate-Mediterranean regions (~17°-36°S), to ~4000 m.a.s.l in the wet-Temperate Andes in Patagonia (Figure 2.1). Precipitation levels in the Subtropical and Mediterranean climates is very low, for example the high Andes of Tarapacá (18°) experience only 400 mm/year. South of ~ 40°S, precipitation levels increase dramatically, reaching ~6000-8000 mm/year on the South Patagonian Icefield (~50°S). In this region, precipitation also shows a strong west to east gradient, reaching a maximum on the windward section of the range adjacent to the Pacific, and decreasing on the eastern side of the Andean main divide (Escobar et al., 1992; Messerli et al., 1998; Viale & Nuñez, 2011). This geographic diversity is reflected in ice bodies which range from small glaciers (≤ 0.25 km^2) located in high mountain peaks (≥5000 m.a.s.l) in the arid north, to large tidewater glaciers in the Patagonian Andes and Cordillera de Darwin. Glaciers in dry-continental regions in the north have a low mass turnover and are frequently surrounded by permafrost, while glaciers in humid-maritime regions to the south show relatively fast flows, have high mass turnover and can extend into forested areas (WGMS 2008; Figure 2.2).

In spite of this glaciological and climatic variety, the majority of glaciers have experienced substantial mass losses since the LIA expansion in the 16th to 19th centuries (Masiokas et al., 2009). Glacier retreat along the Andean mountain range has shaped and exposed steepened rockwalls and drift-mantled slopes and have caused numerous glacial lakes to form (especially in Patagonia). Along with the presence of ice-capped volcanoes, and an active seismicity, this makes glacial and periglacial belts highly dynamic in this region.

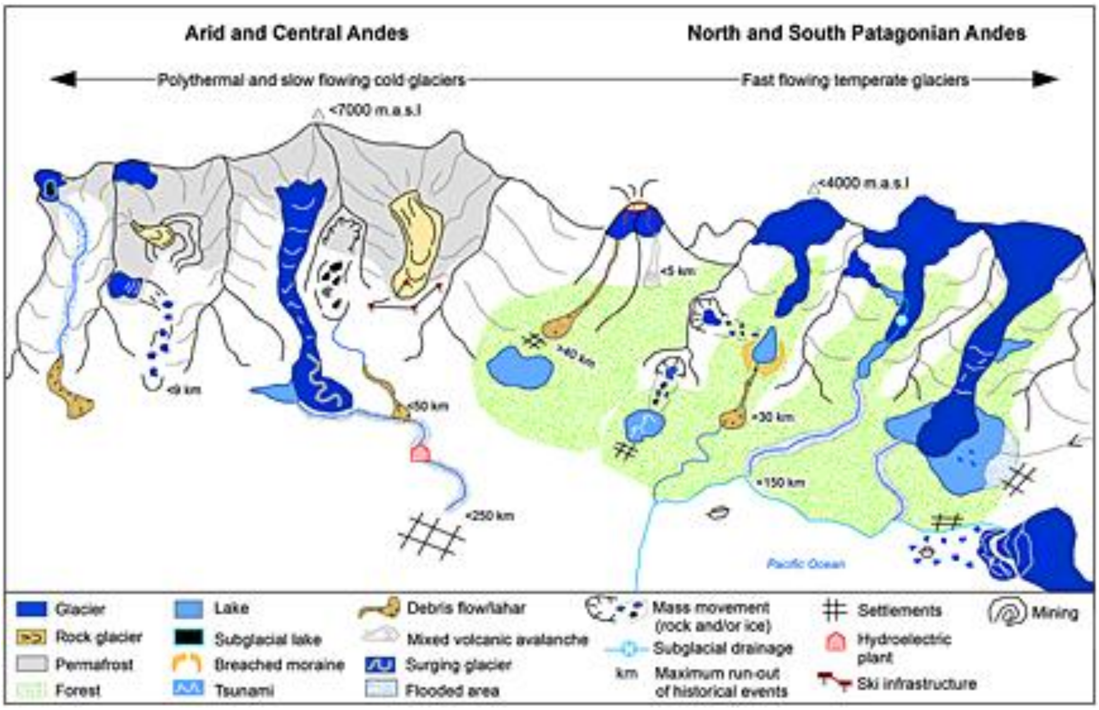

Figure 2.2. Schematic diagram of glacier and permafrost related hazards in the extratropical Andes based on historical records.Note that hazardous processes in the arid and central Andes have been mainly related to glacier advances and the development of economic activities in high mountain areas. In the Patagonian Andes,glacier retreat and fragmentation has influenced most of the hazardous events.

The population living in glacial and periglacial belts in the extratropical Andes is scarce. However, mining and hydropower developments have occupied these areas and large cities such as Santiago (>6000.000 inhabitants) and Mendoza (>114000 inhabitants) are located at the foot of the Andes. Furthermore, more than 30 routes cross the Andes connecting Chile and Argentina and more than 1.5 million people use the main route annually (named Ruta CH-60 in Chile and Ruta Nacional Nº7 in Argentina).

2.4 Glacial lakes and outburst floods

Glacial and periglacial regions of the Andes host geographic characteristics that favour the presence of glacial lakes such as glacially overdeepened troughs, voluminous moraines, narrow valleys and active glaciers. The number and dimension of glacial lakes in the extratropical Andes increases southward, as does the number and size of glaciers. In the Desert and Central Andes, the most common glacial water bodies are small ponds embedded in moraine deposits, thermocarst lakes and temporary lakes formed by episodic glacier advances. In Patagonia, the advance of glaciers during LIA and their subsequent recession has resulted in the formation of numerous moraine-dammed lakes. Glacier shrinkage also has favored the development of glacier-impounded lakes especially in tributary valleys of the Northern and Southern Patagonian Icefields (NPI and SPI respectively). In the NPI, the size of the glacial lakes (especially those in contact with glaciers) increased 64.9% between 1945 and 2011 and the number of glacial lakes augmented (Loriaux & Casassa 2013). This might reflect a generalized phenomenon in Patagonia although with local variations.

2.4.1 Glacier-dammed lake outburst floods

Glacier-dammed lake floods occur when subglacial, englacial, supraglacial or ice-marginal water bodies impounded by ice are discharged rapidly by the formation and/or enlargement of channel(s) under, through, over a glacier or at its margins (Post & Mayo, 1971; Costa & Shuster, 1988). Floods triggered by ice-dam failures have caused damage in glacierised mountains worldwide. They have reached high peak discharges (up to 105,000 m^3/s) and released large volumes of water ($\leq 5400 \times 10^6$ m^3; Mayo, 1989; Walder & Costa, 1996). Water release is controlled by threshold exceedance in the glacial hydraulic system, and is strongly related to changes in glacier extent and ice thickness, lake bathymetry, inflow (Walder & Costa, 1996; Tweed & Russell, 1999) and glacier thermal conditions (Gilbert et al., 2012).

Mechanisms proposed for initiating lake failures include; (a) ice-dam flotation and subglacial drainage (theoretically starts when the water depth exceeds 90% of ice-dam height); (b) plastic yielding of the ice dam, causing subglacial release when the hydrostatic pressure of the lake exceeds the cryostatic pressure (critical lake depth ~200 m); (c) ice-dam weakening by subglacial volcanic activity and widening of sub- or en-glacial conduits by thermal erosion; (d) subglacial cavity formation and subglacial release caused by rapid basal ice flow due to an increase in the water supply; (e) syphoning and sub-glacial and englacial release due to pressure drops in the internal glacial drainage system to which the lake is connected; (f) overtopping of the ice-dam and supraglacial drainage when the lake level exceeds the ice-dam height or the lowest topographical control; (g) widening of a breach in the ice/wall interface that allows supraglacial or ice-marginal discharges (Post & Mayo, 1971; Tweed & Russell, 1999); (h) and the mechanical rupture of highly fractured dams (e.g. surging glaciers or ice avalanches) with immediate peak discharge (Haeberli 1983).The most common mode of drainage is the development and/or widening of sub-glacial conduits caused by one or a combination of these mechanisms (Walder & Costa, 1996).

Glacier-dammed lake outbursts have been documented in at least 15 different sites along the extratropical Andes affecting lakes ranging from several square kilometres in surface area to small ponds (<0.01 km^2). More than 60% of the drained lakes were located in ice-marginal positions although subglacial and supraglacial lakes have also been emptied. Some of these water bodies have drained more than once over a period of months or years in quasi-regular manner such as the Lago Arco outbursts, registered every summer (except in 1954) between 1920 and 1958 (Tanaka, 1980). Conversely, some lakes formed and drained irregularly (e.g. Cachet 2, Grande del Nevado del Plomo) or only once in historical times (e.g. Juncal Sur). In the 9 best documented events, the entire lake drainage occurred very quickly over the course of hours or just a few days, releasing water volumes ranging from 0.4x10^{6}m^3 to 5000x10^{6}m^3, with peak discharges from 150m^3/s to 15000m^3/s (Table 2-1). Four ice dams have been formed by the obstruction of rivers due to glacier advances, and in two cases (Cachapoal and Grande del Nevado del Plomo), lake formation has been attributed to glacier surges (Röthlisberger, 1986; Espizúa & Bengochea, 1990). The causes and periodicity of the surges remain unknown. In at least 8 cases the water was released directly (or after few kilometers) into another lake, delaying or dampening the overall effect of the flood.

Table 2-1 Ice-dammed lake outburst floods.

Location	Lake type[a]	Date(s)[b]	Volume Drained 10^6 m³	Peak Discharge m³/s	Comments	References
Gl. Río Seco de los Tronquitos 28°33ˈ-69°44ˈ	3	14/05/1985	5	11000	A subglacial lake located at 5200 m.a.s.l failed abruptly generating a flood and debris flow. In a lapse of 3 hours, the released water was discharged in a semi empty reservoir located ~105 km downstream. The maximum velocity of the flood was estimated in 12 m/s. Satellite images prior to the event shows a debris fan downstream of the glacier that could correspond to a past outburst flood. A lake is visible in a 2008 image in the site where the subglacial lake was located.	Peña & Escobar (1987); This work
Gl. Grande del Nevado del Plomo 33°07ˈ-69°59ˈ	2	02/01/1788 11/01/1934 Feb 1985 Feb 1985 Feb 1985	? 53 35 21 20	? 2700 284 277 184	These floods have been caused by the blockages of Plomo River by the surge of Grande del Nevado del Plomo Glacier. The 1934 event resulted in more than 20 casualties and damages in infrastructure in order of 6.000.000 Argentinean pesos (1934 USD$ = ~1.800.000) in a corridor of ~200 km. In the 1985 event, no damages or casualties were reported. This glacier experienced a new surge in 2007 without causing a flood.	Prieto, (1986); La Vanguardia, (1934); Fernández et al., (1985, 1991);
Gl. Juncal sur 33°09ˈ-70°07ˈ	2	26/02/1954	0.4	400	This flood was caused by the blockage of a stream by the advance of Juncal Sur Glacier in 1946/47. The ice-dammed lake failed in 1954. The flood interrupted temporarily the operation of a hydropower plant in Olivares River.	Lliboutry, (1956); Peña & Klohn, (1987)
Gl. Cachapoal 34°22ˈ-70°05ˈ	2 3.5	Dec 1847 31/01/1981 to 17/02/1981	1.5-2	150	In 1847, villages located along Cachapoal valley were affected by a large flood that transported large amount of debris and snow. An undetermined number of fatalities and damages in infrastructure and farm settlements were reported. The most damaged village was El Olivar. In 1848, the formation of a lake in the Cachapoal source was documented. This phenomenon caused public concern delaying harvesting with subsequent economic losses. Both events were coincident with the sudden advance of Piuquenes (Cachapoal) Glacier described by Plagemann (1887). River blockage by the advance of Cachapoal Glacier probably caused the lake formation and the 1847	Plagemann ,(1887); Urrutia & Lanza, (1993); Peña & Klohn, (1987)

					flood. In 1981, 8 floods, with their source in the Cachapoal Glacier, were registered in 19 days temporarily interrupting the operation of a hydropower plant.	
Gl. San Rafael 46°42ˈ-73°50ˈ	4	16/12/1985	?	?	The formation and emptying of a supraglacial pond (~3200 m^3), in a lapse of 6 days, and an extraordinary upwelling in San Rafael lake, at the glacier terminus, were observed.	Ohata et al., (1985)
Estero Laguna Bonita 46°44ˈ-72°18ˈ	5	Between 2002 and 2008	?	?	Event registered at least two times between 2002 and 2008. During this period the ice-dammed lake (~0.09 km^2) was filled and drained twice until the shrinkage of the glacier inhibited the formation of a new lake. The floods stripped vegetation patches about 3.8 km from the lake.	This work
Gl. Colonia-L. Cachet 2 47°11ˈ-73°15ˈ	1	07/04/2008 08/10/2008 21/12/2008 05/03/2009 16/09/2009 06/01/2010 03/03/2010 27/05/2011 26/01/2012 31/03/2012	230 190 125 >200 200 146 202 - - -	2500 2500 2000 >2800 2500 - - - - -	Lake Cachet 2 (3.7 km^2) emptied 10 times between 2008 and 2012. Baker River level grew more than 4 m during the floods. Damages to farm settlements, losses of livestock and interruption of terrestrial communications occurred. The type and amount of damages vary among the events.	Dussaillant et al.,(2009);F. Escobar (personal communication, 2012)
Gl. Colonia-L. Arco 47°17ˈ-73°15ˈ	1	1881 25/01/1953 29/12/1955 31/12/1956 07/01/1958	265	?	Several floods affected Colonia River between 1881 and 1963. Between 1920 and 1958 (except in 1954) floods were registered every summer at the end of December or January. Floods lasted 3 days and the water rose up to 7 m above the normal level. Using geomorphic and lichenometric methods the outburst flood volume of 1881 was estimated in 265 x 10^6 m^3. The 1950s events generated livestock losses.	Tanaka (1961, 1980, as cited in Carrión, 2007 and Winchester & Harrison 2000); Winchester & Harrison, (2000)
Gl. Steffen NW lake	1	Between 1987 and	?	?	The empting of an ice-dammed lake of 1.91 km^2 occurred between 1987 and 2000. A significant shrinkage of Steffen Glacier observed in	Maas et al.,2012;This

47°23'-73°48'		2000 and in August and December 2010			this period probably favored or caused the lake drainage. In 2010 a lake emptied and filled twice reducing the water level more than 60 metres in each event.	work
Gl. Témpano 48°41'-73°56'	2	Between April and May 2007	?	?	A lake of 1.8 km^2 emptied in 2007. Event occurred distant from populated areas, no damages reported.	Planet Action, (2010)
Gl. Perito Moreno 50°27'-73°02'	2	1953 1956 1966	2000 5000 3800	12000 20000 15000	Event registered about 24 times between 1917 and 2012. The increase of Brazo Rico and Argentino lake levels occasionally inundates farmlands, roads, and constructions located in lake shorelines and the flood causes damages in bridges over Santa Cruz River. Damming events of Perito Moreno glacier have become a tourist attraction.	Walder & Costa, (1996); Chinni & Warren, (2004); Stuefer et al.,(2007); La Nación, (2012)
Gl. Dickson 50°44'-73°06'	4	18/01/1982 16/12/1983 26/02/1983	220 230 290	360 330 340	Floods in Paine River occurred over 17 and 23 days causing interruption of terrestrial communications and concern about economic losses in local tourism industry.	Peña & Escobar, (1983)
Hernando Lamero 51°19'-73°33'	?	1946 or before	?	?	An empty, and probably recently drained lake containing ice blocks, was observed by Lliboutry in 1946 aerial photographs.	Lliboutry, (1956)
Gran Campo Nevado 52°43'-73°06'	1	2007 or before	?	?	An empty lake containing ice blocks was observed by Gino Casassa in 2007.	Planet Action, (2010)
G. Alemania 54°49'-69°21'	1	Between 2008 and 2011	?	?	Lake of 8.33 km^2 reduced to 5.61 km^2. Event occurred far from populated areas, no damages reported.	Glacier Change World Press (2012);This work

[a] Ice-dammed lake types: 1) lakes in tributary valleys dammed by glaciers in main valleys; 2) lakes in main valleys dammed by glaciers in tributary valleys; 3) lakes within glaciers; 4) lakes on the surface of glaciers; 5) Lakes between glaciers and valley walls. Lake types after Hutchinson (1957). [b] Date refers to the starting day of the flood, in some cases, the discharge occurred in more than one day.

The ice-dammed lake drainage mode had varied amongst these events. For example in Cachet 2 and Dickson outbursts, the water was released via sub-glacial tunnels (Figure 2.3). Circular collapsing features and fractures in the glacier surface were observed in both sites after the outburst indicating the possible sub-glacial pathway (Peña & Escobar, 1983; Dusaillant et al, 2009). In Lago Argentino, and probably the Grande del Nevado del Plomo outbursts, the water began draining through englacial and sub-glacial conduits. This was followed by the collapse of the main tunnel roof which allowed subaerial drainage (King, 1934; Walder & Costa, 1996; Stuefer et al., 2007). The extraordinary peak discharge of the Grande del Nevado del Plomo outburst in 1934 (one order of magnitude larger than the 1985 events) might be related to the blockage of the subglacial drainage system as a consequence of tunnel roof collapse, and the sudden mechanical rupture of the dam. The Cachet 2 hydrographs (Figure 2.3B) shows a steeper rising limb than falling limb, which also may indicate a combination of hydraulic and mechanical ruptures.

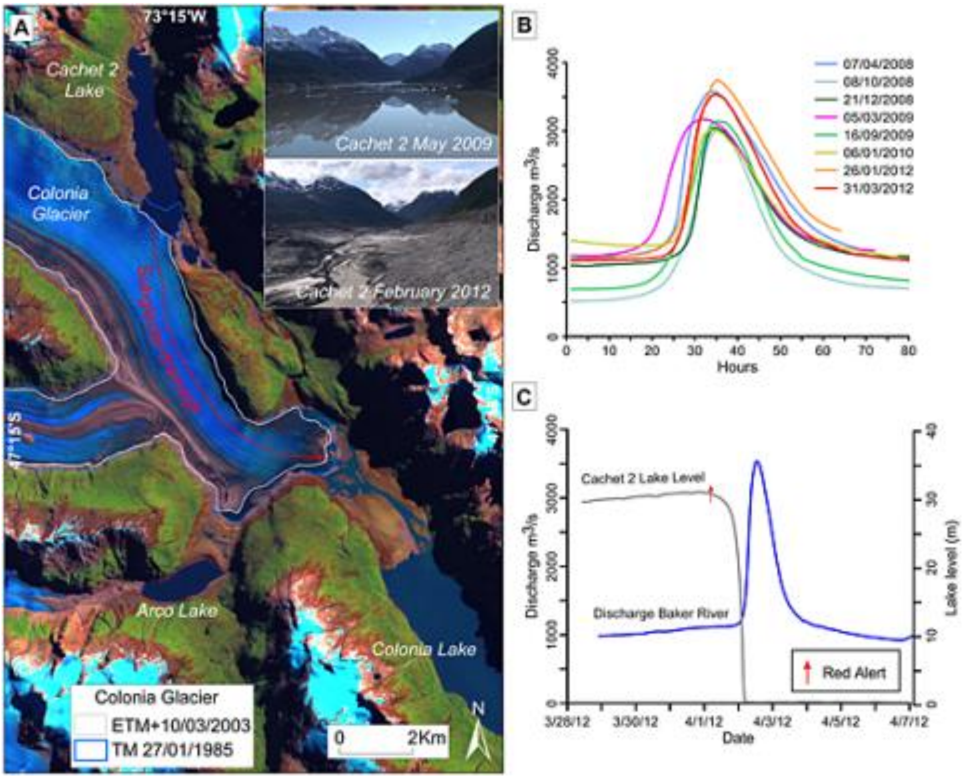

Figure 2.3 Changes in Colonia Glacier between 1985 and 2003 and the sub-glacial pathway (8km) of lake Cachet 2 outburst floods. Note the lake growth (17%) as a consequence of glacier shrinkage.Photographs of Lake Cachet before and after the the outburst flood in A by Adrián Lillo.B) Flood hydrographs from Baker-Colonia gauging station (45 km from the lake) showing discharges of more than three times the base flow during outburst events. Data from Dirección General de Aguas. C) A flood warning system is operating in the Baker Valley since 2009. The flood alert is declared when the level of the lake decreases six or more centimetres per hour (Juan Vilchez, DGA, personal communication).In spite of false alarms, the warning system has been successful in providing several hours of advance warning to evacuate areas at risk.The attenuation of the floods by sub-glacial drainage and the scarce and distant population at risk has helped the succes of the system.

Analysis of the flood discharge of the Rio Seco de los Tronquitos event also indicates a complex initiation process. Peña & Escobar (1987) stated that the most probable cause of the sudden drainage of the sub-glacial lake was an abrupt mechanical failure of the ice-dam. This interpretation was made because it was not possible to explain the high peak discharge at the base of the glacier (11000 m^3/s) by the melt-widening process using the Nye (1976) hydrodynamic model.

These examples illustrate that different mechanisms have operated independently, in conjunction and/or successively in each ice-dam failure. The widening of a breach between the glacier and valley walls seems to be one of the common causes of lake drainages related with advancing glaciers such as Grande del Nevado del Plomo and Perito Moreno. However, drainage triggers, such as volcanic heat and overspill, which have been reported in other mountain ranges of the world, have not been implicated in lake failures in the extratropical Andes. The absence of eyewitness accounts and the lack of geophysical, limnimetric or hydrologic data limits our ability to unravel the exact mechanisms of lake failures in many cases in this region.

The geomorphic and sedimentary consequences of outburst floods have been described in few cases (King 1934; Peña & Escobar 1987; Dusaillant et al., 2009; Bastianon et al., 2012). In some events, this information has been used to reconstruct the peak discharge, velocity and/or flood volume. However, the overall effects of floods on the fluvial system and broader-scale landscape remains poorly investigated. The Río Seco de los Tronquitos event, which occurred in the Arid Andes of Chile in 1985, eroded large amounts of unconsolidated alluvium along its channel (100-150 m wide) and valley margins (Fernando Escobar, personal communication 2013) producing extensive aggradation downstream in the floodplain and burying some wetlands. Where the flow direction changed significantly, a sheet of mainly fine sediment was deposited over river terraces and valley walls producing levees that are still evident in the Manflas valley (Figure 2.4). These elevated sediments were used by Peña & Escobar (1987) to estimate the flow velocity in river cross-sections (4 to 12 m/s). The Grande del Nevado del Plomo flood of 1934, also produced extensive aggradation in the first few kilometers below the ice-dam exit. According to King (1934), the central part of the river bed was raised by 1.5 m over a length of 4 km as a consequence of this flood.

Figure 2.4. Geomorphological consequences of the May 1985 Tronquitos outburst flood and debris flow. A) Ice tunnel (~40m high) formed by the abrupt drainage of a sub-glacial lake. B) Sedimentary deposits from the flood are stranded more than 10m above the floor of the Manflas Valley (indicated by a red arrow). C) The deposits (limited by a black dashed line) consist of matrix-supported sediments, including rocks up to tens of centimetres in diameter.

The largest historic glacial outburst floods in the extratropical Andes occurred in Patagonia, but scarce information indicates that their geomorphic impact has been less significant than floods that affected the regions located farther north. This situation is probably explained by the greater topographic relief and consequent steep channel gradients in the Arid and Central Andes that favor high-energy flows with higher erosive capacity, and the attenuation of flood effects by downstream lakes in Patagonia. According to Dusaillant et al., (2009), the outburst floods of Cachet 2 Lake (CHN) in 2008, the largest floods recorded since the gauge installation in 1963, did not generate significant changes in Colonia River channel. However, Bastianon et al., (2012) suggest increases in suspended sediment concentration of up to 8-fold and increases in load of 10 to 20-fold during Cachet 2 outburst floods.

Fluvial mesoforms and sedimentary sequences illustrate the landscape imprint of large palaeofloods in Patagonia. Dusaillant et al., (2009) recognized high-elevated channels, imbricated boulders and boulder bars containing rocks of ≤5 m of diameter in the Lake Colonia outlet. These features were interpreted as indications of catastrophic paleofloods with peak discharges up to 16.000 m^3/s. Accumulations of sand and gravel below drained lakes and glaciers have also been interpreted as deposits resulting from catastrophic failures of glacier-dammed lakes in Patagonia (Glasser & Jansson 2008). Other features associated with lake drainages in this region are empty basin lakes (e.g. Steffen NW), lake terraces and glacio-lacustrine deposits.

2.4.2 Moraine-dammed lake outburst floods

Floods produced by moraine-dam failures have affected most of the glaciated mountains of the world and can be particularly damaging because they generally release large amount of water in a short time from areas of high relief, and are capable of flooding regions hundred kilometers from their origin (Costa & Schuster, 1988). Furthermore, floods commonly develop into destructive debris flows as a consequence of sediment entrainment from failed dams (Lliboutry et al., 1977; Breien et al., 2008).The drainage mechanism most frequently cited is overtopping, followed by progressive expansion of a breach in the dam. Rainfall, meltwater and wave(s) produced by mass movements often trigger the overflow and dam failures. Other processes such as piping after earthquakes and the mechanical failure of ice-cored moraines have also been stated as possible causes of lake drainages (Lliboutry et al., 1977; Buchroithner et al., 1982). The stability of a moraine dam and the likelihood of an outburst depend on its geometry, internal characteristics and the probability of a triggering event (Richardson & Reynolds, 2000). Statistical analysis shows moraine dams that are more susceptible to failure have low width-to-height ratios, are ice-cored, are composed by readily erodible material (sand and gravel), and/or impound large lakes (MacKillop & Clague, 2007).

There are 16 historically documented cases of outburst floods from moraine-dammed lakes in the extratropical Andes (Table 2-2). All of these events affected lakes in Patagonia, which is the region that concentrates the largest number of moraine dams in the extratropical Andes. Data about water volume released and peak discharges is limited as outbursts have impacted mostly uninhabited areas receiving scarce scientific attention. The outburst flood volume has been assessed in two cases, Cerro Largo and Ventisquero Negro. The first is probably the largest historic outburst flood (in terms of volume) from a moraine-dammed lake failure observed worldwide (Clague & Evans, 2000). This event, occurred in March 1989, released $229x10^6$ m^3 of water and carried a great amount of debris along the Soler Valley (Hauser (2000); Figure 2.5). Eyewitnesses reported a 6-10 metre high wave followed by a steady and then sharp increase in the river level, characteristics probably associated with the initiation and progressive enlargement of a breach in the dam (Hauser 2000). The author estimated, using the empirical formula of Clague & Mathews (1973) that the peak discharge of the Cerro Largo outburst flood was 1800-2000 m^3/s (the peak discharge estimated with the Huggel et al 2002 formula is one order of magnitude larger). The May 2009 Ventisquero Negro outburst, released just $10x10^6$ m^3 of water. However the peak discharge of this event (4100 m^3/s) (Worni et al., 2012) was double the size of the Cerro Largo flood. The Ventisquero Negro event carried a debris volume of approximately 250,000 m^3 and reached a maximum velocity of about 20 m/s (Worni et al., 2012).

Table 2-2 Moraine-dammed lake outburst floods.

Location	Date(s)	Comments	References
Gl.Frías 41°08'-71°48'	Between 1942 and 1953	Complete lake emptying. Event occurred far from populated areas, no damages reported.	Rabassa et al.,(1979)
Gl. Ventisquero Negro 41°12'-71°49'	21/05/2009	Original lake surface of 0.55 km^2 reduced to 0.32 km^2. About 10x10^6 m^3 of water were released in just 3 hours. Roads, bridges and tourist facilities were damaged. Cost of repears was in order of 750.000 Argentinean pesos (2009 USD$ = ~200.000).	Worni et al., (2012); Río Negro, (2009); This work
Río Lacaya 42°18'-72°09'	Between 2000 and 2001	Original lake surface of 0.33 km^2 reduced to 0.15 km^2. The outburst produced a large debris flow that stripped vegetation patches along a ~20 km path. Event occurred far from populated areas, no damage reported.	This work
Monte Erasmo 46°07'-73°14'	Between 1985 and 2000	The outburst flood stripped vegetation patches along a ~6 km path. However, the lake surface (0.65 km^2) was not reduced significantly.	This work
Estero El Blanco 46°14'-72°52'	Between 2000 and 2003	Original lake surface of 0.12 km^2 reduced to 0.04 km^2. The outburst produced a debris flow that stripped vegetation patches along a ~8 km path. Event occurred far from populated areas, no damage reported.	This Work
Río Engaño 46°27'-72°58'	16/07/1955? 11/04/1976	Partial lake emptying, the actual lake surface is 0.8 km^2. The 1976 flood forced a temporary evacuation of Murta village and, in the long term, a change in its location. The origin of the 1955 flood remains uncertain.	Hauser, (2000) This work
Estero El Pedregoso 46°28'-72°25'	Between 1985 and 1987	Original lake surface of 0.12 km^2 reduced to 0.09 km^2. The outburst produced a debris flow that stripped vegetation along a ~3.6 km path. Event occurred far from populated areas, no damage reported.	This work
Río Los Leones 46°44'-73°02'	2000	Original lake surface of 0.02 km^2 reduced to 0.01 km^2. The outburst flood transformed into a debris flow carrying a debris volume of 2x$10^6$$m^3$. No damage reported.	Harrison et al.,(2006); This work
Río Viviano 46°44'-72°19'	Between 1987 and 1998	Original lake surface of 0.02 km^2 reduced to 0.01 km^2. The outburst produced a debris flow that stripped vegetation along a ~2.3 km path. Event occurred far from populated areas, no damage reported.	This work

Cerro Largo 46°57'-73°15'	16/03/1989	Original lake surface of 1.82 km^2 reduced to 0.98 km^2. Three houses were destroyed and significant livestock losses occurred along Soler Valley. The volume of water released was estimated at $229x10^6m^3$, the largest recorded worldwide in historic time. At least $13x10^6m^3$ of debris were transported by the debris flow.	Hauser, (2000); Clague & Evans (2000); This work
Estero Las Lenguas 47°43'-72°52'	Between 1987 and 1998	Original lake surface of 0.67 km^2 reduced to 0.44 km^2. The outburst produced a debris flow that stripped vegetation along a ~7.2 km path. Event occurred far from populated areas, no damage reported.	This work
Gl. Piedras Blancas 49°15'-72°57'	16/12/1913	Partial lake emptying. The actual lake surface is 0.41 km^2. Event occurred far from populated areas, no damage reported.	Lliboutry (1956); Masiokas et al.,(2009)
Gl.Olvidado 50°53'-73°12'	2003	The south front of Olvidado glacier suffered a dramatic retreat (271 metres per year) between 2000 and 2003. As a consequence the proglacial lake (covered by icebergs) grew reaching a surface of 0.68 km^2. The lake failed in 2003 and the outburst flood stripped vegetation patches along a ~4.5 km path. The lake surface not varied significantly as a consequence of the event.	Rivera & Casassa (2004); This work

The volume of water discharged and the flood characteristics of other moraine-failures have not been estimated. However, rapid flows can be inferred from stripped vegetation in the flood plains and channel margins as far as 20 km from the drained lakes. Geomorphic and stratigraphic data and eyewitness accounts indicate that the dam failures have produced different flow types. Debris flow deposits are common in areas proximal to breached moraines. The sediment load and entrainment diminishes downstream generating hyperconcentrated and clear water flows. This flow transition is well exemplified in Ventisquero Negro (Worni et al., 2012) and was described by Hauser (2000) in the Cerro Largo event. Deposits of up to 15 metres in thickness and boulders of 18 meters in diameter in debris flow masses illustrate the high sediment transport capacity of the outburst floods (Worni et al., 2012; Harrison et al., 2006).

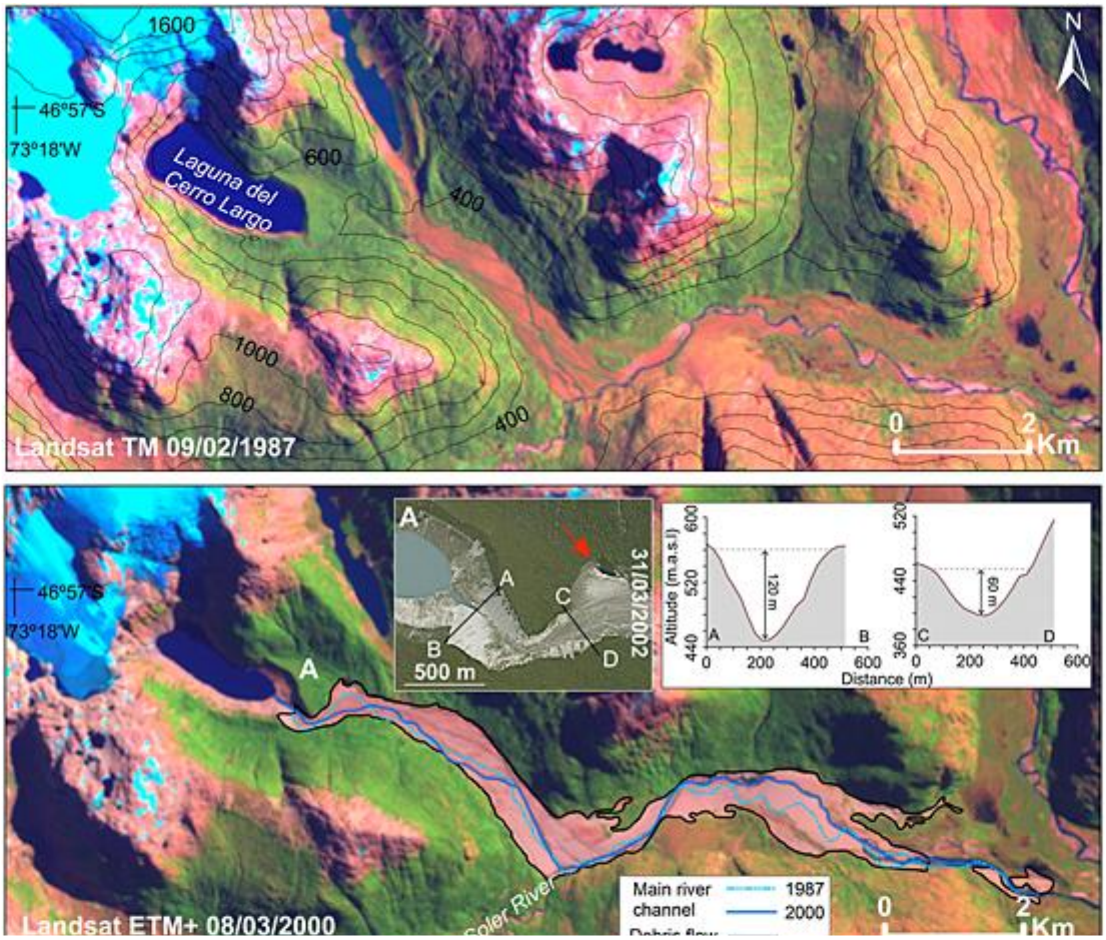

Figure 2.5. Laguna del Cerro largo before and after the 1989 outburst flood. Note the reduced freeboard of the lake prior to the failure and the steep rock walls and glaciers surrounding the lake. An ice-avalanche from the steep and highly crevassed glacier north of the lake is one of the possible triggers of the outburst flood. The erosion of the moraine dam generated significant debris flow and avulsion in the Soler Valley, changing the geometry of the main river channel. It also created a small pond (red arrow in A) and destroyed forest patches along its path. The minimum volume of material transported by the debris flow is 13 x 10^6 m^3 ,considering that the breach area is about 230000 m^2 and the minimum breach heigth is 60m.

None of the events mentioned were directly witnessed in the origin zone and the exact mechanism of moraine failures remains uncertain. However, some possible failure scenarios have been suggested. Harrison et al., (2006) indicate that the cause of Río Los Leones outburst was the direct impact of a large rockfall in the lake and dam. According to the authors the slope failure was conditioned by glacial debuttressing and was probably triggered by a small earthquake, but there are no seismic data to support this hypothesis. Harrison et al., (2006) suggest that the rockfall resulted in the dam failure via overtopping and incision. However, the rockfall, that traveled 1.2 km before impacting the lake, completely covered the lake area (0.02 km^2). This may have induced an almost instantaneous emptying of the lake, corroborated by the high energy of the flow that resulted in large debris flow deposits.

A different cause was postulated in the Cerro Largo outburst, where Hauser (2000) attributes the dam failure to blockage of the lake outlet trough by icebergs. The blockage was postulated to have occurred after a period of warm days and enhanced runoff, which probably caused lake level to rise, finally breaching the dam. An ice-avalanche from the steep and highly crevassed glaciers that surround the lake is another plausible cause of this event. Meteorological conditions also played an important role in Ventisquero Negro outburst flood. Worni et al., (2012) stated that sustained (180 mm of rain in a six-day period) and intense (50 mm of rain in the 48 hours preceding the outburst) rainfall probably augmented the lake outflow, leading to progressive erosion and the subsequent dam failure. The authors point out that the accelerated lake growth and glacier retreat in the last decades also diminished the dam stability by increasing the hydrostatic pressure on the dam and reducing the moraine support at the former ice-contact face.

2.5 Ice and rock-Ice avalanches

Mass movements and ice-avalanches are common processes of mass transfer in glacierised regions. These phenomena are usually restricted to high mountain regions which tend to be unpopulated. However large, infrequent, mass movements (of up to 10^8 m^3 in volume) comprising rock, snow and ice have affected populated areas dozens of kilometers from their origin (Haeberli et al, 2004). Slope failures have also caused complex chain reactions generating far-reaching debris flows and floods (Petrakov et al., 2008). The primary factors that predispose slopes to failure are geology (i.e. lithology and tectonic structures) and topography, whereas the most common triggers are meteorological events and earthquakes. However, complex mass movements also have been initiated without observed triggers (MacSaveney 2002). Meteorological conditions can affect slope stability in several ways. Meltwater or rainfall percolation and permafrost degradation can promote slope failures by reducing the shear strength of the slopes, increasing the hydrostatic or cryostatic pressure in rock fractures or decreasing the adhesion between ice-cemented rocks (Harris et al., 2001; Gruber & Haeberli, 2007). On the other hand, earthquakes can produce slope failures through rapid changes in slope shear stress, by a reduction in the substratum cohesion, or by a decrease in slope frictional strength via shattering rocks or liquefaction (Meunier et al., 2008).

Serac falls and subsequent ice-avalanches are common on step and hanging glaciers. Ice- avalanches can travel several kilometers and mobilize millions of cubic metres of ice (Alean 1985; Schneider et al., 2011). They can start chain reactions and trigger large snow avalanches which increase the magnitude (volume and run out) of the original process (Schneider et al., 2011; Deline et al., 2012). Alean (1985) stressed that serac falls are mainly controlled by glacier basal temperature and slope, and classified the ice-avalanche starting zones into ramp and cliff types. In the European Alps, ice avalanches from ramp type glaciers commonly initiate at slopes ≥ 25° in temperate-based glaciers and at slopes ≥ 45° in cold-based glaciers (Alean 1985). Ice avalanches are probably triggered by friction reduction and/or increase in water pressure at the glacier-bedrock interface or by changes in the internal stress distribution within the glacier that promotes ice-blocks to slide or break off (Alean 1985).

In the extratropical Andes the significance of ice avalanches in terms of glacier mass balance, motion, and hazards, is poorly known in spite of some effort, at local scale, to study these processes. Two studies have focussed exclusively on ice avalanches (Kobayashi & Naruse, 1987; Izumi & Naruse 2002) and others have made incidental reference to this process (Espizúa, 1987). The first study, conducted in January 1984 and February 1985 by Kobayashi & Naruse (1987), showed that the typical duration of ice-avalanches in Soler Glacier (NPA) was 10-30 seconds and that the timing was strongly related with high air temperature. Izumi & Naruse (2002) stated that small ice-avalanches in Soler Glacier were more frequent after receiving strong solar radiation whereas large ice-avalanches occurred approximately 6 to 8 hours after the ice/snow melting peak. The authors attribute the ice-avalanches to ice weakening by meltwater percolation. Large magnitude and low frequency mass movements involving huge amounts of rock and ice have been studied in more detail due their occurrence near infrastructure or inhabited zones or because of their geomorphic and cryospheric significance. Two of these events correspond to the detachment and rapid mobilization of almost entire glaciers in the Central Chilean Andes.

On the morning of March 1st, 1980 ~90% of a debris-covered glacier located at the foot of Cerro Aparejo (33°34ˈS-70°00ˈW), Maipo basin, detached and flowed 3.7 km in ~2 minutes with an estimated velocity of 31 m/s (Marangunic, 1997; Dirección General de Aguas 2010). This phenomenon, witnessed by mountaineers of Club Andino de Chile, involved a volume of ice and debris of 7.2×10^6 m^3 (Marangunic, 1997; Dirección General de Aguas 2010). A similar phenomenon occurred in 1994 and 2006/2007 on the south flank of Tinguiririca Volcano (34°48ˈS-70°21ˈW) (Figure 2.6). In the 2006/2007 event a glacier of 0.46 km^2 detached from its base generating an ice-avalanche that traveled 8.2 km mobilizing $10\text{-}14 \times 10^6$ m^3 of ice and debris (Iribarren & Bodin, 2010; Schneider et al., 2011). There are no published data about the 1994 ice-avalanche but interestingly it occurred few months after the last witnessed eruption of this volcano (Naranjo, 1994).

Rock glaciers also have suffered recent destabilizations in the Arid Andes. Iribarren & Bodin (2010) documented the progressive destabilization and the collapse (spring of 2006) of a small (~0.03 km^2) rock glacier at the foot of Cerro Las Tórtolas (29º58'S-69º55'W). The collapsed mass generated a debris flow that travelled for about 3 km. The causes and triggers of these glacier-scale collapses are uncertain. However, in all cases, the glacier beds were composed of rocks with low geotechnical strength (including rocks with hydrothermal alterations) and meltwater production increased before the failures (Dirección General de Aguas 2010; Iribarren & Bodin, 2010). The signature of the Tinguiririca and Cerro Aparejo ice avalanches has been largely obliterated by fluvial erosion and snow avalanches. A large percentage of these ice masses (if not all) have been melted, removing the geomorphic evidence of these phenomena. However no detailed studies of the ice avalanche dynamics and the associated landforms has been made.

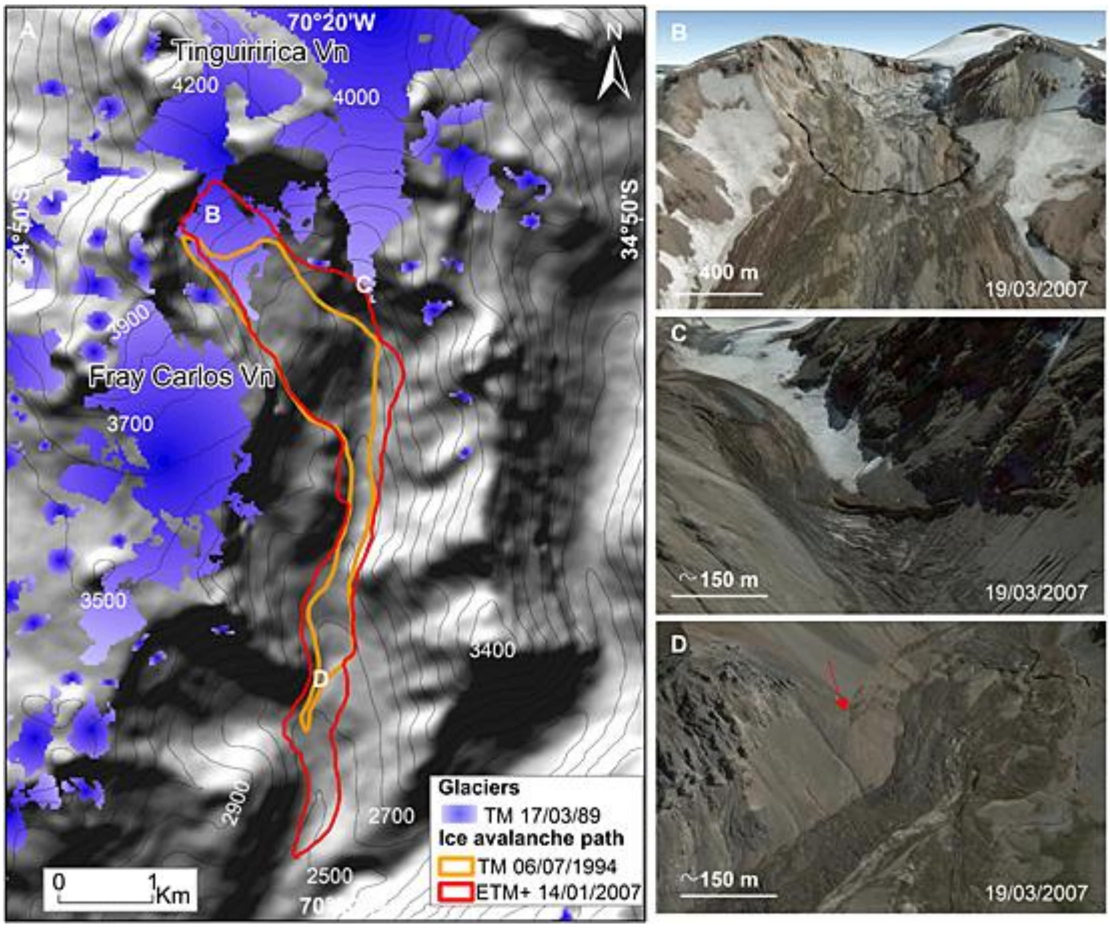

Figure 2.6. A) Paths of the 1994 and 2006/2007 Tinguiririca ice-avalanches and (B) detachment zone after the last event. The steep slope (~20°) and smooth surface of the glacier bed may have favoured the failure. The black dashed line in B indicates the approximate limit of the glacier prior to the 2006/2007 event. The ice-avalanche impacted and eroded another glacier (C) and its flow left super-elevated traces (red arrow in D) indicative of the high velocity of the phenomenon. There are no scars indicative of a major bedrock collapse. Thus, most of the debris visible in D was probably incorporated from the valley floor, which is saturated at the time of failure favouring its erosion. Figures B,C and D sourced from Google Earth.

different (the failure zone included the glacier bed) and more destructive process occurred on 19th February 1965 on the south west flank of Yate Volcano (41°46ˈS-72°23ˈW). An estimated volume of 6.1-10x10^6 m^3 of rock and ice fell from a slope near Yate summit, transforming into a debris flow that impacted Cabrera Lake located 7.5 km downstream. The debris flow entered the lake generating a tsunami with an amplitude of 25 m and a run-up of ~60 m that affected settlements located on the western shore of Cabrera Lake resulting in the loss of 27 lives (Flash 1965; Watt et al., 2009). Rock-ice avalanches also were registered in the North East and South West flanks of Yate Volcano in 1870, 1896 and the 13th of February of 2001. In all cases heavy rain and/or warm temperature preceded the slope failures (Hauser 1985; Watt et al., 2009; Figure 2.7). The 1965 and 2001 rock-ice avalanches occurred during the night. These events may have been triggered by an increase in the pore water pressure produced by the blockage of water pathways by the freezing of rain and/or meltwater. This explanation was also suggested by MacSaveney (2002) and Huggel et al., (2010) for the Mount Cook rock-ice avalanche of 1991, in the New Zealand Southern Alps. Rocks mechanically weakened by faults and glacier debuttressing could predisposed the slope to failure (Watt et al., 2009). Collapse scars near the Yate Volcano summit and debris fan deposits with a hummocky relief are the main geomorphic evidence associated with these mass movements (Watt et al., 2009).

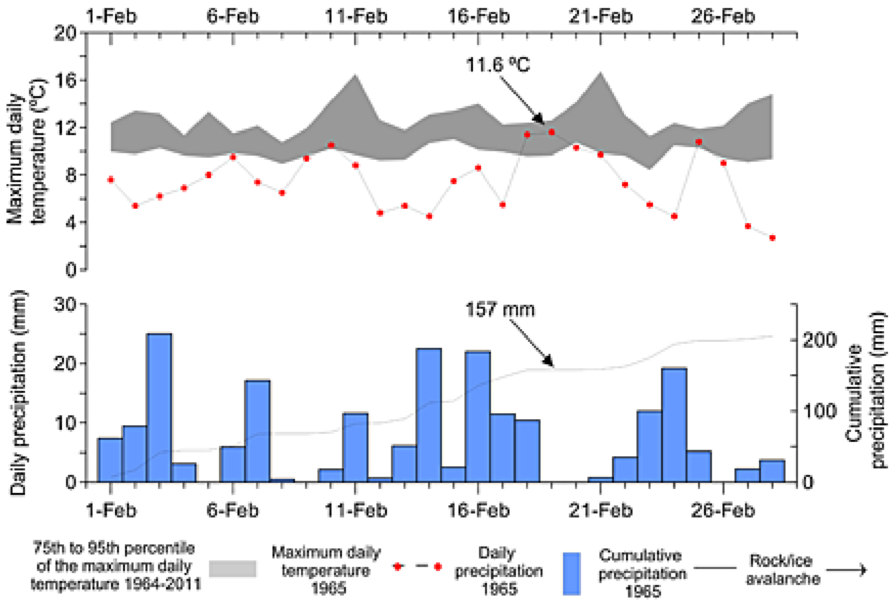

Figure 2.7. Meteorological conditions associated with rock-ice avalanche of the Yate Volcano, 1965. The event took place during the second rainiest February in the period 1964-2011.The maximum daily temperatures one day before and in the day of the event were in the 88th and 89th percentile of the February record, respectively.Tmeperature data was extrapolated from El Tepual meteorological station (41°26'-73°05';85 m.a.s.l) located ~70km northwest of Yate Volcano using a lapse rate of 0.6 °C/100m.

2.6 Glacio-volcanic interactions

Eruptions of ice-caped volcanoes can trigger a variety of mass-flows including floods, hyperconcentrated flows, debris flows (lahars), snow and ice avalanches and mixed avalanches composed of snow, ice and hot pyroclastic material (Major & Newhall 1989; Pierson & Janda, 1994). Lahars are one of the most common and destructive processes that affect volcanic areas mantled by snow and ice worldwide (Major & Newhall, 1989). Historic lahars have had volumes > 4x10^7 m^3, attained velocities >28 m/s, carrying up to 10^8 m^3 of debris impacting areas dozens of kilometers from their origin (Major & Newhall, 1989; Iverson et al., 1998). Mixed volcanic avalanches have travelled for more than 13 km, reaching velocities up to 27 m/s mobilizing as much as 10^7 m^3 of rock and ice (Pierson & Janda, 1994). The primary initiation mechanisms of lahars and mixed volcanic avalanches include explosive ejection of hot pyroclasts that penetrate and melt the snow mantle, pyroclastic surges and flows that thermally and mechanically erode the snow/ice cover and apply shear stress to the slopes, and acoustic and seismic shocks of explosive eruptions that momentarily reduce snow mantle shear strength (Pierson &

Waitt, 1999). Crater lakes on ice-capped volcanoes also have produced lahars as consequence of dam failures (Procter et al., 2010).

In the extratropical Andes at least 33 historically active volcanoes are glacier covered, including stratovolcanoes, cinder cones, subglacial volcanoes and calderas. Many have generated voluminous lahars and floods (e.g Peteroa, Llaima, Villarrica, Calbuco, Hudson) as a result of the ice and snow melted by volcanic activity. In the last five centuries these processes have affected the surrounding areas of eruptive centers many times, mainly in North and South Patagonian Andes, shaping the landscape and sometimes producing extensive damage in inhabited zones. To provide an example, Villarrica Volcano erupted more than 60 times between 1558 and 2009 and in at least 14 eruptions, lahars flowed from the ice-capped mountain (Siebert & Simkin, 2002. In the Table 2-3 some of the most destructive lahars and floods are described.

Table 2-3 Disastrous floods and lahars triggered by volcanic eruptions

Volcano location	Date(s)	Eruptive characteristics	Comments	References
Villarrica 39°25'-71°56'	18/10/1948	Central vent, explosive, lava flow(s) and lava lake eruption. VEI 3.	Lahars descended from different flanks of Villarrica volcano transporting lava blocks up to 10-20 m^3. Villarrica lake level rose 1 m. About 23 people were killed and 31 disappeared. Extensive damages in houses and agricultural lands. At least 18 properties were destroyed.	Casertano, (1963)
	02/03/1964	Central vent, explosive and lava flow(s).VEI 2.	Lahars descended from different flanks of Villarrica Volcano. Coñaripe village was destroyed and about 25 people were killed. Extensive damages in houses and several bridges. After this event Coñaripe was relocated.	Hauser, (2000)
	29/12/1971	Central vent, radial fissure, subglacial, explosive and lava flow(s).VEI 2.	A lahar of about $20x10^6m^3$ travelling at 16 m/s descended from Villarrica North East flank through Correntoso River. Lahars in 1971 eruption caused extensive damage to agricultural land, routes and 5-15 fatalities. The maximum flood/lahars discharge, considering 4 streams together, was 3500 m^3/s and lasted 4 hours.	Peña & Klohn, (1987); Major & Newhall, (1989, and references therein);Hauser, (2000)
Hudson 45°54'-72°57'	11/08/1971	Central vent, subglacial?, explosive, lava flow(s)?.VEI 3.	The 1971 eruption melted between 50% and 80% of the ice within Hudson caldera creating a lahar that reached velocities from 19 to 56 m/s and impacted zones located ~40 km. In the upper reaches of Huemules valley the lahar front was 8 m high and 1-2 km wide. Lahar deposits thickness ranges from 0.7 to 3.1 m. 5 people disappeared and others were evacuated.	Guzmán, (1981); Best, (1992)

According to Siebert & Simkin (2002), most of the floods and lahars in the extratropical Andes have been triggered by Strombolian and Plinian eruptions with Volcanic Explosivity Index (VEI) ≥ 2. The most damaging events have originated during, or a short time following the principal eruptions (e.g. Hudson 1991, Villarrica 1971). However in 1961 a lahar descended from Calbuco volcano and entered in Llanquihue Lake hours before pyroclastic or explosive activity was noted (Klohn 1963) and was probably triggered by basal heating. All documented lahars in the extratropical Andes, have had their origin in eruptions and there are no descriptions of lahars generated by water ejected from crater lakes or significant lahars originated by enhanced runoff as consequence of tephra fall over snow or glaciers. Lava flowing over ice-capped volcanoes (Moreno et al., 1985) and column collapse (Moreno et al., 1981) have also caused volcanic mixed avalanches. During Villarrica eruption of 1984 a mixture of snow, ice and pyroclastic material flowed from the volcano summit for about 5 km (Moreno et al., 1985). The features associated with this event have not been described in the extratropical Andes and volcanic mixed avalanches are not well preserved in stratigraphic records (Pierson & Janda, 1994). Similar processes were documented during Villarrica eruptions of 1908 (Stone 1935), 1913 (Riffo et al., 1987) and Llaima eruption of 1979 (Moreno et al., 1981; Pierson & Janda 1994). Ice cracks, crevasses and the destruction of almost complete glaciers also have been documented during volcanic eruptions (Klohn 1963; Guzmán 1981; Rivera et al., 2008).

Lahar volume and peak discharge have been estimated for the largest and/or most damaging events. One of the most voluminous historic lahars occurred during the eruption of Volcán Hudson in August, 1991. According to Naranjo et al., (1993) a lahar with a volume of about 40-45x10^6 m^3 flowed from the Hudson ice-filled caldera through Huemules Valley for more than 40 km. Historic eruptions of Villarica volcano have generated lahars with volumes up to 40x10^6 m^3, with peak discharges of 20.000 m^3/s that commonly attained velocities >10 m/s (Naranjo & Moreno 2004). The Calbuco eruption of 1961 generated a lahar with a discharge of 3000 m^3/s that traveled at 5.5 m/s (Klohn 1963). In spite of large variations in volume, peak discharge and velocity, many lahars have had significant transporting capacity carrying blocks up to 9 m in diameter and generating deposits more than 3 m thick (Guzmán, 1981; Best, 1992; Moreno & Fuentealba, 1994). Flows have had the behavior and sediment concentration of debris flows, hyperconcentrated flows, and normal stream flows, sometimes varying (temporally) downstream due to sediment entrainment or dilution (Best 1992; Castruccio et al., 2010). Lateral levees, debris fans and other features associated with debris flows (lahars) are common around ice-caped volcanoes. However, other peculiar forms related to ice also are present. Branney & Gilbert (1995) identified circular pits up to 14 metres in diameter, akin to kettle holes, which formed by melting of buried-ice within laharic deposits. Lahars triggered by the Hudson eruptions of 1971 and 1991 also produced conical mounds of 1-3 m in diameter of poorly sorted debris generated by melting of former debris-rich blocks of ice (Branney & Gilbert 1995). The authors also described kettle hole depressions surrounded by rocks formed after ice-block melting. Some of these forms have lasted for decades.

2.7 Other processes and hazards related with glaciers and permafrost

Multiphase mass movements are the processes, indirectly linked with glaciers and permafrost, which have had the largest socioeconomic impact in the extratropical Andes. The most damaging (37 victims and about $40 million USD in losses; Hauser 2002) and best-documented event is the rock-avalanche and debris flow of Estero Parraguirre. On the morning of the 29th November of 1987 a rock mass of about $6x10^6$ m^3 fell over a snow-covered valley, laterally impacting a debris-covered glacier and a rock glacier, resulting in a debris flow with an estimated volume of $15x10^6$ m^3, which travelled more than 50 km down valley (Hauser, 2002). The rock avalanche started at 4350 m.a.s.l, in a zone of discontinuous permafrost, and occurred in an exceptionally snowy year, after days of high temperature (Casassa & Marangunic, 1993; Figure 2.8).

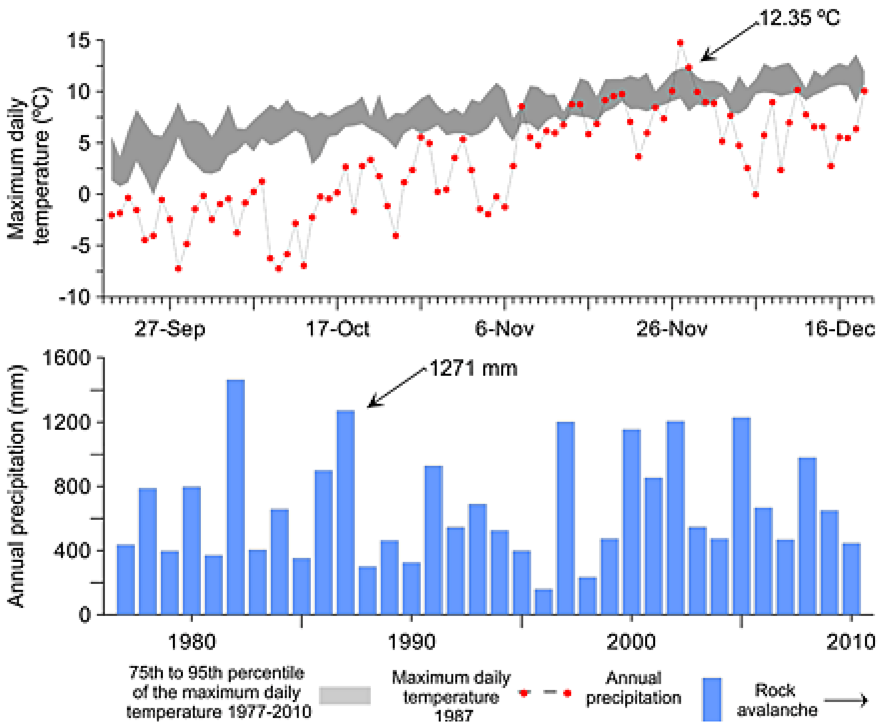

Figure 2.8. Meteorological conditions associated with the Parraguirre rock avalanche, 1987. The event took place during the second rainiest year in the period 1977-2010.The maximum daily temperatures one day before and in the day of the event were in the 99th and 98th percentile of the spring record, respectively. Temperature data was extrapolated from El Yeso station (33°40'-70°05';2475 m.a.s.l)located ~40km south of the source area using a lapse rate of 0.6 °C/100m.

These unusual meteorological conditions promoted high rates of snowmelt percolation which probably reduced the slope shear strength and increased the pore water pressure in the detachment zone, triggering the failure (Casassa & Marangunic, 1993; Hauser 2002). Highly fractured rocks and slope stress relief after glacier recession during the Holocene may have favored unstable slope conditions (Hauser 2002). Lateral levees, eroded edge terraces, mud splashes and deposits between 0.6 and 4 m in thickness are some of the geomorphic and sedimentary consequences of Parraguirre debris flow (Hauser 2002). Glacier changes probably conditioned other mass movements in the region during the Holocene (Welkner et al., 2010) and in historic times (Harrison et al, 2006 and Figure 2.9).

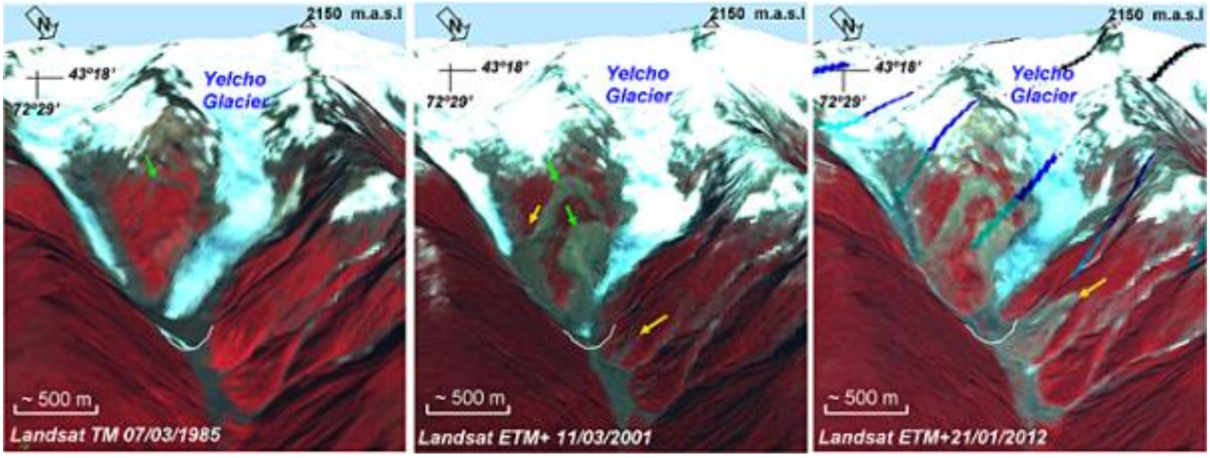

Figure 2.9 Deep-seated gravitational slope deformation (green arrows) and debris-avalanches (yellow arrows) possibly associated with slope unloading, and subsequent stress redistribution, after the shrinkage and thinning of Yelcho and other adjacent glacier. A small trench in the slope is visible in the March 1985 image. This trench has widened in subsequent years coinciding with glacier change. The white line indicates the debris-covered front of Yelcho glacier in 1985, at the toe of a debris-avalanche visible in the 2012 image.

There are many other processes triggered or conditioned by glaciers or permafrost that have had negative socioeconomic effects in the extratropical Andes. For example, glacier retreat and fragmentation in fiords and lakes in Patagonia has generated transport problems for local inhabitants and tourists due to the increased presence of icebergs in navigation routes. This situation is illustrated by the collapse and disintegration of 1.5 km^2 of ice from Grey Glacier (SPI) in 1997 that interrupted tourist transportation services in Grey Lake over a three-year period (Rivera & Casassa, 2004). An increase in ice velocity and subsequently glacier longitudinal stretching and fracture probably enhanced icebergs production (Rivera & Casassa, 2004).

Mining activities in the Desert and Central Andes of Chile and Argentina have penetrated in glacial and periglacial environments and also have been affected by landscape dynamics. The Sur Sur mine (33°09'S-70°15'W), Codelco's Andina Division, in Chile, for instance had experienced operational problems due to slope instabilities, triggered by the accelerated advance of a rock glacier in the upper benches of the pit. The high rate of movement of the rock glacier (maximum 30-35 m/year) was caused by loading of mine waste material of up to 30 m thick (Apablaza et al., 2001). The displacement rate of the rock glacier before the deposition ranged between 0.3 and 1.9 m/year (Contreras & Illanes, 1992; Valenzuela, 2004; Brenning & Azócar, 2010). The normal, relatively slow, movement of rock glaciers and debris-covered glaciers has also generated minor problems in the operation of ski lift towers in Morenas Coloradas, Central Andes of Argentina (D. Trombotto, personal communication, 2012) and also destroyed part of a mountain hut near Laguna del Diamante, East flank of Maipo Volcano (Alonso & Trombotto Liaudat 2013). In both cases the structures were located over active rock glaciers or debris covered glaciers and were damaged by differential movement (D. Trombotto, personal communication, 2012).

2.8 Summary and Conclusions

The extratropical Andes are subject to a range of geomorphic and hydrologic processes and hazards related to glaciers and permafrost dynamics. This region has hosted some of the largest outburst floods that have occurred worldwide (Cerro Largo and Perito Moreno) (Evans & Clague 2000; Walder & Costa 1996). It has suffered disastrous consequences from infrequent, but large (>$10x10^6m^3$) and complex mass movements involving permafrost and glaciers, and has been repeatedly affected by lahars. The events described so far shed light on the geomorphic impacts of these phenomena, but also reveal important gaps in our knowledge, especially in understanding the role of glacier and permafrost dynamics in conditioning or triggering these events. This knowledge is critical to face potential geomorphic changes, and associated hazards, linked with higher atmospheric temperatures in mountainous regions (see e.g. Evans & Clague 1994; Huggel et al., 2012).

Outburst floods have been reported in the extratropical Andes since the Eighteenth century AD (Prieto 1986). However their frequency has apparently increased considerably in the last three decades (Figure 2.10). This trend may be partially explained by an increase in the availability of records (i.e. satellite images and gauging stations) that allowed identification of otherwise unnoticed events in remote areas. Nevertheless the increasing number of outburst floods, especially in the Patagonian Andes is also likely related to long term (decades to centuries) climatic changes (Villalba et al., 2003), glacier retreat and thinning (Rignot et al., 2003), and the subsequent formation and/or growth of glacial lakes (Loriaux & Casassa 2013). At least two lakes that formed in the last three decades have failed. Naturally, the larger the number of lakes in existence, the higher the likelihood of outburst floods, for example, when multiple landslide events occur. Further, lake growth, and the subsequent rise of hydrostatic pressure, can aid or trigger moraine and ice dam failures (Glen 1954; Richardson & Reynolds, 2000). Outburst floods also are more likely as a consequence of glacier thinning, which reduces outburst initiation thresholds (Costa & Shuster 1988; Clague & Evans 1997). In this context, if glaciers continue their downwasting trend an increasing number of outburst floods would be expected in the highly glaciated Patagonian Andes.

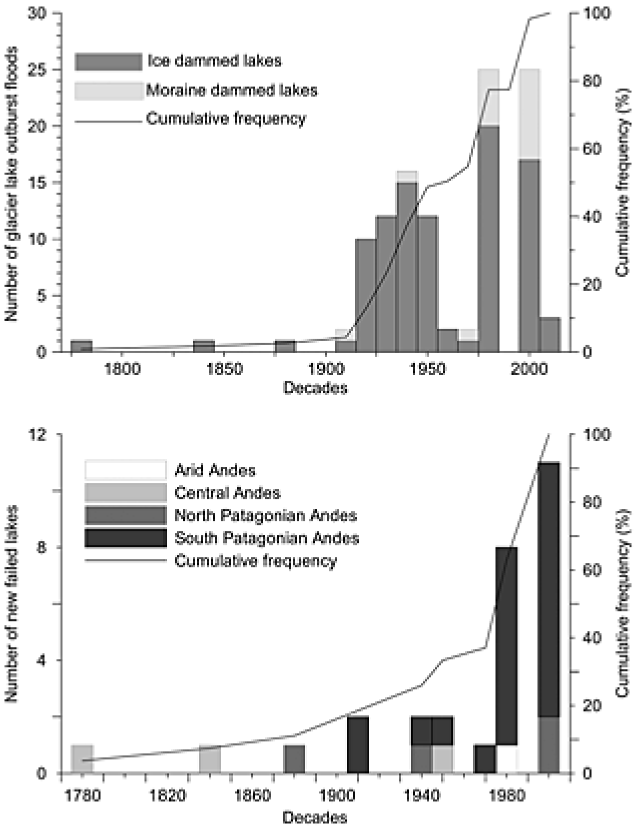

Figure 2.10.Frequency of historic glacier lake outburst floods in the extratropical Andes. At least 31 lakes have failed since 1780, producing more than 100 floods. In the cases where the exact date of the outburst flood is unknown the minimum age was considered. Data from Tables 1 and 2.

The cause of outburst flood in the extratropical Andes in most cases remains uncertain. Short term (days to weeks) meteorological conditions (prolonged and intense rainfall and warm days) have been related to moraine dam failures (Hauser 2000; Worni et al., 2012). However the sparse and incomplete meteorological data in this region limits our knowledge of the frequency and intensity of potential climatic drivers. The relationship between meteorological events and outburst floods is not always clear (Figure 2.11). The analysis of outburst floods from the ice-dammed lake Cachet 2 shows that there is not a direct relationship between cumulative precipitation, maximum daily temperature and Cachet 2 outburst flood timing. The large variation of the meteorological conditions prior to the outburst floods makes it difficult to indentify thresholds for the initiation of these events. The erratic timing of Cachet 2 outburst floods may be related to the seasonal development of the internal hydrological network and rates of lake refilling. The last aspect can be studied further using non-linear physical models as suggested by Ng & Liu (2009).

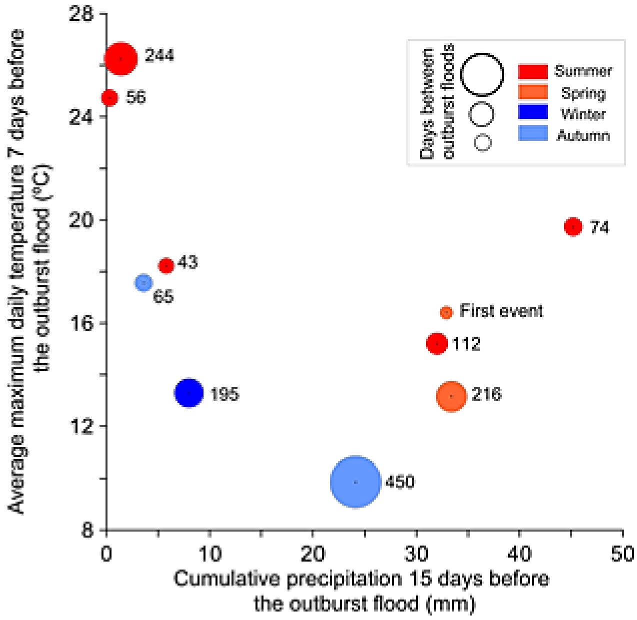

Figure 2.11. Meteorological conditions prior to Cachet 2 outburst floods. Temperature and precipitation data includes the day of the outburst flood. Most events have occurred during the melting season. However there is no clear relationship between daily maximum temperature, cumulative precipitation and the outburst timing. Meteorological data from Lord Cochrane station (47°14'–73°35'; 196 m.a.s.l.) located ~50 km east of Cachet 2. Missing data (23%) of maximum daily temperature were interpolated from Balmaceda station (45°54'–71°41'; 520 m.a.s.l.) using a simple linear regression model ($r = 0.89$)

In spite of the active seismicity of the extratropical Andes, especially north of 46°S (see Barrientos, 2007), no recorded outburst floods are clearly associated with earthquakes. However, coseismic landslides, triggered by tectonic or volcanic activity, may cause outburst floods in the future. In 2007 the tectonic activity of the Liquiñe-Ofqui fault zone caused hundreds of coseismic landslides in Aysen (Sepúlveda et al., 2010), an area with historically low seismicity. These seismic swarms illustrate the necessity of considering seismicity in the assessment of outburst floods hazard in the North Patagonian Andes.

The extratropical Andes have been affected by large and destructive mass movements involving glacier ice and permafrost. The most damaging rock avalanche (Parraguirre) and rock-ice avalanches (Yate Volcano) were related to extreme (in terms of frequency and intensity) meteorological events (Figures 2.7 and 2.8) and produced chain reactions after impacting glaciers, snow-covered valleys or lakes. The infiltration of large amounts of rain and/or meltwater promoted these failures in slopes weakened by faults and possibly glacier debuttressing (Casassa & Marangunic 1993; Hauser 2002; Watt et al., 2009). Extreme meteorological events (particularly high temperatures) such as those that triggered these mass movements, are likely to be more frequent during the XXI Century (Tebaldi et al., 2006; Marengo et al., 2009). However climatic changes will differ regionally. In the period 2070-2100 (under the scenario A2 of the Intergovernmental Panel on Climate Change) the average temperature is expected to increase between 2 and 4 °C in the extratropical Andes, and these changes will be higher in the Dry Andes, decreasing southward (Comisión Nacional del Medio Ambiente 2007). Annual precipitation is expected to rise on the East side and decrease on the West side of the Andes (Comisión Nacional del Medio Ambiente 2007), although the frequency of extreme precipitation events could decrease (Marengo et al., 2009).The projected temperature rise and the reduction in precipitation extremes may alter the frequency and magnitude of mass movements in the extratropical Andes due to concomitant changes in the mechanical and hydraulic conditions of the slopes and sediment availability after glacier retreat and permafrost thawing. However, the effects of climatic changes can be expressed in slope instabilities in periods of days to millennia (Huggel et al., 2012) and can be highly variable spatially, especially in the geographically diverse extratropical Andes.

Geomorphic processes triggered by glacio-volcanic interactions have aroused public and scientific attention in the extratropical Andes due to their frequency and socioeconomic impacts. Lahars and, to a lesser extent, volcanic mixed avalanches, have been common during explosive activity on glacier-covered volcanoes. These processes will continue to threaten inhabited areas, unless glaciers diminish significantly or disappear, reducing the amount of ice available for melting during eruptions (Huggel et al., 2007a; Tuffen 2010). Other geomorphic processes associated with glacio-volcanic interactions remain poorly investigated in the extratropical Andes. For example, the potential relationship between changing geothermal heat fluxes and the Tinguiririca ice-avalanches is unknown. Ice-avalanches and rock-ice avalanches have irregularly affected Tinguiririca and Yate volcanoes, showing the strong influence of local factors, such as topography and structural instabilities, in conditioning these processes. However, it seems likely that these processes will affect more volcanoes in the future, as glaciers become thinner and more fragmented, and/or as sub-glacial water pressures rise as a consequence of increased melting.

The apparent increase in frequency of outbursts in the extratropical Andes is in accordance with statistics from the European Alps (Haeberli 1983). Furthermore, the growth in lakes size and number (Loriaux & Casassa 2013) is commonly observed in areas where glaciers retreat (Gardelle et al., 2011; Bolch et al., 2011). A special feature of the extratropical Andes is the enormous magnitude of some outburst floods which include the largest ever recorded (Evans & Clague 2000; Walder & Costa 1996). Slope failures are also widespread in high-mountain regions where climatically sensitive permafrost and glaciers occur. Thus, slope failures preceded by warm periods (days to weeks) in the extratropical Andes resemble events that have occurred in, for example, the European Alps and New Zealand Southern Alps (see e.g. Huggel et al., 2010). Finally, hazards related with glacio-volcanic interactions such as lahars are well-known internationally due to their recurrence and tragic outcomes (see e.g. Voight 1994). Hence, the glacier and permafrost related hazard described in the extratropical Andes provide good examples of phenomenon observed globally, including the extreme end members of climate and relief, from arid high-elevation mountains with small glaciers and abundant permafrost, to hyper-maritime glaciers that descend into forested areas

2.8.1 Gaps in our knowledge and future research directions

The diversity and magnitude of geomorphic process in the extratropical Andes makes it a remarkable region to study the effects of climatic changes on the cryosphere and the associated hazards. However our knowledge of event characteristics (e.g. date, causes, frequency, and geomorphological impact) is insufficient. As a result, our understanding of the climatic and cryospheric processes that cause and trigger these events is limited. We suggest the following research directions may fill some of these gaps.

- *Improved knowledge of the frequency and geomorphological impact of outburst floods.* The outburst floods impact in riverine lanscapes has been studied in only a few cases (Hauser 2000; Harrison et al., 2006; Worni et al., 2012). These studies focused on the immediate geomorphic effects of the phenomenon but the long-term (decadal) effects in the fluvial system are unknown. It is necessary to better understand the geomorphic changes produced by outburst floods in river channels, especially in areas where riverine infrastructure is planned. Clearer identification of the geomorphic signature of outburst floods could help to unravel the mechanism involved in the dam failures, and could help to understand the significance of outburst floods in the sediment regime. Further, the analysis of morphometric characteristics of the lakes and dams may help to identify hazardous lakes (MacKillop & Clague 2007; Bolch et al., 2011). The record of outburst floods could be extended using sedimentary evidence, which is well preserved in the Arid and Central Andes. In addition, dendro-geomorphological methods could be used to establish the age, extent, and magnitude of historic and prehistoric events (see e.g. Stoffel & Bollshweiler., 2009), especially in the heavily forested Patagonian Andes. Flood frequency analysis of such longer datasets could better constrain the underlying thresholds and drivers of outburst floods.

-*Testing the sensitivity of the influence of cryospheric changes in past and future slope failures.* In the extratropical Andes, the role attributed to ongoing deglaciation in conditioning historic (Hauser 2000; Watt et al., 2009) and prehistoric (Tormey 2010) rock-slope failures has so far relied on inferences (excepting Welkner et al., 2010). Numerical modelling of slope failures, incorporating the effects of glacier changes in slope form and stress distribution, may shed light on past and future mass movements in glaciated environments (McColl 2012). Further, inventories of historical mass movements in glacier and periglacial belts could help to identify the geological, topographical, glaciological and thermal conditions associated with slope instabilities, including the possible influence of permafrost thawing (see e.g. Allen et al., 2011; Fischer et al., 2012). In addition, permafrost distribution mapping can help to understand and predict slope instabilities. Indeed, rock glacier kinematics (Kääb et al., 2007), serac falls and rock-wall stability (Gruber & Haeberli 2007) are closely linked with permafrost occurrence and its thermal conditions. This information might improve future landslide hazard assessments.

-*Determine the hydrological and geomorphic processes associated with glacier retreat on volcanoes*. Lahars are the major geomorphic and hydrologic processes affecting glacier-covered volcanoes. However glacio-volcanic interactions also can cause other remarkable phenomena. It is not currently known whether the dramatic glacier-scale ice-avalanches of Tinguiririca Volcano were related to volcanic activity, as has been suggested in similar events in other volcanic regions (Huggel et al., 2007b). The relationship between ice-avalanches and volcanic activity (geothermal fluxes and eruptions) should be investigated further in order to identify potential hazardous zones. Furthermore, glaciers in volcanic craters (e.g. Sollipulli) have to be monitored in order to detect the formation of potentially hazardous lakes early and anticipate changes in the style and timing of volcanic eruptions. Investigating the relationship between glacier changes and volcanic eruptions could lead to insights into climate-crustal feedback systems (Tuffen 2010)

2.9 References

Alean J (1985) Ice avalanches: some empirical information about their formation and reach. *Journal of Glaciology*, 31(109): 324–333.

Allen SK, Cox SC, Owens IF (2011) Rock avalanches and other landslides in the central Southern Alps of New Zealand: a regional study considering possible climate change impacts. *Landslides* 8: 33–48.

Alonso V, Trombotto Liaudat D (2013) Mapping and permafrost altitudes in a periglacial environment: the Laguna del Diamante Reserve (Central Andes, Argentina).*Zeitschrift für Geomorphologie*.57(2):171-186.

Apablaza R, Farías E, Morales R, Díaz J, Karzulovic A (2001) The Sur Sur mine of Codelco's Andina division. In: HUSTRULID, W. A.; MCCARTER, M. K. & VANZYL, D. J. A. Slope stability in surface mining. Colorado: Society for Mining Metallurgy and Exploration. 171-176.

Barrientos S (2007) Earthquakes in Chile, in: The Geology of Chile, edited by: Moreno, T. and Gibbons, W., Geological Society of London, 263–287.

Bastianon E, Bertoldi W, Dusaillant A (2012) Glacial-lake outburst flood effects on Colonia River morphology, Chilean Patagonia. in River Flow 2012 - Proceedings of the International Conference on Fluvial Hydraulics, London: Taylor & Francis Group, 2012, p. 573-579. - ISBN: 9780415621298. Proceedings of: International Conference on Fluvial Hydraulics, River Flow 2012, San Jose, Costa Rica, 5-7 September 2012 .

Best JL (1992) Sedimentology and event timing of a catastrophic volcaniclastic mass-flow, Volcán Hudson, Southern Chile. *Bulletin of Volcanology* 54:299-318.

Björnsson H (2002) Subglacial lakes and jökulhlaups in Iceland. *Global and Planetary Change*.35(3–4): 255–271.

Bolch T, Peters J, Yegorov A, Pradhan B, Buchroithner MF, Blagoveshchensky V (2011) Identification of potentially dangerous glacial lakes in the northern Tien Shan. *Natural Hazards*.59(3):1691–1714.

Branney MJ, Gilbert JS (1995) Ice-melt collapse pits and associated features in the 1991 lahar deposits of Volcán Hudson, southern Chile: criteria to distinguish eruption-induced glacier melt. *Bulletin of Volcanology* 57:293-302.

Breien H, De Blasio FV, Elverhøi A, Høeg K (2008) Erosion and morphology of a debris flow caused by a glacial lake outburst flood, Western Norway.*Landslides* 5:271-280.

Brenning A, Azócar G (2011) Minería y glaciares rocosos: impactos ambientales, antecedentes políticos y legales, y perspectiva futuras. *Revista de Geografía Norte Grande* 47:143-158.

Buchroithner MF, Jentsch G, Waniverhaus B (1982) Monitoring of Recent Geological Events in the Khumbu Area (Himalaya, Nepal) by Digital Processing of Landsat MSS data. *Rock Mechanics* 15 (4): 181-197.

Carey M (2005) Living and dying with glaciers: People's historical vulnerability to avalanches and outburst floods in Peru. *Global and Planetary Change* 47:122–124.

Carrión D (2007) Riesgos Naturales Asociados a Glaciares en Chile. Informe final de práctica profesional, DGA/UChile, Santiago, 79 pp.

Casassa G, Marangunic C (1993) The 1987 Río Colorado rockslide and debris flow, Central Andes, Chile, *Bulletin of the Association of Engineering Geologists*, XXX, 321–330.

Casertano L (1963) General characteristics of active Andean volcanoes and a summary of their activities during recent centuries. *Bulletin of the Seismological Society of America* 53(6): 1415-1433.

Castruccio A, Clavero J, Rivera A (2010) Comparative study of lahars generated by the 1961 and 1971 eruptions of Calbuco and Villarica volcanoes, Southern Andes of Chile. *Journal of Volcanology and Geothermal research* 190: 297-311.

Chinni GA, Warren CR (2004) Correspondence.The 2004 outburst flood at Glaciar Perito Moreno, Argentina. *Journal of Glaciology* 50(171):615–616.

Clague JJ, Mathews WH (1973) The magnitude of Jökulhlaups. *Journal of Glaciology*, 12: 501–504.

Clague JJ, Evans SG (1997) The 1994 jökulhlaup at Farrow Creek, British Columbia, Canada. *Geomorphology* 19: 77-87.

Clague JJ, Evans SG (2000) A review of catastrophic drainage of moraine-dammed lakes in British Columbia. *Quaternary Science Reviews* 19: 1763–1783.

Contreras A, Illanes JL (1992) Depósito de lastre glaciar Infiernillo Sur, mina Los Bronces. En: Santiago, Minería en altura, 43a Convención del Instituto de Ingenieros de Minas de Chile, La Serena, 1992.

Costa JE, Schuster RL (1988) The formation and failure of natural dams. *Geological Society of America Bulletin* 100, 1054–1068.

Costa JE, Schuster RL (1991) Documented Historical Landslide Dams from Around the World: U.S. Geological Survey Open-File Report 91-239, 486p.

Comisión Nacional del Medio Ambiente (2007) Estudio de la variabilidad climática en Chile para el siglo XXI. Informe Final, realizado por el Departamento de Geofísica, Universidad de Chile.

Davies BJ, Glasser NF (2012) Accelerating recession in Patagonian glaciers from the "Little Ice Age" (c. AD 1870) to 2011. *Journal of Glaciology*, 58 (212): 1063-1084.

Deline P, Gardent M, Magnin F, Ravanel L (2012) The morphodynamics of the Mont Blanc massif in a changing cryosphere: a comprehensive review*. Geografiska Annaler: Series A, Physical Geography.94:265-283.*

Dirección General de Aguas (2010) Estrategia Nacional de Glaciares. Ministerio de Obras Públicas, Santiago, Chile, 275pp.

Dussaillant A, Benito G, Buytaert W, Carling P, Meier C, Espinoza F(2009) Repeated glacial-lake outburst floods in Patagonia: an increasing hazard? *Natural Hazards* 54: 469–481.

Escobar F, Vidal V, Garin C, Naruse R (1992) Water balance in the Patagonian Icefield. In: Naruse, R. (Ed.), Glaciological Researches in Patagonia, 1990, Institute of Low Temperature Science, Hokkaido University, Sapporo, 060 Japan, pp. 109–119.

Espizúa LE (1987) Fluctuaciones de los glaciares del Río del Plomo, Mendoza. *Revista de la Asociación Geológica Argentina* 42 (1-2): 112-121.

Espizúa LE, Bengochea, JD (1990) Surge of Grande del Nevado Glacier (Mendoza, Argentina) in 1984: its evolution through satellite images. *Geografiska Annaler* 72A (3–4): 255–259.

Evans SG, Clague JJ (1994) Recent climatic change and catastrophic geomorphic processes in mountain environments. *Geomorphology* 10: 107–128.

Evans SG, Bishop NF, Smoll LF, Valderrama Murillo P, Dalaney KS (2009) A re-examination of the mechanism and human impact of catastrophic mass flows originating on Nevado Huascarán, Cordillera Blanca, Peru in 1962 and 1970. *Engineering Geology* 108: 96–118.

Fernández P, Fornero L, Maza J, Rollan RA, Yañez H, Nuñez MS, de Alpeggiani EB (1985) Hidrología del río Mendoza: simulación matemática del las hipótesis de rotura del dique natural formado por el Glaciar Grande del Nevado del Plomo y del traslado de las crecientes desde el glaciar hasta 200 metros aguas abajo de Álvarez Condarco. Instituto Nacional de Ciencia y Técnicas Hídricas, Centro Regional Andino, Mendoza, Argentina, 135 pp.

Fernández P, Fornero L, Maza J, Yañez H (1991) Simulation of flood waves from outburst of glacierdammed lake. *Journal Hydraulic Engineering* 117:42–53.

Fischer L, Purves RS, Huggel C, Noetzli J, Haeberli W (2012) On the influence of topographic, geological and cryospheric factors on rock avalanches and rockfalls in high-mountain areas. *Natural Hazards and Earth System Sciences* 12:241-254.

Flash (1965) El lago Cabrera ahogó a un pueblo. Flash, Santiago, Chile, 26th February 1965, no. 84, Año 11, aero norte.

Glasser NF, Jansson KN (2008) The glacial map of southern South America. *Journal of Maps* 2008: 175-196.

Glacier Change World Press.2012. http://glacierchange.wordpress.com/2012/04/15/alemania-glacier-retreat-lago-martinic-expansion-contraction-chile/ Accessed 10 November 2012.

Glen JW (1954) The stability of ice-dammed lakes and other waterfilled holes in glaciers: *Journal of Glaciology* 2(15): 316-318.

Gilbert A, Vincent C, Wagnon P, Thibert E, Rabatel A (2012) The influence of snow cover thickness on the thermal regime of Tête Rousse Glacier (Mont Blanc range, 3200m a.s.l.): Consequences for outburst flood hazards and glacier response to climate change, *Journal of Geophysical Research*, Vol. 117.OI: 10.1029/2011JF002258

González-Ferrán O (1995) Volcanes de Chile. Instituto Geográfico Militar, Santiago, Chile. 635 p.

Grove M (1987) Glacier fluctuations and hazards. *Geographical Journal* 153(3), 351-369.

Gruber S, Haeberli W (2007) Permafrost in steep bedrock slopes and its temperature-related destabilization following climate change. *Journal of Geophysical Research* 112: F02S18. DOI. 10.1029/2006JF000547

Guzmán J (1981) Preliminary report on eruption of volcano north Hudson or volcano Huemules.*Trapananda* 1(2)35-42.

Haeberli W (1983) Frequency and characteristics of glacier floods in the Swiss Alps. *Annals of Glaciology* 4: 85–90.

Haeberli W, Huggel C, Kääb A, Zgraggen-Oswald S, Polkvoj A,Galushkin I, Zotikov I,Osokin N (2004) The Kolka-Karmadon rock/ice slide of 20 September 2002: an extraordinary event of historical dimensions in North Ossetia, Russian Caucasus. *Journal of Glaciology* 50(171): 533–546.

Haeberli W (2013) Mountain permafrost — Research frontiers and a special long-term challenge. *Cold Regions Science and Technology* 6–11.

Hambrey M, Alean J (1992) Glaciers: New York, Cambridge University Press, 208 p.

Harris C, Davies MC, Etzelmüller B (2001) The assessment of potential geotechnical hazards associated with mountain permafrost in a warming global climate. *Permafrost and Periglacial Processes* 12: 145–156.

Harrison S, Glasser N, Winchester V, Haresign E, Warren CR, Jansson K (2006) A glacial lake outburst flood associated with recent mountain glacier retreat, Patagonian Andes. *Holocene* 16: 611–620.

Hauser A (1985) Flujos aluvionales de 1870 y 1896 ocurridos en la ladera norte del volcan Yates, X región: su implicancia en la evolución de riesgos naturales. *Revista Geológica de Chile* 25–26:125–133.

Hauser A (2000) Remociones en masa en Chile. Second ed. Boletín No. 59. Servicio Nacional de Geología y Minería, Santiago.89 p.

Hauser A (2002) Rock avalanche and resulting debris flow in Estero Parraguirre and Rio Colorado, Región Metropolitana, Chile. In: Evans, S.G., DeGraf, J.V. (Eds.), Catastrophic Landslides: Effects, Occurrence, and Mechanisms: *Geological Society of America Reviews in Engineering Geology* 15: 135–148.

Hewitt K (1982) Natural dams and outburst floods in the Karakorum Himalaya. In Hydrological aspects of alpine and high-mountain areas. Edited by J.W. Glen. *International Association of Hydrological Sciences* (IAHS) 138: 259–269.

Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A (2005) Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology* 25(15): 1965-1978.

Holm K, Bovis M, Jakob M (2004) The landslide response of alpine basins to post-Little Ice Age glacial thinning and retreat in southwestern British Columbia. *Geomorphology* 57: 201–216.

Huggel C, Kääb A, Haeberli W, Teysseire P, Paul F(2002) Remote sensing based assessment of hazards from glacier lake outbursts: A case study in the Swiss Alps. *Can Geotech J* 39:316-330.

Huggel C, Ceballos JL, Pulgarin B, Ramirez J, Thouret JC (2007a) Review and reassessment of hazards owing to volcano–glacier interactions in Colombia. *Annals of Glaciology* 45: 128–136.

Huggel C, Caplan-Auerbach J,Waythomas CF,Wessels RL (2007b) Monitoring and modeling ice-rock avalanches from ice-capped volcanoes: a case study of frequent large avalanches on Iliamna Volcano,Alaska. *Journal of Volcanology and Geothermal Research* 168(1–4): 114–136.

Huggel C, Salzmann N, Allen S, Caplan-Auerbach J, Fischer L, Haeberli W, Larsen C, Schneider D, Wessels R (2010) Recent and future warm extreme events and high-mountain slope failures. *Philosophical Transactions of the Royal Society* A, 368:2435-2459.

Huggel C, Clague JJ, Korup O (2012) Contemporary Climate Change and Landslide Activity in High Mountains. *Earth Surface Processes and Landforms* 37:77-91.

Iribarren Anacona P, Bodin X (2010) Geomorphic consequences of two large glacier and rock glacier destabilizations in the Central and Northern Chilean Andes. *Geophysical Research Abstracts* 12: 7162–7165.

Iverson RM, Schilling SP, Vallance JW (1998) Objective delineation of lahar-inundated hazard zones, *Geological Society of America Bulletin*. 110: 972–984.

Izumi K, Naruse R (2002) Ice avalanche activity at Soler Glacier, Northern Patagonia, in the summer of 1998.*Bulletin of Glaciology Research* 19: 81-84.

Kääb A, Huggel C, Fischer L, Guex, S, Paul F, Roer I, Salzmann N, Schlaefli S, Schmutz, K., Schneider D, Strozzi T, Weidmann Y (2005a) Remote sensing of glacier- and permafrost related hazards in high mountains: an overview, *Natural Hazards and Earth System Sciences* 5: 527–554.

Kääb A, Reynolds, JM, Haeberli W (2005b) Glacier and permafrost hazards in high mountains. In: Huber, U.M., Bugmann, H.K.M., Reasoner, M.A. (Editors): Global change and mountain regions - a state of knowledge overview. Springer, Dordrecht, 225-234.

Kääb A, Frauenfelder R, Roer I (2007) On the response of rockglacier creep to surface temperature increases. *Global and Planetary Change*. 56(1-2):172-187.

King W (1934) The Mendoza River flood of 10-1 1 january, 1934, Argentina. *Geographical Journal* 84: 321-326

Klohn E (1963) The February 1961, eruption of Calbuco Volcano. *Seismological Society of America Bulletin* 53: 1435-1436

Kobayashi S, Naruse R (1987) Ice avalanches on Soler Glacier, Patagonia. *Bulletin of Glacier Research* 4: 87-90.

La Nación (2012) Empezó la espectacular ruptura del Glaciar Perito Moreno. Viernes 2 de Marzo de 2012.

La Vanguardia (1934) El desbordamiento del Mendoza. Sábado 13 de Enero de 1934. 26-27.

Lliboutry L (1956) Nieves y glaciares de Chile. Fundamentos de Glaciología. Ediciones de la Universidad de Chile, Santiago, Chile, 472 p.

Lliboutry L, Arnao BM, Pautre A, Schneider B (1977) Glaciological problems set by the control of dangerous lakes in Cordillera Blanca, Peru. I. Historical failures of morainic dams, their causes and prevention. *Journal of Glaciology* 18(79): 239-254.

Lliboutry L (1998) Glaciers of Chile and Argentina. In: Williams, R.S., Ferrigno, J.G., (eds.), Satellite Image Atlas of Glaciers of the World: South America. USGS Professional Paper 1386-I, Online version 1.02.

Loriaux TH, Casassa G (2013) Evolution of glacial lakes from the Northern Patagonian Icefield and terrestrial water storage in a sea-level rise context.*Global and Planetary Change*.102:33-40.

Major JJ, Newhall CG (1989) Snow and ice perturbation during historical volcanic eruptions and the formation of lahars and floods: a global review. *Bulletin of Volcanology* 52 (1):1-27.

Marangunic C (1997) Deslizamiento catastrófico del glaciar en el Estero Aparejo. Actas del 4° Congreso Chileno de Geotecnia 2: 617-626.

Marengo JA, Jones R, Alves LM, Valverde MC (2009) Future change of temperature and precipitation extremes in South America as derived from the PRECIS regional climate modeling system. *International Journal of Climatology* 29:2241-2255.

Masiokas MH, Rivera A, Espizúa LE, Villalba R, Delgado S, Aravena, JC (2009) Glacier fluctuations in extratropical South America during the past 1000 years. *Palaeogeography, Palaeoclimatology, Palaeoecology* 281: 242-268.

Maas HG, Mulsow C, Wendt A, Casassa G (2012) Pilot studies with a photogrammetric glacier lake outburst flood early warning system, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XXXIX-B5, 523-527, doi:10.5194/isprsarchives-XXXIX-B5-523.

Mayo LR (1989) Advances of Hubbard Glacier and the 1986 outburst of Russell Fjord, Alaska, USA.*Annals of Glaciology* 13:189-94.

McColl ST (2012) Paraglacial rock-slope stability. *Geomorphology* 153-154: 1-16.

McKillop RJ, Clague JJ (2007) Statistical, remote sensing-based approach for estimating the probability of catastrophic drainage from moraine-dammed lakes in southwestern British Columbia. *Global and Planetary Change* 56:153-171.

McSaveney MJ (2002) Recent rockfalls and rock avalanches in Mount Cook National Park, New Zealand. In Catastrophic Landslides: Effects, Occurrence and Mechanism, Evans SG, DeGraff JV (eds).Geological Society of America, *Reviews in Engineering Geology*: Boulder, CO; 35-70.

Messerli B, Ammann C, Geyh M, Grosjean M, Jenny B, Kammer K, Vuille M (1998) The problem of the “Andean dry diagonal”: current precipitation, Late Pleistocene snow line, and lake level changes in the Atacama Altiplano (18 S–28 S/29 S). *Bamberger Geographische Schriften* 15: 17-34.

Moreno H, Gonzales-Ferran O, Riffo P (1981) Descriptions of volcanic eruptions—Chile: *Bulletin of Volcanic Eruptions*, v. 19, p. 76.

Moreno H, López L, Riffo P,Fuentealba G (1985) News volcanic events. Eos.66(1)1:4.

Moreno H, Fuentealba G (1994) The May 17 - 19, 1994 Llaima volcano Eruption, Southern Andes (38º 42' S - 71º 44' W). *Revista Geológica de Chile* 21(1):167-171.

Meunier P, Hovius N, Haines J (2008) Topographic side effects and the location of earthquake induced landslides. *Earth and Planetary Science Letters* 275: 221-232.

Naranjo J, Moreno H, Banks NG (1993) La erupción del volcán Hudson en 1991 (46°S), Región XI, Aisén, Chile. Servicio Nacional de Geología y Minería-Chile, Boletín 44, 50 p.

Naranjo J(1994) Tinguiririca (Chile) phreatic explosion in January 1994.Bulletin of the Global Volcanism network.V.19(11): 7.

Naranjo J, Moreno H (2004) Laharic debris-flows from Villarrica Volcano. En: Lara, L., Clavero, J. (eds.), Villarrica Volcano (39.5ºS) Southern Andes, Chile. Servicio Nacional de Geología y Minería-Chile. Boletín 61, 66 p.

Ng F, Liu S (2009) Temporal dynamics of a jökulhlaup system. *Journal of Glaciology* 55(192): 651-665.

Naruse R (2006) The response of glaciers in South America to environmental change. In: Knight, P. (Ed.), In Glaciers and Earth's Changing Environment. Blackwell, Oxford, UK, pp. 231-238.

Nye JF (1976) Water flow in glaciers: jökulhlaups, tunnels and veins. *Journal of Glaciology* 17: 181-207.

Ohata T, Enomoto H, Kondo H (1985) Characteristics of ablation at San Rafael Glacier. Glaciological Studies in Patagonia, Northern Icefield, 1983–1984. Data Center for Glacier Research., JSSI, 37-45.

Peña H, Escobar F(1983) Análisis de las crecidas de Río Paine, XII región. Publicación Interna Estudios Hidrológicos No. 83/7, Dirección General de Aguas, Ministerio de Obras Públicas, Santiago,Chile, 78 p.

Peña H, Escobar F (1987) Análisis del aluvión de mayo de 1985 del río Manflas, cuenca del río Copiapó. Publicación Interna Estudios Hidrológicos 87/3, Ministerio de Obras Públicas, Dirección General de Aguas, Santiago, Chile, 14p.

Peña H, Klohn W (1989) Non-meteorological flood disasters in Chile, in Starosolszky, O. and Melder,O.M. (Eds), Hydrology of Disasters, James & James,London,243-258.

Petrakov DA, Chernomorets SS, Evans SG, Tutubalina OV (2008) Catastrophic glacial multi-phase mass movements: a special type of glacial hazard. *Advances in Geosciences* 14: 211-218.

Pierson TC, Janda RJ (1994) Volcanic mixed avalanches - a distinct eruption-triggered mass-flow process at snow-clad volcanoes. *Geological Society of America Bulletin* 106:1351-1358.

Pierson TC, Waitt RB (1999) Hydrologic consequences of hot rock-snowpack interactions at Mount St. Helens Volcano, Washington, 1982-1984, in Pierson, T.C., ed., Hydrologic consequences of hot rock--snowpack interactions at Mount St. Helens Volcano, Washington, 1982-84: US Geological Survey Professional Paper 1586, p. 1-8.

Planet Action (2010) Monitoring of glacial lake outburst floods (GLOFs) in Chile. Proposal presented to Planet Action-SPOT image. 8p. Available at: http://www.planet-action.org/automne_modules_files/polyProjects/public/r4130_93_planet_action_glof.pdf

Prieto M del R (1986) The glacier dam on the Rio Plomo: A cyclic phenomenon?. *Zeitschrift fur Gletscherkunde und Glazialgeologie* 22 (H. 1): 73-78.

Procter J, Cronin SJ, Fuller IC, Lube G, Manville V (2010) Quantifying the geomorphic impacts of a lake-breakout lahar, Mount Ruapehu, New Zealand. *Geology* 38: 67-70.

Plagemann A (1887) Das andine Stromgebiet des Cachapoal. Petermanns Geogr. Mitteilungen. Heft III, Gotha. pp. 65-82.

Post A, Mayo LR (1971) Glacier dammed lakes and outburst floods in Alaska. U.S. Geological Survey. Hyd. Inv.Atlas HA-455, 10 pp., 3 sheets.

Rabassa J, Rubulis S, Suárez J (1979) Rate of formation and sedimentology of (1976–1978) push-moraines, Frías Glacier, Mount Tronador (41°10′S; 71°53′W), Argentina. In: Schluechter, C. (Ed.), Moraines and Varves. A.A. Balkema, pp. 65-79.

Reynolds, JM, Dolecki A, Portocarrero C (1998) Construction of a drainage tunnel as part of glacial lake hazard mitigation at Hualcán, Cordillera Blanca, Peru. *In* Geohazards in engineering geology. *Edited by* J.G. Maund and M. Eddleston. Geological Society Special Publication (London), No. 15, pp. 41-48.

Riffo P, Fuentealba G, Urra LH (1987) Síntesis histórica de las erupciones del volcán Villarrica (Chile): *Boletín de Vulcanologia, Universidad Nacional, Observatorio Vulcanológica y Sismológica de Costa Rica* 18: 8-11.

Richardson SD, Reynolds JM (2000) An overview of glacial hazards in the Himalayas. *Quaternary International* 65/66: 31-47.

Rignot E, Rivera A, Cassassa G (2003) Contribution of the Patagonia Icefields to sea level rise. *Science* 30: 434-437.

Río Negro (2009) Rehabilitaron el camino hasta Ventisquero Negro en el Tronador. Miércoles 5 de Agosto de 2009. 28p.

Rivera A, Casassa G (2004) Ice elevation, areal, and frontal changes of glaciers from National Park Torres del Paine, Southern Patagonia Icefiled. *Artic, Antarctic and Alpine Research* 36(4): 379-389.

Rivera A, Corripio JG, Brock B, Clavero J, Wendt J (2008) Monitoring ice capped active Volc\protect'an Villarrica in Southern Chile by means of terrestrial photography combined with automatic weather stations and GPS. *Journal of Glaciology* 54(188) 920-930.

Röthlisberger F (1986) 10,000 Jahre Gletschergeschichte der Erde. Verlag Sauerländer, Aarau.

Salzmann N, Kääb A, Huggel C, Allgöwer, B, Haeberli W (2004) Assessment of the hazard potential of ice avalanches using remote sensing and GIS-modelling. *Norwegian Journal of Geography* 58(2):74-84.

Sepúlveda SA, Serey A, Lara M, Pavez A, Rebolledo S (2010) Landslides induced by the 2007 Aysen Fjord earthquake, Chilean Patagonia. *Landslides* 7:483-492.

Siebert L, Simkin T (2002) Volcanoes of the World: an Illustrated Catalog of Holocene Volcanoes and their Eruptions. Smithsonian Institution. Global Volcanism Program Digital Information Series, GVP-3, (http://www.volcano.si.edu/world/).

Stoffel M, Bollschweiler M (2009) What tree rings can tell about earth-surface processes. Teaching the principles of dendrogeomorphology. *Geography Compass* 3: 1013–1037.

Stone J (1935) The volcanoes of southern Chile.*Zeitschrift für Vulkanologie* 16:81-97.

Stuefer M, Rott H, Skvarca P (2007) Glaciar Perito Moreno, Patagonia: climate sensitivities and glacier characteristics preceding the 2003/04 and 2005/06 damming events. *Journal of Glaciology* 53(180):3-16.

Schneider D, Huggel C, Haeberli W, Kaitna R (2011) Unraveling driving factors for large rock–ice avalanche mobility. *Earth Surface Processes and Landforms* 36: 1948-1966.

Tanaka K (1961) Geographical Contribution to a Periglacial Study of the Hielo Patagónico Norte with Special Reference to the Glacial Outburst Originated from

Glacier-Dammed Lago Arco, Chilean Patagonia". Faculty of Economics, Kobe University. Japan. 109 p.

Tanaka K (1980) Geographical Contribution to a Periglacial Study of the Hielo Patagónico Norte with Special Reference to the Glacial Outburst Originated from Glacier-Dammed Lago Arco, Chilean Patagonia. Center Co. Ltd, Tokyo, p. 97.

Tebaldi CK, Hayhoe JM, Arblater G, Meehl A (2006) Going to the extremes: An intercomparison of model-simulated historical and future changes in extreme events. *Climate Change* 79:185 – 211, doi:10.1007/s10584-006-9051-4.

Tormey D (2010) Managing the effects of accelerated glacial melting on volcanic collapse and debris flows: Planchón-Peteroa Volcano, Southern Andes. *Global and Planetary Change* 74:82-90.

Tuffen H (2010) How will melting of ice affect volcanic hazards in the 21st century? *Philosophical Transactions of the Royal Society* A, 368: 2535-2558.

Tweed FS, Russell AJ (1999) Controls on the formation and sudden drainage of glacier-impounded lakes: implications for jökulhlaup characteristics. *Progress in Physical Geography* 23: 79-110.

Urrutia R, Lanza L(1993) Catástrofes en Chile: 1541-1992. Editorial La Noria. Santiago, 440p.

Valenzuela L (2004) Stability issues in natural and man made slopes in mining. In: LACERDA, W. A.; EHRLICH, M.; FONTOURA, S. A. B. & SAYÁO, A. S. F. Landslides: evaluation and stabilization. Leiden: Balkema. 467-473.

Viale M, Nuñez MN (2011) Climatology of winter orographic precipitation over the subtropical central Andes and associated synoptic and regional characteristics. *Journal of Hydrometeorology* 12(4): 481-507.

Villalba R, Lara A, Boninsegna JA, Masiokas M, Delgado S, Aravena JC, Roig FA, Schmelter A, Wolodarsky A, Ripalta A (2003) Large-scale temperature changes across the southern Andes: 20th-century variations in the context of the past 400 years. *Climatic Change* 59: 177-232.

Voight B (1994) The 1985 Nevado del Ruiz volcano catastrophe: anatomy and retrospection, *J. Volcanol. Geoth. Res*., 42:151-188.

Walder JS, Costa JE (1996) Outburst floods from glacier-dammed lakes: the effect of mode of lake drainage on flood magnitude. *Earth Surface Processes and Landforms* 21: 701-723.

Warren C, Aniya M (1999) The calving glaciers of southern South America. *Global and Planetary Change* 22: 59-77.

Watt S. Pyle FL. David M. Naranjo J, Mather T (2009) Edifice destruction on strike-slip fault zones: Landslide and tsunami hazard at Yate volcano, Chile. *Bulletin of Volcanology* 71(5): 559-574.

Welkner D, Eberhardt E, Hermanns RL (2010) Hazard investigation of the Portillo Rock Avalanche site, central Andes, Chile, using an integrated field mapping and numerical modeling approach. *Engineering Geology* 114: 278-297.

WGMS (2008) Global glacier changes: facts and figures. In: Zemp, M., Roer, I., Kääb, A., Hoelzle, M., Paul, F., Haeberli, W. (Eds.), UNEP, World Glacier Monitoring Service. University of Zurich, Switzerland.

Winchester V, Harrison S (2000) Dendrochronology and lichenometry: an investigation into colonization, growth rates and dating on the east side of the North Patagonian Icefield, Chile. *Geomorphology* 34(1-2): 181-194.

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

3 Moraine-dammed lake failures in Patagonia and assessment of outburst susceptibility in the Baker Basin

3.1 Abstract

Glacier retreat since the Little Ice Age has resulted in the development or expansion of hundreds of glacial lakes in Patagonia. Some of these lakes have produced large (≥10^6 m^3) Glacial Lake Outburst Floods (GLOFs) damaging inhabited areas. GLOF hazard studies in Patagonia have been mainly based on the analysis of short-term series (≤ 50 years) of flood data and until now no attempt has been made to identify the relative susceptibility of lakes to failure. Power schemes and associated infrastructure are planned for Patagonian basins that have historically been affected by GLOFs, and we now require a thorough understanding of the characteristics of dangerous lakes in order to assist with hazard assessment and planning. In this paper, the conditioning factors of 16 outbursts from moraine dammed lakes in Patagonia were analysed. These data were used to develop a classification scheme designed to assess outburst susceptibility, based on image classification techniques, flow routine algorithms and the Analytical Hierarchy Process. This scheme was applied to the Baker Basin, Chile, where at least 7 moraine-dammed lakes have failed in historic time. We identified 386 moraine-dammed lakes in the Baker Basin of which 28 were classified with high or very high outburst susceptibility. Commonly, lakes with high outburst susceptibility are in contact with glaciers and have moderate (>8°) to steep (>15°) dam outlet slopes, akin to failed lakes in Patagonia. The proposed classification scheme is suitable for first-order GLOF hazard assessments in this region. However, rapidly changing glaciers in Patagonia make detailed analysis and monitoring of hazardous lakes and glaciated areas upstream from inhabited areas or critical infrastructure necessary, in order to better prepare for hazards emerging from an evolving cryosphere.

3.2 Introduction

Amongst the most frequent and damaging processes related to glaciers are Glacial Lake Outburst Floods (GLOFs). The failure of glacial lakes can release millions of cubic metres of water in a short time (minutes to days) and produce floods with high peak discharges ($10^4 m^3/s$) and remarkable erosive and transport capacity (Costa and Schuster, 1988; Breien et al., 2006). GLOFs can occur through different mechanisms. Moraine-dammed lakes commonly fail due to overtopping and the progressive enlargement of a breach in the dam. Rainfall, meltwater and waves produced by mass movements, ice avalanches or calving often trigger the overflow and subsequent moraine-dam failures (Costa and Schuster, 1988; Emmer and Cochachin, 2013). Piping after earthquakes, the mechanical failure of ice-cored moraines and flow waves from upstream lake failures have also been related to GLOFs (Lliboutry et al., 1977; Buchroithner et al., 1982).

In the Himalayas, European Alps and the Andes GLOFs have affected mountain communities for centuries, resulting in thousands of casualties (Hewitt, 1982; Grove, 1987; Reynolds, 1998). However, the generation of new glacial lakes as a consequence of glacier retreat, and the economic exploitation of previously uninhabited valleys make the emergence of new endangered areas likely. For example, in Chilean Patagonia, hydro-electric generation plants are being planned in areas that have historically been influenced by GLOFs (Dussaillant et al., 2009; Vince, 2010). Thus, there is now an urgent need to better understand and assess the GLOF hazard in these regions where detailed analyses are lacking.

A first step towards the analysis of GLOF hazards is the identification of glacier lakes. Remote sensing methods (e.g. image classification techniques) are especially suitable for this task allowing rapid analysis of large areas (hundreds of square kilometres) in an inexpensive way (Huggel et al.,2002; Kääb et al., 2005). Using these method, hazardous lakes can be identified, and subsequently, if they are found to pose a potential risk to lives or infrastructure, more detailed local studies (e.g. GLOF modelling) might be developed (Mergili and Schneider 2011) (e.g. Bajracharya et al., 2007; Worni et al., 2012). Hazardous lakes are identified by comparing lake characteristics (e.g. dam geometry and potential for ice-avalanche impacts entering the lake) with those of failed lakes and their surroundings (MacKillop and Clague, 2007; Bolch et al., 2011; Wang et al., 2011; Emmer and Vilímek, 2013). In Patagonia, data about failed moraine-dammed lakes have not been systematically analyzed and the contributing factors of most of the failed moraine-dammed lakes are unknown.

Since the beginning of the twentieth century, at least 16 moraine-dammed lakes have failed in Patagonia (Iribarren Anacona et al., 2014). Seven of these lakes are located in the Baker Basin where major hydroelectric generation plants are planned. One of these GLOFs (Laguna del Cerro Largo) is probably the largest outburst of a moraine-dammed lake (in terms of water volume released, $229 \times 10^6 m^3$) reported worldwide (Hauser, 1993; Clague and Evans, 2000). In the Baker Basin GLOFs have destroyed houses, forced the relocation of a village and have damaged inhabitant's livelihoods (Iribarren Anacona et al., 2014). Furthermore, a flood wave with GLOF characteristics killed three people boating in the Baker River in January 1977 (El Diario de Aysén, 1977a; El Diario de Aysén, 1977b). This makes the Baker Basin an important location to study the GLOF hazards.

In spite of the damage and the increasing frequency of GLOFs in Patagonia, and the Baker Basin, GLOFs hazards studies have been limited and based mainly on statistical analysis of short series (< 50 years) of flood data (Hidroaysén, 2008; Vince, 2010). The relative susceptibility to failure of moraine-dammed lakes in the Baker Basin is currently unknown as well as the extent to which these lakes pose a threat to infrastructure or human life.

In summary, GLOFs might pose a significant hazard to lives and newly developing infrastructure in Patagonia, but several questions remain unanswered concerning their past behaviour. The current status of moraine-dammed lakes, one of the prime sources of GLOFs, remains uncertain. We aim to analyse previously failed moraine-dammed lakes in Patagonia to identify the conditioning factors that led to failure, and to use these data to identify the moraine-dammed lakes most susceptible to future failure in the Baker Basin.

3.3 Setting

Patagonia is a region located in the southernmost part of South America (≥40°S) in the territories of Chile and Argentina (Figure 3.1). This region hosts some of the largest temperate ice masses on Earth (Harrison, 2011). However, glaciers in Patagonia have suffered significant losses in mass since the maximum Little Ice Age (LIA) expansion (between the 16th and 19th centuries) (Masiokas et al., 2009a), resulting in the formation or growth of several ice, bedrock and moraine-dammed lakes (Loriaux and Casassa, 2013). North-facing, land-terminating glaciers with surfaces < 5 km^2 have shown the fastest retreat in the region (Davis and Glasser, 2012).

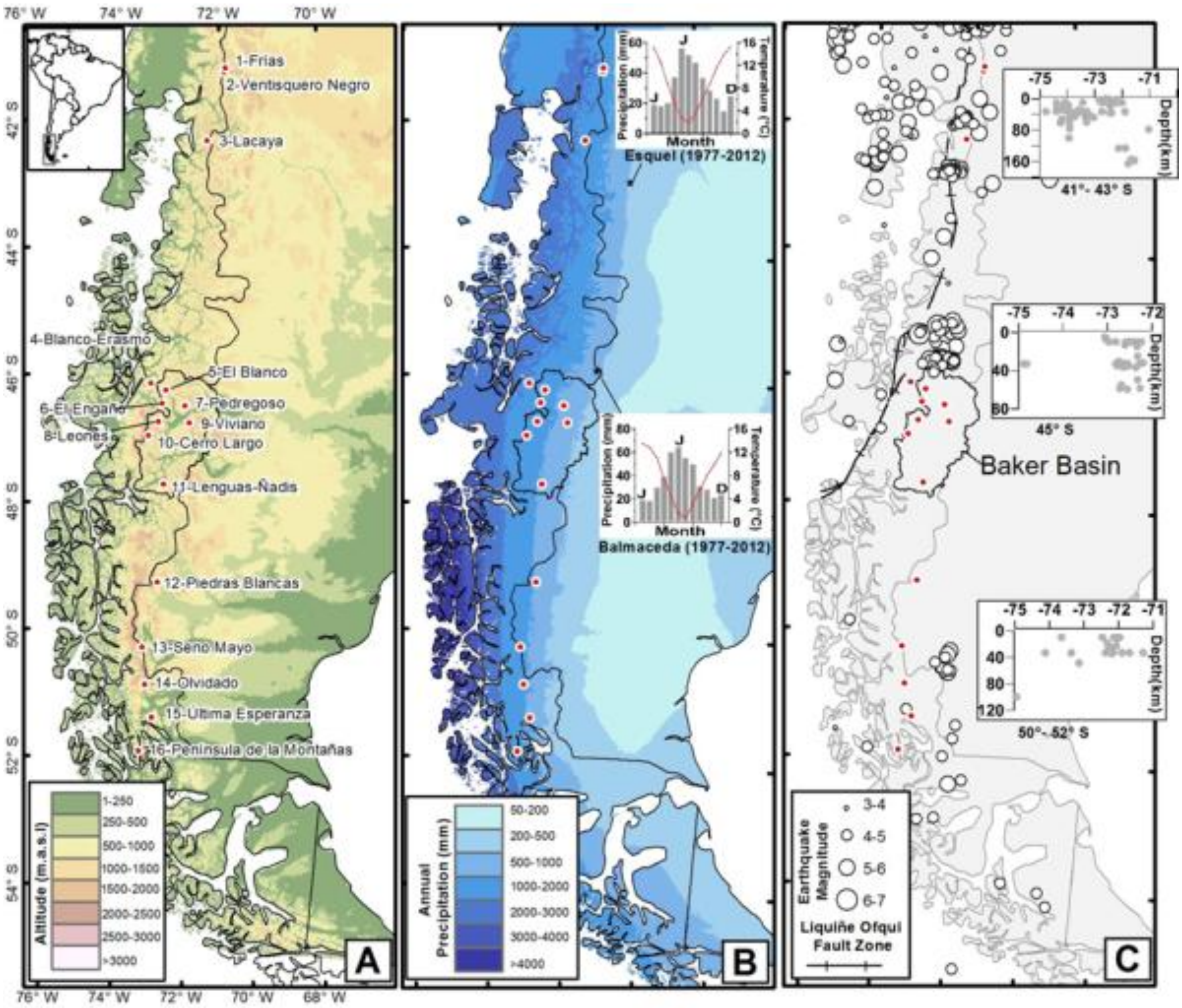

Figure 3.1 A) Geographical setting and name (unofficial) of failed moraine-dammed lakes in Patagonia used to develop a GLOF susceptibility classification scheme. B) Failed dams are located in zones with annual precipitation ranging from 500 to 2000 mm and where mean monthly temperature in winter is generally above 0°C. C) Note the decrease in the number and magnitude of earthquakes south of the 46°S and the high frequency of shallow earthquakes (hypocentre <30 km). Climate data extracted from Hijmans et al. (2005) and from the National Climatic Data Center (http://www.ncdc.noaa.gov). Seismic data (period 1973-2012) retrieved from the Northern California Earthquake Data Center (http://www.ncedc.org/anss/catalog-search.html).

The Baker Basin is located between 46° and 48° S, in the eastern side of North Patagonian Icefield (NPI) and has a surface area of about 20,500 km^2 of which c.a. 1940 km^2 are covered by ice (Figure 3.2). Climate varies from arid continental, in the East (precipitation c.a. 200 mm/year) to maritime hyperhumid on the west side of the

Andean main divide (precipitation c.a. 2000 mm/year). Seismicity in the Baker basin is low. Seismic activity has been concentrated in the north associated with Hudson Volcano eruptions; however seismicity decreases south of 46°S (Barrientos, 2007) and no recent seismicity (from 1973 onwards) has been recorded in the rest of the basin. The Baker Basin is sparsely populated, mainly by low-density rural settlements. The number of tourists that visit the region is low (Muñoz et al., 2006). The basin hosts pristine rainforest, lakes and glaciers. Hundreds of glacier lakes exist in the Baker Basin where major hydroelectric schemes are planned. This makes the basin an ideal site to study the hazard posed by glacier lakes in Patagonia.

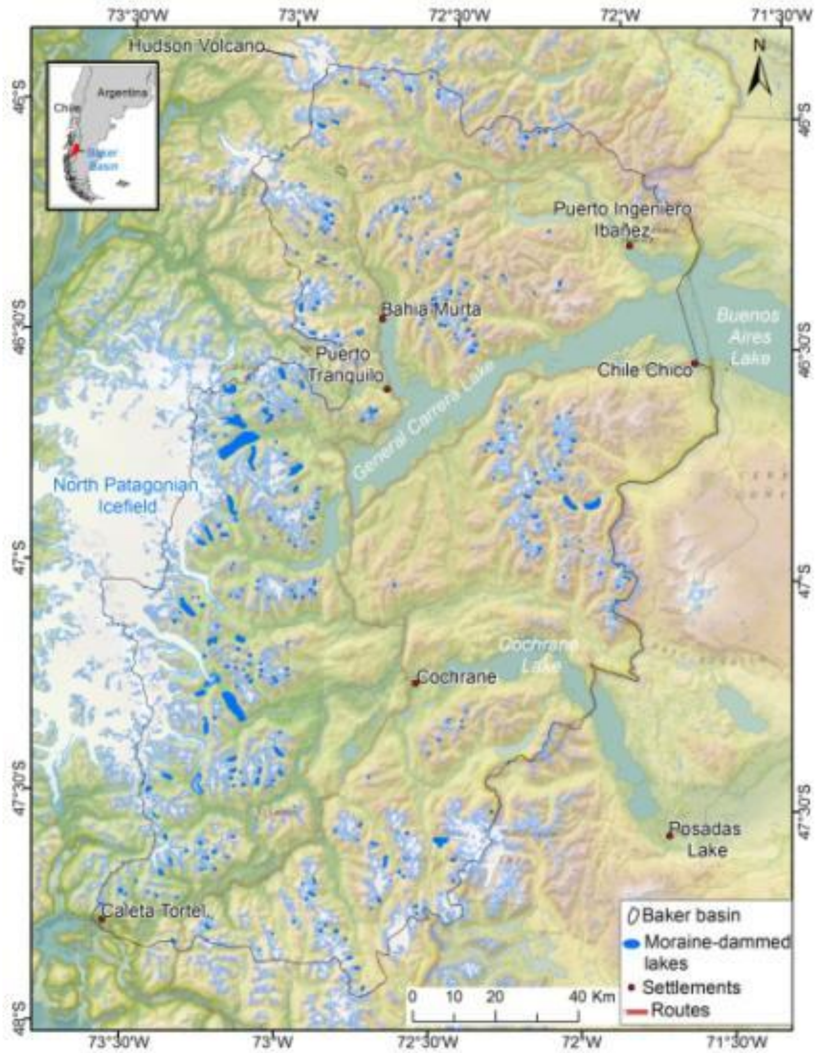

Figure 3.2 Location of moraine-dammed lakes and settlements in the Baker Basin.

3.4 Data and methods

Data from historical outburst floods in Patagonia were used to develop an outburst susceptibility classification scheme which was applied in the Baker Basin. This section details the data used and procedures followed to a) characterize the failed moraine dams in Patagonia b) to select, measure, and weight the outburst susceptibility factors and to c) define the outburst susceptibility classes (Figure 3.3).

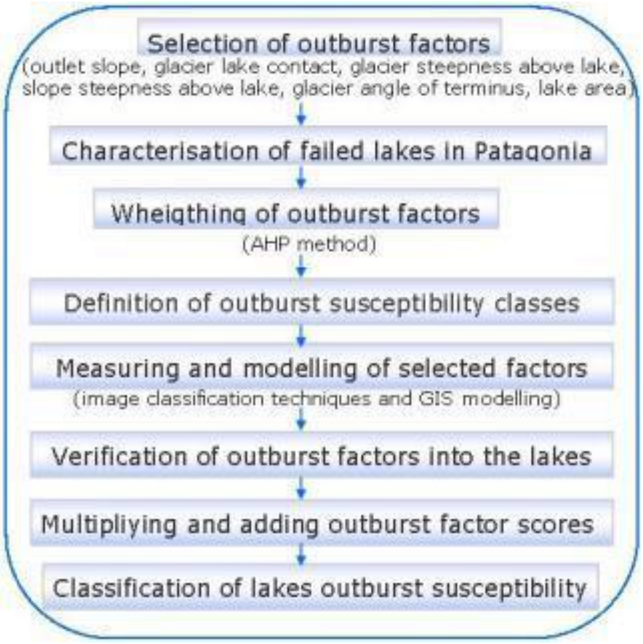

Figure 3.3. Flow chart of procedures followed to classify the lakes outburst susceptibility in the Baker Basin

3.4.1 Data

Morphometric characteristics of dams, glaciers and lake catchments were extracted from Landsat TM and ETM+ images. Both Landsat TM and ETM+ images have a spatial resolution of 30m (15m for the ETM+ panchromatic band) and were acquired from http://glovis.usgs.gov/. Topographic data were derived from the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM V2). The spatial resolution of the ASTER GDEM V2 is 1 arcsecond (approximately 30 m) and the DEM has a vertical accuracy of 17 m (Tachikawa et al., 2011).

3.4.2 Characterization of failed moraine-dammed lakes in Patagonia

The 16 moraine-dammed lakes that failed in historic time in Patagonia were mapped manually using Landsat images. In the oldest events (before 1985) the lake area and glacier extent prior to the outbursts were reconstructed using historical documents or geomorphic features (e.g. trimlines and lake shorelines). Morphometric parameters in these cases are less accurate than in GLOFs which occurred after 1985 but they still provide an approximation of the lake and glacier conditions prior the dam failures (Table 3-1). The basin and glacier topography were extracted automatically from the ASTER GDEM using standard spatial analysis tools (see Reuter and Nelson, 2008).

Table 3-1 Data of 16 GLOFs in Patagonia and characteristics of the moraine-dammed lakes and their surroundings prior to the failure.

Site	Date	Lake area (km^2)		Ov	Pd	Pl	H/L	Dh	Dos	Glc	Ias	Mms	Plg
		Before	After	(m^3 x 10^6)	(m^3/s)	(km)	(°)	(m)	(°)				
1.*Gl.* Frías	1942-1953	0.01	0	0.06	81	-	-	≤10?	35	Y(b)	Y	Y	N
2.*Gl.* Ventisquero Negro	21/05/2009	0.55	0.32	4.36	1301	7.1	1.1	30	18	Y	N	Y	Y
3.Río Lacaya	2000-2001	0.33	0.15	3.14	1048	21.5	3	≤10?	9	Y	Y	Y	N
4.Monte Erasmo	1985-2000	0.71	0.69	0.16	150	6.0	2.1	≤10?	8	Y	N	Y	Y
5.Estero El Blanco	2000-2003	0.12	0.04	1.05	511	5.4	5.1	≤10?	11	N	N	Y	N
6.Río Engaño	11/03/1977	1.15	0.81	7.36	1839	6.5	2.1	50	24	Y	Y	Y	Y
7.Estero El Pedregoso	1985-1987	0.12	0.09	0.28	214	5.0	8.4	-	4	Y(c)	N	Y	Y
8.Río Los Leones	2000	0.02	0	0.16	150	2.3	7.4	40	22	N	N	Y	N
9.Río Viviano	1987-1998	0.02	0.01	0.06	81	2.3	7.3	15	26	N	Y	Y	N
10.Cerro Largo	16/03/1989	1.82	0.98	24.73	4092	13.0	1.1	160	26	Y	Y	Y	N
11.Estero Las Lenguas	1987-1998	0.67	0.44	4.36	1301	23.8	1.3	110	21	Y	Y	Y	N
12.*Gl.* Piedras Blancas	16/12/1913	0.21	-	-	-	4.5	2.6	80	21	Y	Y	Y	Y
13.Seno Mayo	2001-2003	0.07	0.03	0.41	277	2.3	19	≤10?	8	Y	N	Y	Y
14.*Gl.* Olvidado	2003	0.53	-	-	-	5.8	2.6	20	10	Y	N	Y	Y
15.Última Esperanza	1999-2006	0.09	0.08	0.06	81	10.6	4.0	≤10?	5	Y(c)	Y	Y	Y

16.Peninsula de las Montañas	2005-2006	0.07	0.06	0.06	81	2.0	8.4	≤10?	20	Y	N	Y	Y

Abbreviations: Outburst volume (Ov), Peak discharge (Pd), Path length (Pl), Angle of reach (H/L), Dam height (Dh), Dam outlet slope (Dos), Glacier lake contact (Glc), Ice avalanche susceptibility (Ias), Mass movement susceptibility (Mms) and Potential lake growth (Plg). Ov was calculated using the lake area lost after the GLOFs. B) Data inferred from the position of Glacier Frías front in 1935-1938 (see Villalba et al., 1990). C) Lake in contact with a debris-covered glacier. GLOFs data sourced from Iribarren Anacona et al. (2014) and references therein

The GLOF paths were mapped on Landsat images, and when available, high resolution satellite images (≤5 m) from Google Earth. GLOFs angle of reach were measured along the flow path, from the dam breach to the lowest area of stripped vegetation or sediment deposition. Thus, path lengths may be underestimated in the oldest events due to vegetation regrowth. The dam height and outlet slope were derived from topographic profiles drawn over the ASTER GDEM (30 m of spatial resolution) on undisturbed sections of the dam near the original lake outlet. Breaks in the topographic profile were not straight forward to map in the case of small dams (probably ≤ 10 m in height), making it difficult to estimate the dam geometry.

Lake volume and outburst peak discharges were calculated using empirical formulae. Several formulae exist that relate lake area and volume. Formulations by Huggel et al. (2001) and Loriaux and Casassa (2013) are based on data of ice and moraine-dammed lakes, whereas the O'Connor et al. (2001) formula is based on a small number of moraine-dammed lakes. Ice and moraine dammed lakes often have different geometries (MacKillop and Clague, 2007) and therefore different volumes. Thus, we collected data from literature of a large number of moraine dammed lakes worldwide (38 measurements of lake area and volume from 25 lakes; Figure 3.4) and derived the following empirical formula to calculate the lakes volume

$$V = 31.249A^{1.3399}$$

where V is the lake volume in $m^3 x10^6$ and A is the lake area in km^2 .

We compared the measured volume of 38 data of moraine dammed lakes with the volume estimated with the derived empirical formula. The mean error of the volume estimates was ±71%.

The peak discharge was calculated using the following formula proposed by Walder and O'Connor (1997)

$$Q = 0.054V^{0.66}$$

where V is the lake volume in m^3.

Outburst parameters estimated by regression-based methods have large uncertainty. Dam breach peak discharge estimates can have uncertainties of up to ±1 order of magnitude (Wahl, 2004).

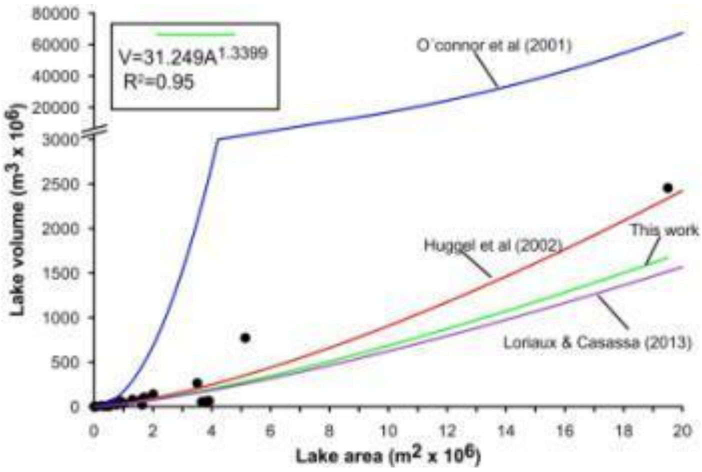

Figure 3.4. Empirical curves showing the relationship between area and volume of glacial lakes. The green curve was obtained from 38 data of lake area and volume of 25 moraine-dammed lakes worldwide. Note that the lake volume does not increase proportionally with an increase in the lake area and that the major diverge between curves occurs on the largest lakes where less data is available. Data extracted from O´connor et al (2001), Huggel et al (2002), Allen et al (2011), Rivas (2012) and Loriaux and Casassa (2013).

3.4.3 Selection of outburst susceptibility factors

Lakes dammed by temperate glaciers may be considered inherently unstable since ice-dam characteristics (e.g. glacier thickness, crevassing and bed adhesion) are subject to frequent changes, affecting the ice-conduit dynamics (Tweed and Russell, 1999). Consequently, we considered all the ice-dammed lakes as hazardous. Thus, we centred our analysis on selecting variables to identify moraine-dammed lakes susceptible to failure. Several variables have been used to identify hazardous moraine-dammed lakes (see Emmer and Vilímek's, 2013 review paper). The dam geometry (e.g. width-to-height ratio, flank steepness and dam freeboard) and internal structure (e.g. presence of ice and particle size distribution) are probably the most important conditioning factors of outburst floods (Richardson and Reynolds, 2000). However, most dam characteristics can only be measured accurately in the field or by using high resolution satellite images or DEMs. We chose six characteristics of lakes, dams and their surroundings that can be measured and modelled using medium resolution satellite images and DEMs. These variables comprise outburst conditioning and triggering factors and also give an idea of the outburst damaging potential. Due to the low spatial and temporal resolution of meteorological data in Patagonia, extreme meteorological events were not included in the analysis. The selected outburst factors are described below.

3.4.3.1 Lake area

Lake dimensions have been directly related to outburst volume, peak discharge and the flood damage potential (Costa and Schuster, 1988). Accordingly, larger lakes are considered to be more hazardous than small lakes. Furthermore, lakes with larger areas are generally deeper (see e.g. Diaz et al, 2007 database), and may exert higher hydrostatic pressures over the dams making them more susceptible to failure (Richardson and Reynolds, 2000). Larger lakes also have a greater surface area potentially exposed to mass movement and ice avalanche impacts, increasing their outburst susceptibility.

3.4.3.2 Glacier-lake contact

Lakes in contact with glaciers can be affected by calving and the sudden floating of dead ice. Both mechanisms can produce waves capable of overtopping dams starting a breaching process and subsequent dam failure (Richardson and Reynolds, 2000). Icebergs also can block the lake outlet, raising the water level potentially overtopping and breaching the dam. Thus, lakes in contact with glaciers are considered more hazardous than lakes detached from the glacier snout.

3.4.3.3 Slope of glacier terminus

A glacier with a low-angle terminus can be an indicator of a negative mass balance. Consequently lakes in contact with flat glacier fronts (slopes less than 5°) are likely to grow as a consequence of glacier retreat (Frey et al., 2010b). Lakes that are expected to grow are more hazardous than lakes which areas are expected to remain stable or shrink (examples of minor moraine dammed lake area reduction, not related to GLOFs, have been observed in Patagonia; see figure 5d in Loriaux and Casassa 2013), since the potential area exposed to mass movements or ice avalanches may increase and the dams may be subject to higher hydrostatic pressures.

3.4.3.4 Lake outlet slope

Steep outlets can be more easily enlarged than low gradient outlets if an increase in the lake discharge occurs. Progressive erosion can widen and deepen the outlet leading to lake drainage. Consequently, dams with steep outlets are more susceptible to failure (O'Connor et al., 2001). Furthermore, high dams which produce outbursts with high peak discharges (Walder and O'Connor, 1997) usually have steep outlets (see Table 3-1).

3.4.3.5 Glacier steepness above lake

Steep (≥25°) temperate glaciers are a common source of ice avalanches (Alean, 1985). Ice avalanches impacting lakes can generate impulse waves capable of overtopping dams starting catastrophic lake drainage. The likelihood of an ice avalanche impacting a lake depends on the distance, slope and roughness of the terrain between the glacier and the water body. Ice avalanches are the most common cause of outburst floods in the Himalayas (Wang et al., 2009) and has also been reported in the Tropical Andes (Lliboutry et al., 1977).

3.4.3.6 Steepness of slopes above lake

Steep unvegetated slopes are common source of mass movements (Peduzzi 2010) and can be indicators of high geomorphic activity. Large and high-velocity landslides can generate impulse waves of hundreds of metres of run up that can easily overtop dams starting progressive erosion and lake drainage (Walder et al., 2003). Lakes can also be suddenly drained by large waves without a dam breaching process (Clague and Evans, 2000). Mass movement impacts have been related to outburst floods in Patagonia and other Andean regions (Hubbard et al., 2005; Harrison et al., 2006).

3.4.4 Measuring and modelling of selected factors

3.4.4.1 Glacier and lakes delimitation

Glaciers and lakes were delimited using multispectral classification techniques that exploit the maximum reflectance difference of a surface (i.e. glaciers and lakes) in different spectral channels to identify the desired object (Huggel et al., 2002; Paul et al., 2002). Thresholded band ratios have been successfully used in glacier inventories (e.g. Andreassen et al., 2008; Svoboda and Paul, 2009). We mapped glaciers via band rationing the Near-infrared and Mid-Infrared bands of Landsat images in reflectance values (i.e. pixel values not converted to radiance) (Paul et al., 2002). The thresholds values to identify glaciers (bare ice) were defined comparing visually the band ratio image with false composite Landsat images (Table 3-2). Debris covered glaciers were drawn manually.

Table 3-2 Satellite images and threshold used to identify glaciers, lakes and vegetation

Sensor	Image date	Path/Row	Glaciers Band ratio threshold ≥	Lakes NDWI threshold ≥	Vegetation NDVI threshold ≥
Landsat ETM+	08/03/2000	232/092	3	-0.5	0.1
	08/02/2013	232/092	-	-	-
	18/02/2002	231/093	2.5	-0.45	0.1
	18/02/2002	231/092	1.5	-0.45	-
	08/03/2000	232/093	3	-0.5	-
	22/02/2012	232/093	-	-	-

Lakes in the Baker Basin were mapped using the Normalized Difference Water Index (NDWI) of Huggel (2002) obtained from the following equation

NDWI= (Near-Infrared Band - Blue Band) /(Near-Infrared Band + Blue Band)

The NDWI was applied on Landsat images in Digital Numbers. A cast shadow mask was used to eliminate shadowy areas mistakenly classified as lakes (see Huggel et al., 2002).

A median filter of 3x3 kernels was applied to smooth the glacier and lake surfaces incorporating or eliminating isolated pixels in the classified image (Paul et al., 2002). Misclassified lakes in shadowy areas and debris covered glaciers were corrected manually. The error in lake and glacier delimitation is estimated to be one pixel (i.e. ±30 m) although it can be larger in shadowy areas. The lake inventory was developed using images from the years 2000 and 2002. However, Landsat images of the years 2012 and 2013 also were analysed to manually incorporate recently formed lakes in the inventory and to assess the glacier-lake contact status. Only the area of lakes in contact with glaciers was determined using 2012-2013 images since the area of other lakes probably remained stable (see Loriaux and Casassa, 2012). The 2012-2013 images were not used as base for the entire inventory since about 20% of the data in each Landsat 7 image were lost after the failure of the scan-line corrector in May 2003 (USGS et al., 2003). Google Earth images were used to classify the dams (i.e. moraine, bedrock or ice dams). Only lakes located in valleys glaciated during the LIA were included in the analysis since lakes situated far from the LIA expansion (including very large moraine-dammed lakes such as General Carrera and small lakes dammed by bedrock) were considered to be stable. Published geomorphological maps were used to identify the glacier extent during LIA (Glasser et al., 2011; Glasser and Jansson, 2008), which was also inferred from trimlines and terminal moraines.

3.4.4.2 Slope steepness above lake and mass movement modelling

Mass movement paths were mapped using the Modified Single Flow Direction (MSF) model of Huggel et al. (2003). The MSF simulates the trajectory of mass movements from the source area following the steepest descent with a maximum deviation of 45°. The mass movement stops (i.e. the end of the path) when it reaches a predetermined ending condition generally set as the angle of reach (i.e. the angle of the line connecting the starting and the ending zone of a mass movement; Hsu 1978) (see Huggel et al., 2003 and Gruber et al., 2008 for model details).

Published data of the angle of reach of mass movements and typical angles of detachment zones were used as input to model the flow paths. The angle of reach and the slope of the starting zone of rock falls, debris flows and other complex mass movements vary locally according to the geology, terrain roughness and vegetation coverage. Steep unvegetated slopes may indicate high geomorphic activity and can be associated with loose, readily erodible material. Thus, we assume potential starting zones for all mass movements are unvegetated or sparsely vegetated slopes ≥ 30°. We have not distinguished between solid bedrock slopes and non-cohesive slopes since this task can only be accurately accomplished by photo interpretation or fieldwork, which are costly or time consuming, and consequently not suited to our preliminary regional analysis.

Vegetation was mapped using the Normalised Vegetation Index (NDVI) calculated using the following equation

NDVI= (Near Infrared Band-Red Band)/(Near Infrared Band+Red Band)

The angle of reach of mass movements was considered similar to that of rock-avalanches (about 15°; see Nicoletti and Sorriso-Valvo, 1991) which are the events most likely to start catastrophic lake drainages.

3.4.4.3 Glacier steepness above lake and ice avalanche modelling

The ice avalanche paths were also delineated using the MSF model based on empirical data of ice avalanches source and angle of reach (Figure 3.5). According to Alean (1985) ice-avalanches commonly start at slopes ≥ 25° in temperate glaciers (such as Patagonian glaciers) and have an angle of reach of 17° (data derived from about 100 ice-avalanches mostly from the European Alps). Thus, we mapped glacier surfaces with slopes ≥ 25° and used these areas as ice-avalanche detachment zones. The stopping condition in the MSF model was set at an angle of reach of 17°.

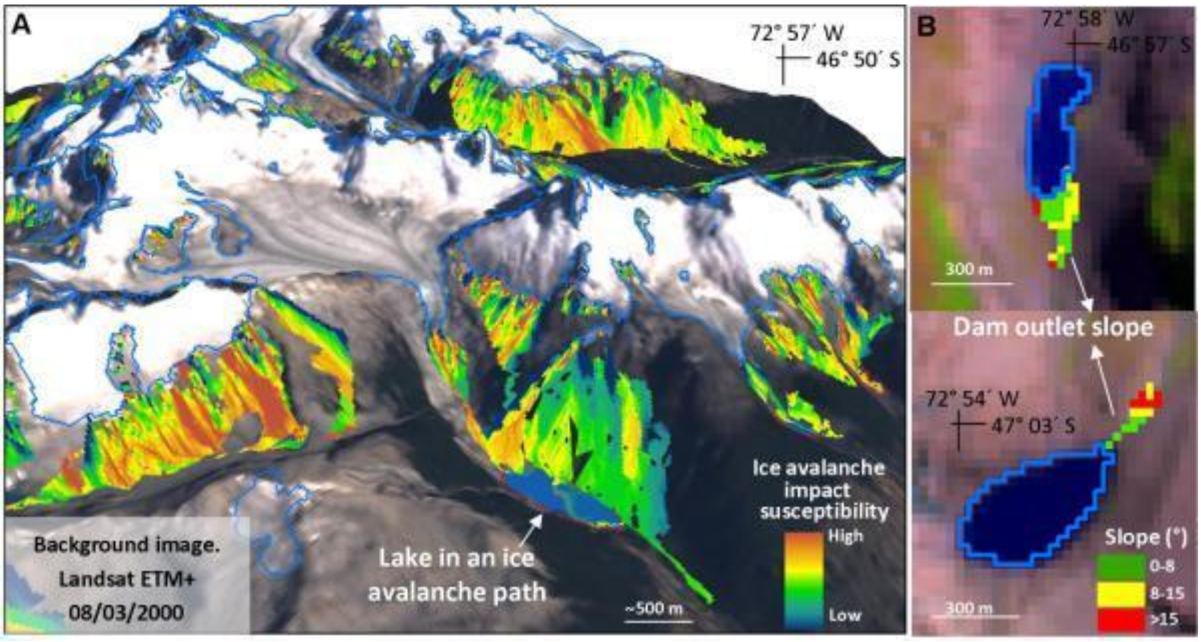

Figure 3.5. A) Results of ice avalanche modelling and automatic classification of glaciers, (B) lakes and dam outlet slope measurements

3.4.4.4 Lake outlet slope measurement

The lake outlet and the outlet slope were identified and measured automatically following a series of GIS procedures. First, we identified the lake outlet as the point with maximum flow accumulation in the lake (see Gruber and Peckham, 2008). From this point the steepest descent path 200 metres downstream (with a maximum deviation of 45°) was calculated using the Path Distance tool of ArcGIS. We assumed that moraine-dam widths are less than 200 metres. Dam widths of the largest failed lakes in Patagonia are ≥300 metres. However, we used a smaller value since most of the moraine-dammed lakes in the Baker Basin are small and this value (200 metres) does not significantly affect the average slope of larger dams. Finally, the mean slope of the steepest descent path was calculated.

3.4.5 Weighting process

After analysing 16 GLOFs in Patagonia, the six conditioning factors were weighted using the Analytical Hierarchy Process (AHP) (Saaty, 1980). We chose this method since it allows evaluation of the consistency of the subjective judgements which is not accomplished by other qualitative or semi-quantitative GLOF hazard approaches (see Emmer and Vilímek, 2013 for a review). The AHP is a multicriteria decision-making technique which allows estimation of the relative significance of factors contributing to an event based on pairwise comparison, expert judgment and the linear algebra transformation of the comparison factors matrix (Table 3-3). The aim of the pairwise comparison is to assess the significance of one factor compared to another. Values from 1 to 9 can be assigned to each factor, where a value of 1 means that both factors have equal importance and a value of 9 means that a factor has an extreme prevalence over another.

Table 3-2 Pairwise comparison of outburst predictor variables and consistency ratio

Matrix	Glacier-lake contact	Lake area	Glacier steepness above lake	Slope steepness above lake	Slope of glacier terminus	Dam outlet slope
Glacier-lake contact	1	2	2	2	3	1
Lake area	1/2	1	1/2	2	2	1/3
Glacier steepness above lake	1/2	2	1	3	3	1/2
Slope steepness above lake	1/2	1/2	1/3	1	2	1/3
Glacier angle of terminus	1/3	1/2	1/3	1/2	1	1/5
Dam outlet slope	1	3	2	3	5	1
Consistency ratio: 0.026						

Factor intensity

1 Equal importance

3 Moderate prevalence of one over another

5 Strong or essential prevalence

7 Very strong or demonstrated prevalence

9 Extremely high prevalence

2, 4, 6, and 8 express intermediate values. (After Saaty and Vargas 2001).

.

The AHP method has been used in natural hazard assessments by several authors (e.g. Ayalew et al., 2005; Lari et al., 2009). The AHP also allows the evaluation of the consistency of the judgements based on the estimation of the eigenvalue of the factors matrix. Generally only consistency ratios <0.1 are considered acceptable (Satty, 1980). We assigned the higher weights to the GLOF factors more frequently associated with GLOFs in Patagonia. After weighting the six GLOF factors, each factor was subdivided into classes for which we assigned weights (Table 3-4). The total GLOF susceptibility score for each lake was obtained multiplying the weight of the factor by the weight of the classes and then adding up the six factor scores. The highest possible score is 100.

Table 3-3 Weight of variables associated with moraine-dammed lake failures

		Variable weight									
Dam outlet slope		Glacier-lake contact		Glacier steepness above lake		Lake area		Slope steepness above the lake[a]		Slope of glacier terminus	
30		25		18		12		9		6	
		Classes weight									
≥15°	1	Yes	1	Yes	1	>0.5 km²	1	Yes	1	Yes	1
≥8°and <15°	0.75	No	0	No	0	>0.1 to 0.5 km²	0.75	No	0	No	0
<8°	0					0.01 to 0.1 km²	0.5				

[a] Mass movements are a common cause of outburst floods. However, we assigned to this variable a low weight because the slope steepness and vegetation cover only provides a rough idea of potential detachment zones.

To define the outbursts susceptibility classes we applied the outburst classification scheme to the failed lakes in Patagonia. Five categories that represent five relative scales of outburst susceptibility were defined (Figure 3.6). Twelve (75%) of the 16 recorded failed lakes in Patagonia had scores ≥65. Thus, a score of 65 was used as threshold to classify lakes with high outburst susceptibility.

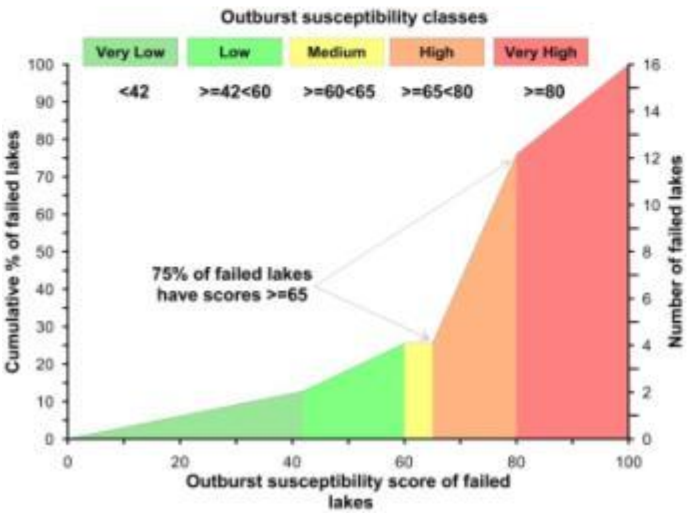

Figure 3.6. Outburst susceptibility score of the 16 moraine-dammed lakes failed in Patagonia. These data were used to define 5 outburst susceptibility classes.

3.5 Results

This section summarizes characteristics of moraine-dammed lakes failed in Patagonia. The data provide insights to identify moraine-dammed lakes with high outburst susceptibility in the region.

3.5.1 Characteristics of GLOFs, failed lakes and their surroundings

3.5.1.1 GLOFs characteristics

Moraine-dammed lakes that failed in historic time in Patagonia had areas ranging from 0.01 to 1.82 km^2 (Table 3-1). Fourteen lakes experienced just a partial emptying; including the largest lake (Laguna del Cerro Largo) which released an estimated water volume of ~229 x 10^6 m^3 (Hauser, 2000). The outburst paths (patches of stripped vegetation and/or debris deposition visible in Landsat images) range from few kilometres up to ~27 kilometres in length and commonly are less than 100 metres wide. However, GLOFs probably reached farther areas since vegetation recovery might conceal evidence of flow after just a few years. This has been corroborated by eyewitness's accounts (interviews held by the authors with inhabitants of Los Leones valley and Bahía Murta Village) which indicate that floating debris (large trees) were transported during GLOFs to the river outlets, kilometres from the preserved geomorphic evidence, clearly posing a risk for inhabited areas. GLOF paths are dominated by steep slopes up to five kilometres from the lakes (Figure 3.7). These sections of the GLOF paths favour the development of debris flows and the transport of coarse material from failed dams. In the lowest areas, patches of stripped vegetation and bank erosion are common, although the flows attenuate due to wider valleys and lower slopes.

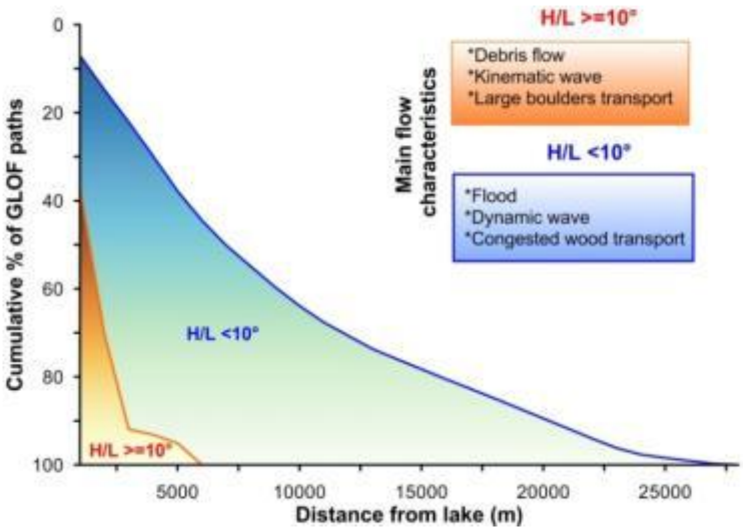

Figure 3.7 Accumulated percentage of GLOF paths within different angles of reach (H/L). Most path sections with H/L ≥10° (were debris flows often occur) are located at distances ≤3000m from failed lakes. Sections with H/L ≤10° (89% of the total path lengths) often have diffusive and rapidly attenuating flows. H/L was measured every 10 m from 15 failed moraine-dammed lakes in Patagonia.

3.5.1.2 Dam characteristics

Outbursts have affected moraine dams with different geometries. Drained lakes were dammed by both, steep moraine arcs and relatively flat ground moraines. No relationship between moraine heights and failure was evident, although higher dams (associated with larger lakes) resulted in GLOFs with higher peaks discharges. The heights of the failed dams vary from a few metres to up to 160 metres. In 8 cases the dams were small making it difficult to accurately estimate their dimensions. However, they were probably ≤ 10 metres high. Nine dams were vegetated at the time of failure and one of them (Piedras Blancas) was covered by mature forest dating from the early 1600s (Masiokas et al., 2009b). Most of the failed lakes had moderate to steep outlet slopes. The outlet slope of 14 lakes was ≥8° and 8 lakes had outlet slopes ≥15°. The dam's internal composition is known in just one case. The Ventisquero Negro dam was composed by non-cohesive coarse material (boulders and blocks) in a matrix of sand and gravel. This dam was vegetated and also presented an ice-core at the time of failure (Worni et al., 2012). Estero el Pedregoso Lake was dammed by (or was embedded in) glaciofluvial deposits and was partially dammed by bedrock (Figure 3.8).

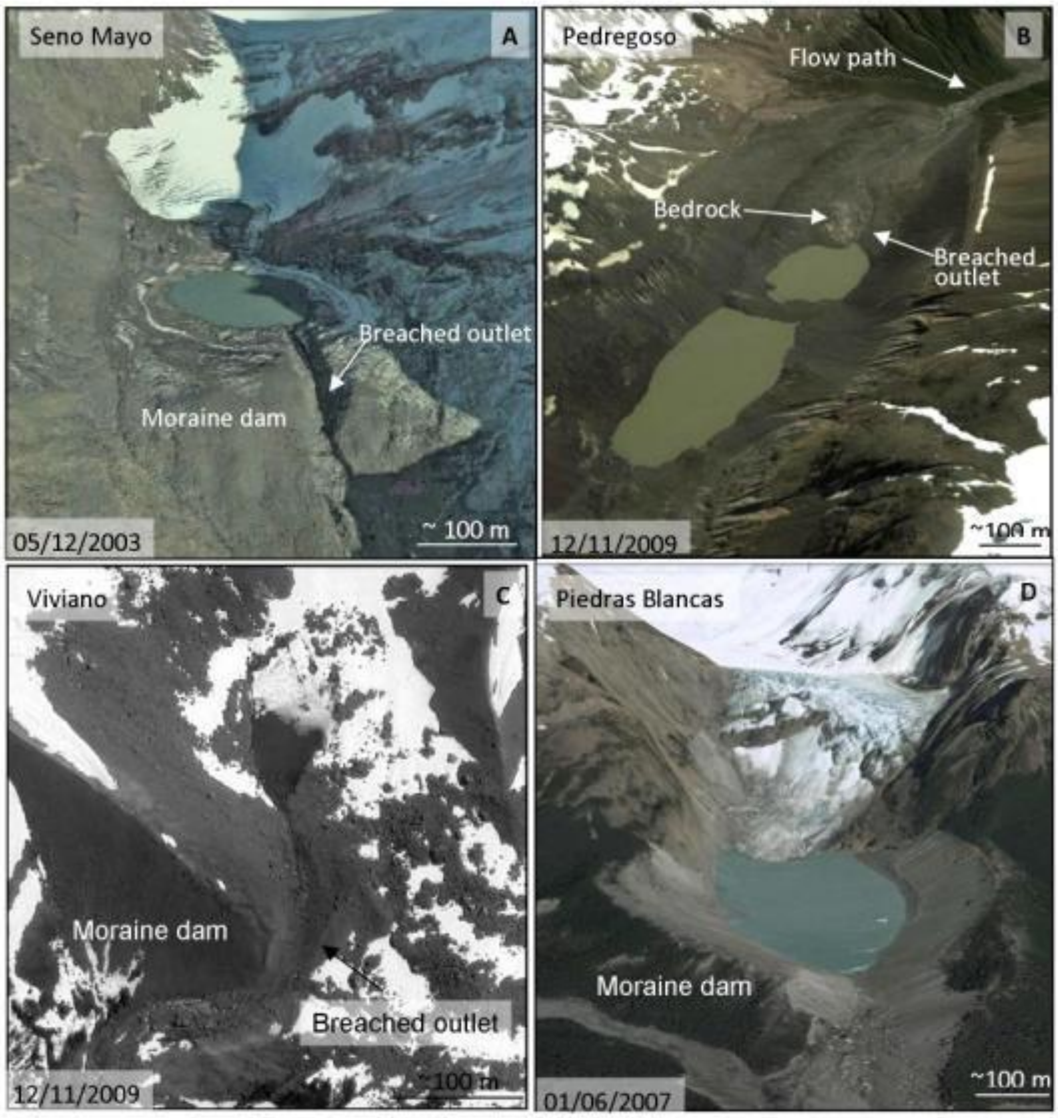

Figure 3.8 Type of moraine dams failed in Patagonia; (a) lake perched over moraine deposits (b) lake dammed by ground moraines and partially by bedrock (c) lake dammed by a small crest-shaped dam and (d) lake behind large and steep vegetated dam. Images sourced from Google Earth.

3.5.1.3 Characteristics of upstream catchments

Moraine-dammed lakes that produced outburst floods in Patagonia were located in different settings. Thirteen lakes were in contact with a glacier at the time of failure and in at least 3 cases (Ventisquero Negro, Olvidado and Península de las Montañas) glaciers exhibited rapid retreat before the outburst floods (Figure 3.9). For example, between 2000 and 2003 the Olvidado Glacier retreated 271 metres per year (Rivera and Casassa., 2004) significantly increasing the lake surface before the failure. Half of the lakes were located in areas prone to ice-avalanches. In fact, the upper-edge of Lacaya and Las Lenguas lakes were at the toe of reconstituted glaciers, clear indicators of high snow and ice-avalanche activity (Figure 3.9). All of the lakes were surrounded by steep (≥25°) valley walls or moraines. Rock-falls, snow-avalanches and debris flows are common in this setting. However, a mass movement was definitely identified as the cause of the dam failure in just one case (see Harrison et al., 2006). In the other cases (excluding Piedras Blancas and Frías outbursts) no evidence of large mass movements (i.e. fresh landslide scars or deposits) in the lake´s surroundings were identified when comparing images before and after the outburst floods.

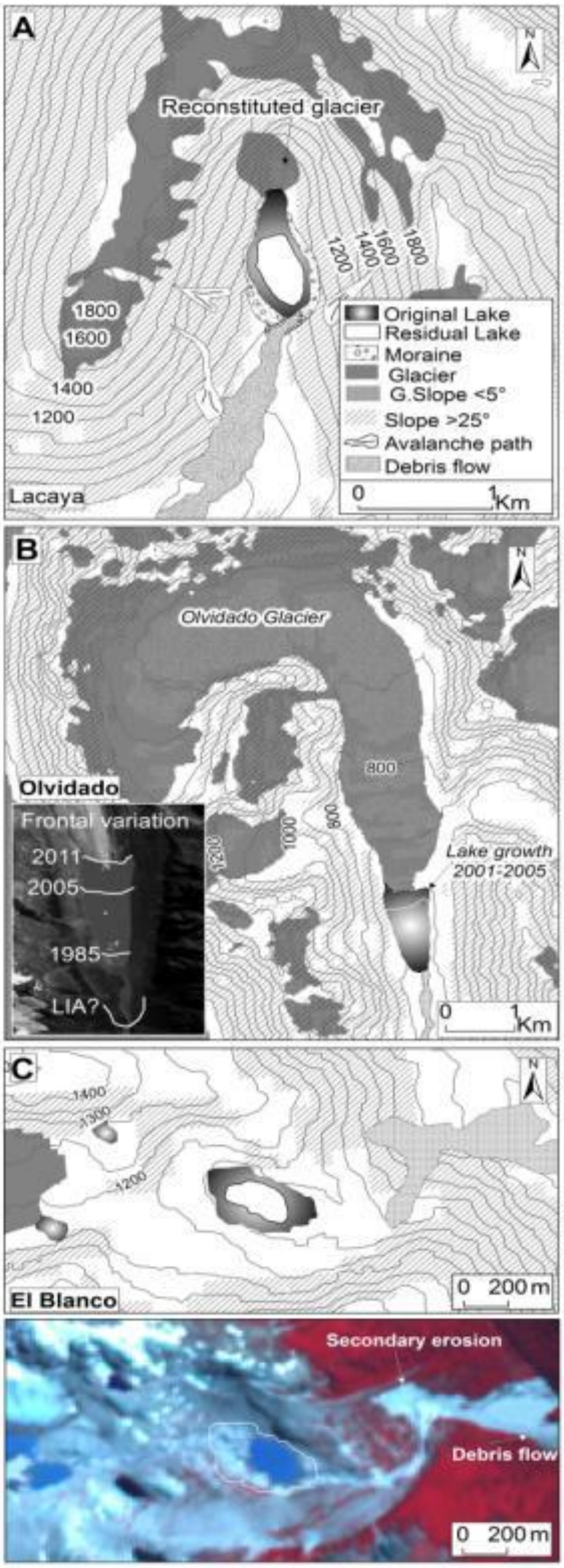

Figure 3.9 Settings of moraine-dams failed in Patagonia; (a) lake in the head of a catchment at the toe of a reconstituted glacier (b) growing lake in contact with a retreating glacier and (c) lake distant from the glacier tongue. Note the steep slopes and glaciers surrounding the lakes.

3.5.1.4 Triggering factors

The triggering of only three of the sixteen GLOFs is known. However, these events exemplify the variety of factors that can cause outburst floods. These factors include gravitational processes and meteorological events. The outburst of the Calafate Lake in the Río Los Leones Valley was caused by the impact of a rock-fall into the lake. The rock-fall detached from a recently deglaciated slope and completely covered the lake´s area (Harrison et al. 2006) generating impact waves that probably caused an almost instantaneous lake emptying. The Río Engaño outburst was caused by a different gravitational process. Reconnaissance flights carried out few days after the Río Engaño outburst indicate that the lake was impacted by glacier ice (this might correspond to an ice avalanche or calving) that probably caused waves which overtopped the dam and started the lake drainage (El Diario de Aysén, 1977c). The Ventisquero Negro outburst occurred after prolonged (180 mm of rain in six days) and intense (50 mm of rain in the 48 hours prior the outburst) rainfall that possibly caused an overflow and subsequent dam breach and failure (Worni et al., 2012).

3.5.2 Glacial lakes in the Baker Basin

Overall, 480 glacial lakes with surfaces ≥ 0.01 km^2 were identified in the Baker Basin. Distinguishing between bedrock and moraine-dammed lakes proved to be difficult. All uncertain cases (<10%) were classified as moraine dammed lakes in order to evaluate their outburst susceptibility. A preliminary classification indicated that eighty five lakes are dammed by bedrock and 386 (80%) lakes are dammed by moraines. Only three lakes are dammed by glaciers. Two of them are dammed by the Colonia Glacier, the Lake Cachet 2 (drained 10 times between 2008 and 2012) and a smaller (0.35 km^2) unnamed lake located 10 km to the north. A fourth ice-dammed lake (Laguna Bonita) emptied at least two times between 2002 and 2008. However, glacier retreat since the last outburst now impedes the lake refilling (Iribarren Anacona et al., 2014). Of the 386 moraine-dammed lakes at least 7 have produced outburst floods.

3.5.2.1 Lake outburst susceptibility in the Baker Basin

According to our classification scheme, the majority of the moraine-dammed lakes in the Baker Basin have low outburst susceptibility. The lakes have low-gradient outlets, are disconnected from glaciers or are small (<0.1 km^2) (Fig.3.10). However, such lakes may still produce outburst floods as they are subject to ice avalanches or mass movement impacts. Seven moraine-dammed lakes are in the range of very high outburst susceptibility and 21 lakes are in the range of high outburst susceptibility (Figure 3.6). A closer look of these lakes, however, shows that the largest lakes are located in flat valleys and have superficial drainage through large (several metres) low-gradient outlets making a catastrophic lake drainage unlikely. This is the case for example of the Fiero, Laguna Soler and Cachet 1 lakes. While these lakes are exposed to ice avalanches or mass movements, impact waves may be attenuated after travelling long distances (Slingerland and Voight, 1979), reducing the outburst susceptibility. Low gradient outlets also limit the transformation of eventual outburst floods into debris flows since this phenomenon generally starts in slopes ≥10° (Hungr et al., 1984). Smaller lakes with high or very high outburst susceptibility which are in the surface range (≤1.82 km^2) of failed lakes in Patagonia more closely resemble their characteristics (i.e. lakes with steep outlet slopes in contact with glaciers and exposed to ice avalanches and mass movements) (Figure 3.11). The computed (hypothetical) peak discharge of GLOFs from the 28 lakes most susceptible to failure range from 70 to more than 10000 m^3/s in the worst scenario (100% of the lake volume drained) (Figure 3.12). However, the complete drainage of moraine-dammed lakes is uncommon.

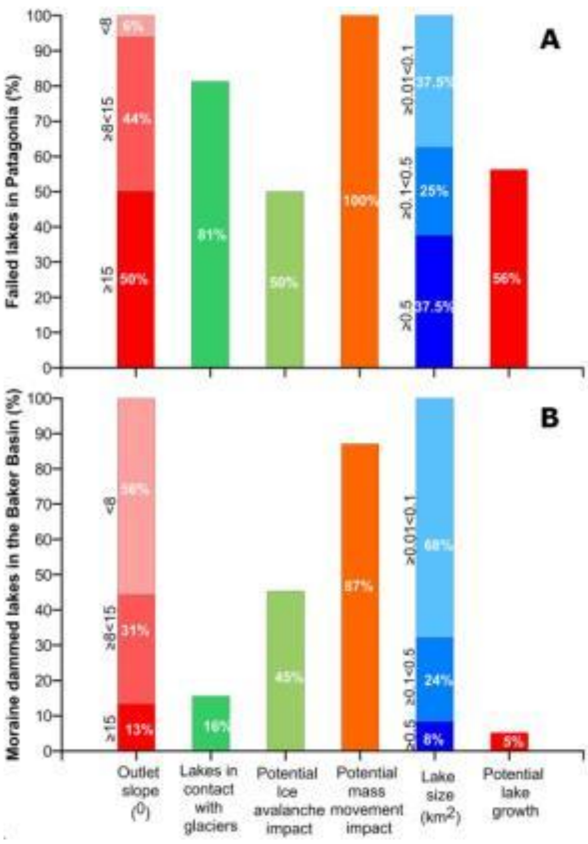

Figure 3.10. A) Characteristics of 16 failed moraine-dammed lakes in Patagonia and B) characteristics of 386 moraine dammed lakes in the Baker Basin.

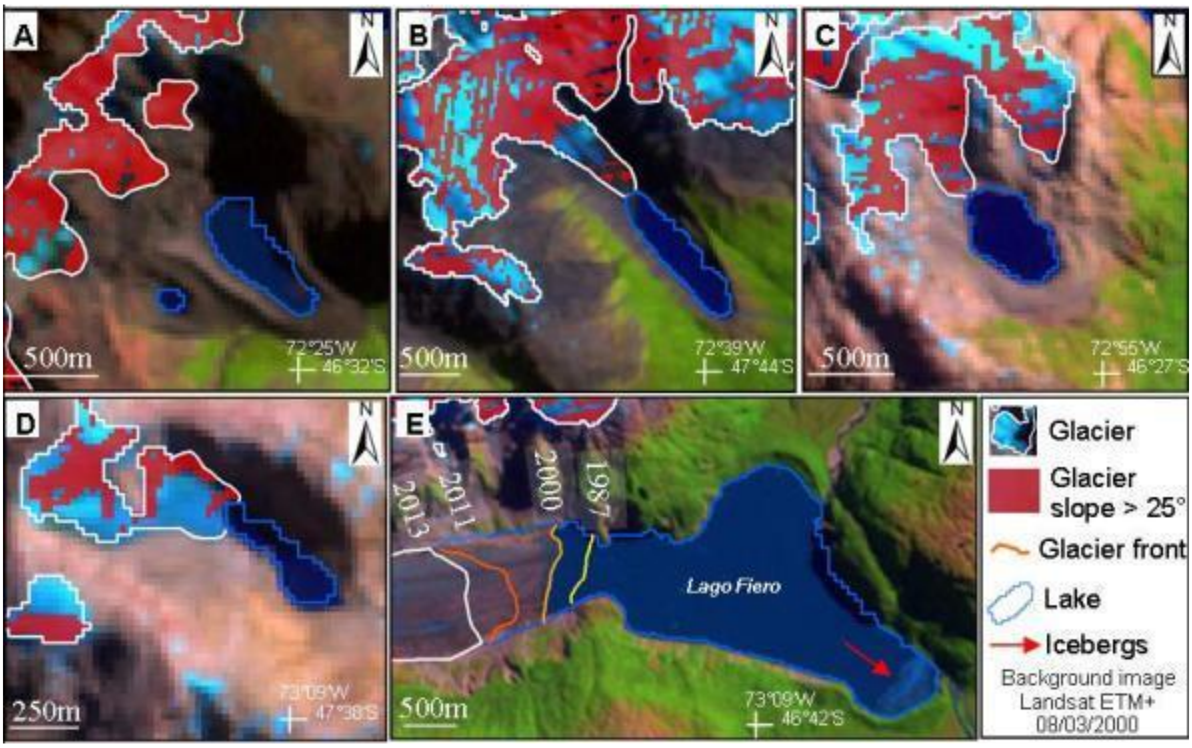

Figure 3.11. Examples of lakes classified with high or very high outburst susceptibility. Steep glaciers, moraines and rock-slopes surround small and medium-sized lakes. Large growing lakes are in contact with retreating glaciers and have vegetated dams (Figure E). Icebergs are common in proglacial lakes in contact with grounded glaciers.

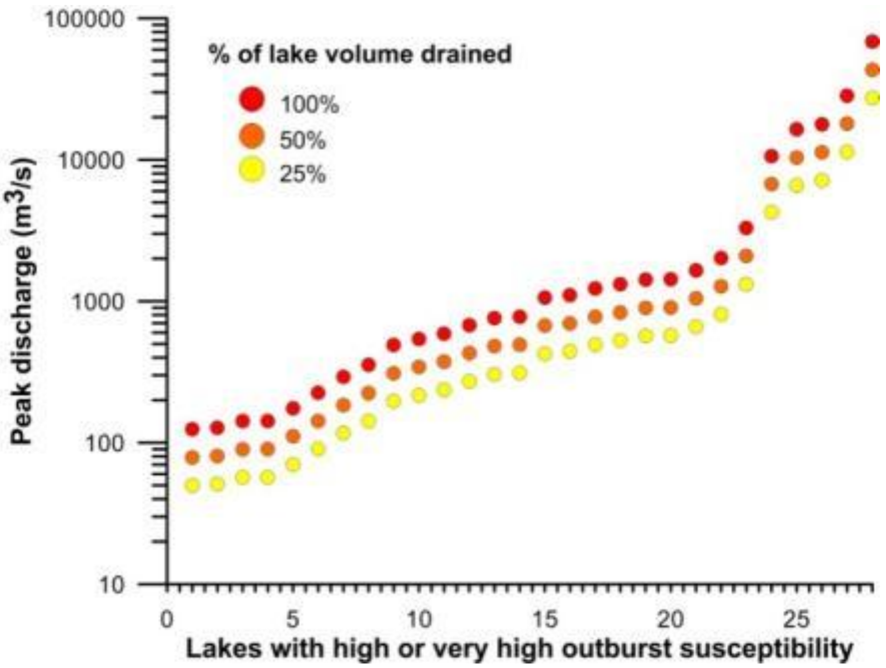

Figure 3.12. Potential peak discharge of GLOFs from lakes with high or very outburst susceptibility in the Baker Basin.

The risk from GLOFs remains low in spite of the large number of glacial lakes existing in the Baker Basin, with 28 lakes having high or very high outburst susceptibility. This is because the population and infrastructure threatened by outburst floods is scarce, since the region is mostly uninhabited (Figure 3.13). Debris flows are the most damaging process triggered by the sudden drainage of glacial lakes since they can develop high-impact pressures, can obstruct rivers causing back water flooding or floods from the sudden drainage of these ephemeral lakes. However, not all outburst floods can develop into debris flows, as they depend on sediment availability, channel morphology and slope gradient.

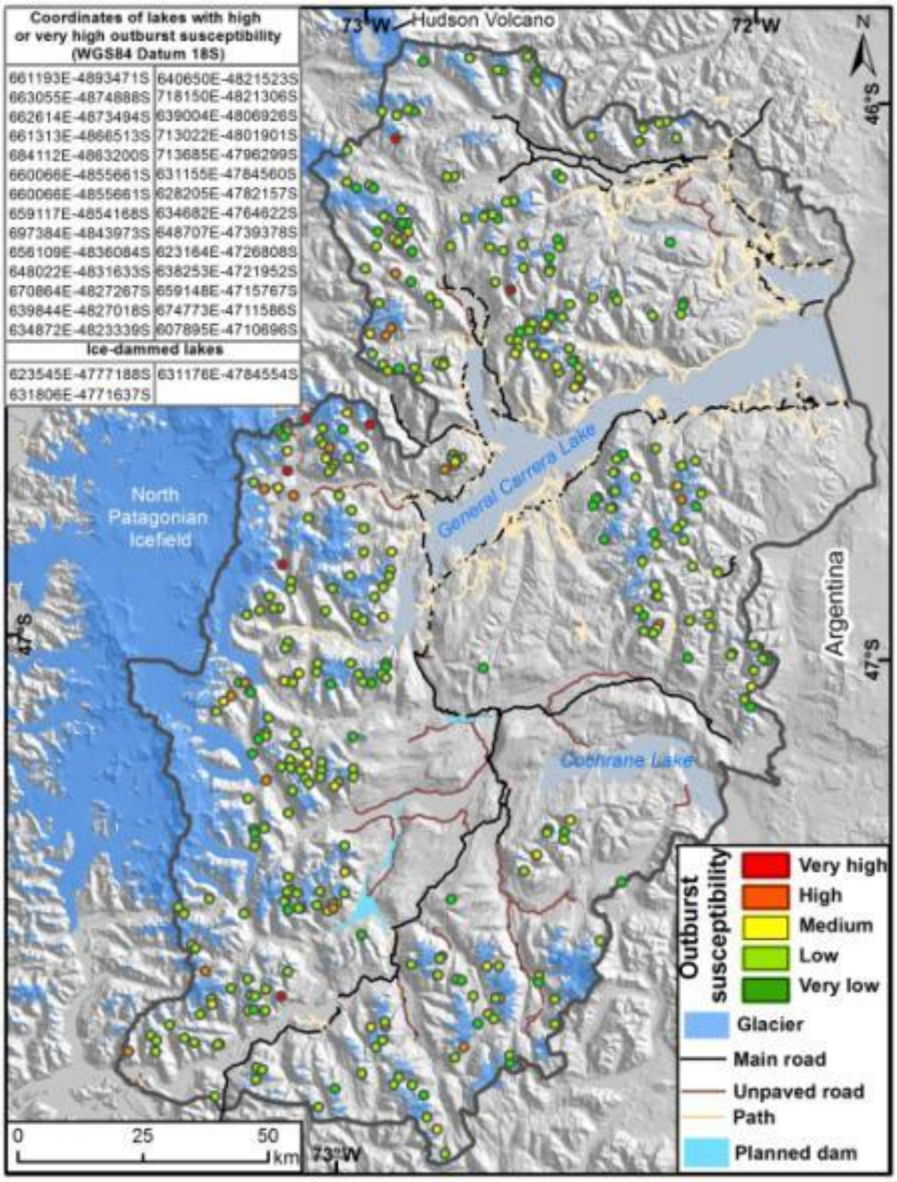

Figure 3.13. Classification of lake´s outburst susceptibility in the Baker Basin. Note that most of the lakes with high or very high outburst susceptibility are located on the west side of the basin.

We modelled debris flow paths from the 28 moraine-dammed lakes with higher outburst susceptibility in the Baker Basin (using the MSF model described in section 3.4.2, and setting as a source zone the lake area and as stopping condition an angle of reach of 10°) and none of them reached currently inhabited zones (Figure 3.14). However, flood waves travel larger distances and could potentially flood forest and agricultural lands, damaging local inhabitants' livelihoods (Table 3-5). Floods can also affect transport routes isolating populated areas, as has been demonstrated by historical events (Hauser, 2000; Worni et al., 2012).

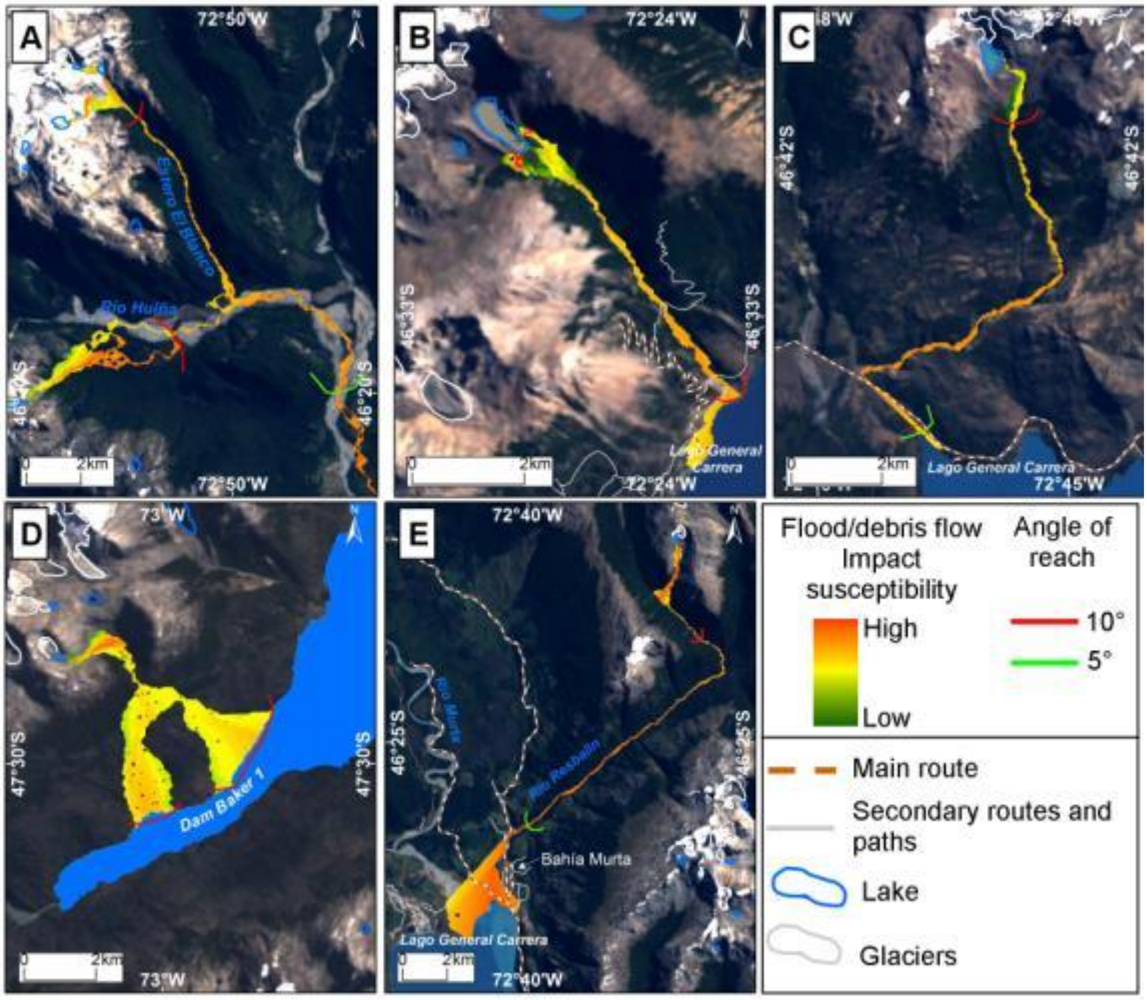

Figure 3.14. GLOF modelling from lakes with high or very outburst susceptibility closest to inhabited zones. Forestry land, routes and a planned dam are in the path of potential debris flows (angle of reach ≥10°) and floods. The flow width in D is probably exaggerated in its unchannelized path

Table 3-5 Potential damages caused by debris flows and floods originated from moraine-dammed lakes with high or very high outburst susceptibility in the Baker Basin.

	Routes (m)	**Others**	**Forest and bush (km^2)**
Debris flow (angle of reach 10°)	-Vehicle track = 300 Foot paths = 1600	-Mining camp (disused) -1 Bridge -1 planned dam	16
Flood (angle of reach 5°)	-Route 7 = 1000 -Vehicle track = 300	-1 Bridge in secondary route -1 Bridge in Route 7	1.3

3.6 Discussion

3.6.1 Documented outburst floods from moraine-dammed lakes in Patagonia

The sixteen documented lakes that produced outburst floods in Patagonia are located in areas which became ice free as a consequence of 20th and early 21st century ice retreat, and most of the lakes (13 = 81%) were in contact with glaciers at the time of failure. Calving induced-waves, the obstruction of the lakes outlets by icebergs, and the increase in the hydrostatic pressure over the dams as a result of lake growth/deepening may explain some of these outburst floods. The melting of ice-cored moraines also may be related to dam failures (through dam subsidence or the erosion of otherwise ice-cemented debris (Richardson and Reynolds, 2000; MacKillop and Clague, 2007) since at least one of the failed moraine-dammed lakes in Patagonia had an ice-core (Worni et al., 2012). Other recently formed dams, close to glacier fronts, may also contain buried ice. Thus, most of the outburst floods may be an expression of the adjustment of the landscape to new and evolving glacial conditions after LIA (Clague and Evans, 2000).

Most of the failed lakes had steep (≥ 15°) dam outlet slopes. The higher shear stress in these steep slopes probably favoured the dam's erosion when overflows or an increase in the lake discharge occurred. The four largest dams (≥ 50 m in height) were covered by mature forest at the time of failure. However, the vegetation could not stop the progressive erosion of these steep dams and subsequent catastrophic lake drainages. In fact, trees were incorporated in the flow increasing its damaging capacity. The largest dams had narrow fronts, closely resembling classic examples of failed moraine-dammed lakes worldwide (e.g. Lliboutry et al., 1977). These lakes could be identified as potentially hazardous through a quick examination of aerial photographs or satellite images. However, two small failed lakes had low dams with flat and broad surfaces and superficially appeared stable. A possible factor contributing to their failure is that lower dams can be easily overtopped by waves or a rise in lake level since they have less potential freeboard (i.e. there is less height difference between the lake surface and the lowest point of the dam).

All the failed lakes were located in areas prone to mass movements but only one outburst flood was certainly caused by this phenomenon (Harrison et al., 2006). The dimensions of impact waves, and hence the likelihood of a dam overtopping, are directly related to the volume and velocity of the mass movements and the lake bathymetry (Walder et al., 2003). Large and high velocity mass movements are more likely to trigger outburst floods (Walder et al., 2003). Mass movement modelling shows that lakes in Patagonia are exposed to this phenomenon. However, frequent low-magnitude rock-falls, debris flows or snow-avalanches are probably not capable of generating large impact waves, dam overtopping, and catastrophic lake drainage.

There is evidence of just one outburst flood that might have been triggered by an ice avalanche. However, ice-avalanche modelling shows that several failed lakes were located in areas prone to ice avalanching. The deposits of ice avalanches can be rapidly obliterated hampering their identification after few months or years (Kellerer-Pirklbauer et al., 2012). Thus, this process cannot be discarded as one of the triggers of other outburst floods. The failure of lakes as a consequence of an upstream outburst is another potential cause of large floods (Xin et al., 2008). However, none of the failed lakes in Patagonia is known to have occurred by this mechanism. Large lakes (>0.5 km^2) in areas of low relief are common in Patagonia and may delay or attenuate outburst floods as has been demonstrated in the Cachet

2 events (Dussaillant et al., 2009). Therefore, chain lake ruptures may be restricted to smaller lakes in high-relief catchment heads which show quick responses to large and rapid water influxes.

Only 2 lakes were completely emptied by outburst floods. This is because moraine dams generally impound only part of the lake´s water volume (the rest of the water occurs below the moraine base in over deepened valleys). Hence, in spite of the existence of lakes of hundreds of metres in depth in Patagonia (see e.g. Warren et al., 2001), complete lake drainage is unlikely.

Failed moraine-dammed lakes in Patagonia ranged in area from 0.01 to 1.82 km². Although larger lakes exist, they have not failed in historic time. A probable explanation for the failure of these, comparatively, smaller lakes is that the area and volume of small lakes can grow quickly after small glacier changes, dramatically altering the catchment hydrology. Furthermore, large lake systems have had longer periods of adjustment (e.g. development of large low gradient outlets) to new climatic, glacial and hydrologic conditions since most of the large lakes were formed during or before the LIA. This adjustment may have included prehistoric outburst floods that helped to shape lower and wider outlets.

3.6.2 Outburst susceptibility classification

Here we have carried out the first systematic analysis of the conditioning and triggering factors of outburst floods from moraine-dammed lakes in Patagonia. We weighted these factors (using the AHP method) to define outburst susceptibility classes. In conjunction, these data were used to develop a methodological scheme to assess the outburst susceptibility of glacier lakes in Patagonia. The approach builds on similar analyses (e.g. Bolch et al., 2009), however, the weighting of the outburst factors was based on empirical data from past outburst floods in Patagonia and thus is representative of the Patagonian geographical context. Thus, it can be used as a first order approach to identify hazardous lakes in this region.

Twelve (75%) of the sixteen failed lakes in Patagonia had scores ≥ 65 (other failed lakes had scores ranging from 30 to 49) and thus we selected this score to identify lakes with high outburst susceptibility. This score does not comprise all the failed lakes in Patagonia but includes lakes with at least three characteristics that make them susceptible to failure. The suggested approach, however, has drawbacks, for example, the omission of dam characteristics in the analysis and the subjectivity of the weighting scheme. Furthermore, the rapid nature of glacier changes in Patagonia (see Davies and Glasser, 2012) means that this analysis needs to be updated regularly.

The use of medium resolution (15-30 m) satellite images and DEMs limit the inclusion of dam characteristics that can be critical to explain outburst floods, such as dam freeboard and resistance to erosion. However, these resources allow a rapid extraction of data from hundreds of lakes in a short time. The relatively coarse spatial resolution of the imagery means that distinguishing between lakes dammed by moraines and bedrock was not straightforward in all cases. In some examples, categorical identification of features is not even possible using finer resolution satellite images and aerial photographs. Thus, detailed local-scale analyses of the lakes classified with high or very high outburst susceptibility needs to be carried out to judge if outburst preventive or mitigation measures are required. The identification of potential source of mass movements (slope steepness and vegetation coverage) can be refined using empirical data from landslide inventories in glacial and periglacial belts in Patagonia, or geomorphic features such as fresh scars and landslide deposits.

Although the weighting scheme used in the Baker Basin is subjective, it has the advantage of being based on GLOFs conditioning and triggering factors in Patagonia. It is thus better suited to the identification of potentially hazardous lakes in this region than approaches developed for other geographical contexts. Furthermore, the evaluation of the consistency of the judgments in the weighting scheme (Table 3-3) is an advantage of the AHP method in relation to other qualitative or semi-quantitative approaches used in GLOF hazard assessments (see Emmer and Vilímek, 2013 for a review).

Glacier fluctuations can shift the source area of ice avalanches and expand or generate new glacial lakes, resulting in a change in outburst susceptibility and hazard over time (Huggel et al., 2001; Huggel et al., 2004). This makes periodic monitoring of glaciers, lakes and their surroundings necessary in Patagonia, particularly near inhabited areas or critical infrastructure. The rapid growth of the

Olvidado Lake three years before the outburst in 2003 is an example of the speed at which glacier and lake changes can occur in this region (Rivera and Casassa, 2004).

In the Baker Basin 28 lakes were classified with high or very high outburst susceptibility. Most of the lakes are located in uninhabited valleys or dozens of kilometres from settlements or infrastructure. However, modelled debris flows and floods from hazardous lakes reached forestry land, a planned dam, and transportation routes. Damage to access routes by GLOFs can increase accessibility problems faced by Patagonian settlements (Muñoz et al., 2006). These 28 lakes, based on the results of this study, are more susceptible to failure than other lakes. However, this does not imply that other lakes cannot also fail. For example, large, albeit, infrequent landslides or ice avalanches can cause the sudden drainage of otherwise stable lakes (Figure 3.15).

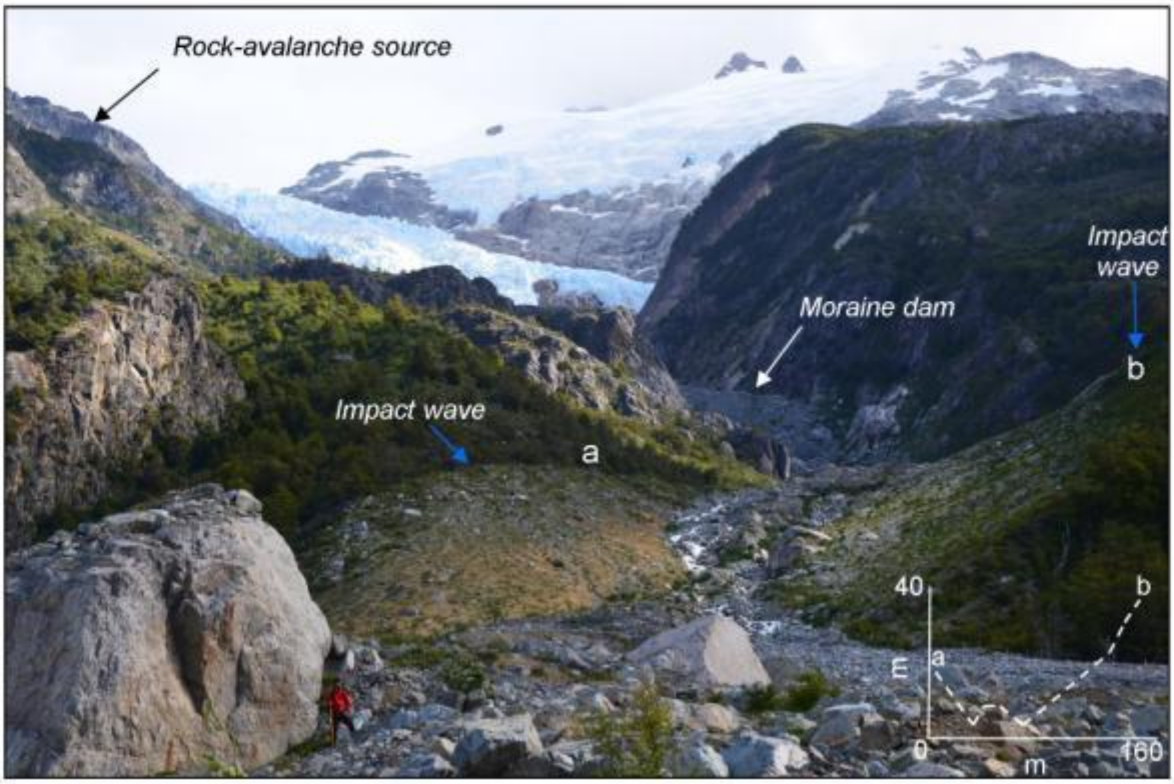

Figure 3.15. Geomorphic effects of an outburst flood (Los Leones Valley) produced by the impact of a rock avalanche. The small lake, detached from the glacier tongue at the time of failure, was classified with low outburst susceptibility in spite of the steep outlet slope. Note the elevated traces (~40 m) of the impact wave and the large boulders (> 6 m in diameter) transported by the flow.

The approach used in this study has the advantage that can be applied at regional-scale using publically available satellite images and DEMs allowing the analysis of hundreds of lakes in an inexpensive way. Also, it is based on simple and robust image classification and flow modelling techniques proven in different geographical settings (Paul et al., 2002; Huggel et al., 2003; Frey et al., 2010b; Bolch et al., 2011). Thus, it is suitable for identifying the lakes most susceptible to fail in Patagonia as a first approach to GLOF hazard assessments.

3.7 Conclusions

We analysed 16 historic outburst floods from moraine dammed lakes in Patagonia and our analysis shows that lakes in contact with glaciers and having moderate (≥ 8°) to steep (≥ 15°) outlet slopes are more likely to fail. The influence of other factors, such as dam height and vegetation coverage, on the lake outburst susceptibility is less clear. The dam geometry and vegetation coverage, however, had a direct influence on the flow hydrology (e.g. peak discharge and debris transport) and hence the damage potential of flows. GLOF paths in Patagonia display a rapid decrease in damage potential downstream of the lakes. Most of the steep path slopes favouring debris flow occurrence and fast flows (the most damaging processes linked with GLOFs) were at distances ≤3000 m from failed dams. However, as has been demonstrated by historical events, attenuated flows might still endanger widespread areas in unconfined valleys. Furthermore, wood transport has been common during GLOFs and can affect distant zones.

The characteristics of failed lakes in Patagonia were used to develop an outburst susceptibility scheme (based in the AHP method and remote sensing and GIS techniques) which was applied in the Baker Basin, Chilean Patagonia. The scheme allowed categorising the outburst susceptibility of hundreds of lakes in a short time in a qualitative, yet reproducible way. The scheme integrated data from past GLOFs in Patagonia making it suitable for wider application in the region. The scheme might be used to complement GLOF hazard assessments in Patagonia which until now have relied mostly on statistical analysis of short term series of flood data. The identification of the lakes more susceptible to failure, and the empirical modelling of the floods, are first steps toward a full GLOF hazard assessment which should ultimately include data on potential flood intensity (e.g. flood volume, velocity and sediment entrainment/deposition) and GLOF probability in a determined time span.

3.8 References

Alean, J (1985) Ice avalanches: some empirical information about their formation and reach. *J Glaciol* 31:324-333.

Allen SK, Schneider D and Owens IF(2009) First approaches towards modelling glacial hazards in the Mount Cook region of New Zealand's Southern Alps. *Natural Hazards and Earth System Sciences* 9: 481-499.

Andreassen LM, Paul F, Kääb A and Hausberg JE (2008) Landsat-derived glacier inventory for Jotunheimen, Norway, and deduced glacier changes since the 1930s. *The Cryosphere* 2: 131-145.

Ayalew L, Yamagishi H, Marui H and Kanno T (2005) Landslides in Sado Island of Japan: Part II. GIS-based susceptibility mapping with comparisons of results from two methods and verifications, *Eng. Geol*., 81, 432-445.

Bajracharya B, Shrestha AB and Rajbhandari L (2007) Glacial lake outburst floods in the Sagarmatha region, *Mountain Res. Develop* 27:336-344.

Barrientos S (2007) Earthquakes in Chile, in: The Geology of Chile, edited by: Moreno, T. and Gibbons, W. Geological Society of London, 263-287.

Bolch T, Peters J, Yegorov A, Pradhan B, Buchroithner MF and Blagoveshchensky V (2011) Identification of potentially dangerous glacial lakes in the northern Tien Shan. *Natural Hazards* 59(3):1691-1714.

Buchroithner MF, Jentsch G and Waniverhaus B (1982) Monitoring of Recent Geological Events in the Khumbu Area (Himalaya, Nepal) by Digital Processing of Landsat MSS data. *Rock Mechanics* 15(4):181-197.

Breien H, De Blasio FV, Elverhøi A and Høeg K (2008) Erosion and morphology of a debris flow caused by a glacial lake outburst flood, Western Norway, *Landslides* 5:271-280.

Carey M (2005) Living and dying with glaciers: people's historical vulnerability to avalanches and outburst floods in Peru, *Global Planet.Change* 47:122-134.

Clague JJ and Evans SG (2000) A review of catastrophic drainage of moraine-dammed lakes in British Columbia. *Quat Sci Rev* 19:1763-1783.

Costa JE and Schuster RL (1988) The formation and failure of natural dams. *Geological Society of America Bulletin* 100:1054-1068.

Davies BJ and Glasser NF (2012) Accelerating recession in Patagonian glaciers from the "Little Ice Age" (c. AD 1870) to 2011. *Journal of Glaciology*, 58 (212): 1063-1084.

Diaz M, Pedrozo F*,* Reynolds CS and Temporettia P (2007) Chemical composition and the nitrogen-regulated trophic state of Patagonian lakes*. Limnologica* 37*:*17-27.

Dussaillant A, Benito G, Buytaert W, Carling P, Meier C and Espinoza F(2009) Repeated glacial-lake outburst floods in Patagonia: an increasing hazard? *Natural Hazards* 54: 469-481.

El Diario de Aysén (1977a) Perecen ahogados 4 pobladores en Caleta Tortel. January 12 1977.

El Diario de Aysén (1977b) Avalancha de agua provocó la tragedia. January 13 1977.

El Diario de Aysén (1977c) Auxilian a pobladores en Murta. March 14 1977.

Emmer A and Cochachin A (2013) The causes and mechanisms of moraine-dammed lake failures in the Cordillera Blanca, North American Cordillera, and Himalayas. *AUC Geographica,* 48(2):5-15.

Emmer A and Vilímek V (2013) Review article: Lake and breach hazard assessment from moraine-dammed lakes: an example from the Cordillera Blanca (Peru). Nat. Hazards Earth Syst. Sci. 13:1551-1565.

Fujita K, Sakai A, Takenaka S, Nuimura T, Surazakov AB ,Sawagaki T and Yamanokuchi T (2013) Potential flood volume of Himalayan glacial lakes. Nat. Hazards Earth Syst. Sci., 13, 1827-1839.

Frey H, Haeberl W, Linsbauer A, Huggel C and Paul F (2010a) A multi-level strategy for anticipating future glacier lake formation and associated hazard potentials. *Nat Hazard Earth Syst Sci* 10(2):339-352.

Frey H**,** Huggel C, Paul F and Haeberli W (2010b) Automated detection of glacier lakes based on remote sensing in view of assessing associated hazard potentials. In: Kaufmann, V. and Sulzer, W. (eds.): *Proceedings of the 10th Internatinal Symposium on High Mountain Remote Sensing Cartography*. Grazer Schriften der Geographie und Raumforschung, 45: 261-272.

Glasser NF, Harrison S, Jansson KN, Anderson K and Cowley A (2011) Global sea-level contribution from the Patagonian Icefields since the Little Ice Age maximum.*Nature Geoscience* 4:303-307.

Glasser NF and Jansson KN (2008) The glacial map of southern South America. *Journal of Maps*, v2008: 175-196.

Grove M (1987) Glacier fluctuations and hazards. *Geographical Journal* 153(3): 351-369.

Gruber S, Huggel C and Pike R (2008) Modelling mass movements and landslide susceptibility using geomorphometry. In: Hengl, T. and Reuter, H.I. (Eds), Geomorphometry: Geomorphometry: Concepts, Software, Applications.

Developments in Soil Science, vol. 33, Elsevier B.V. ISSN 0166-2481, doi: 10.1016/S0166-2481(08)00023-8.

Gruber S, Peckham S (2008) Land surface parameters and objects specfic to hydrology. In: Hengl, T. and Reuter, H.I. (Eds), *Geomorphometry: Geomorphometry: Concepts, Software, Applications*. Developments in Soil Science, vol. 33, Elsevier B.V. ISSN 0166-2481, doi: 10.1016/S0166-2481(08)00007-X.

Hauser A (2000) Remociones en masa en Chile. Second ed. Boletín No. 59. Servicio Nacional de Geología y Minería, Santiago.89 p.

Harrison S, Glasser N, Winchester V, Haresign E, Warren CR and Jansson K (2006) A glacial lake outburst flood associated with recent mountain glacier retreat, Patagonian Andes. *Holocene* 16: 611-620.

Hewitt K (1982) Natural dams and outburst floods in the Karakorum Himalaya. In hydrological Aspects of Alpine and High-mountain Areas, Glen JW (ed.). *International Association of Hydrological Sciences* (IAHS) 138. IAHS Press: Wallingford; 259-269.

Hijmans RJ, Cameron SE, Parra JL, Jones PG and Jarvis A (2005) Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology* 25(15): 1965-1978.

Hubbard B, Heald A, Reynolds JM, Quincey D, Richardson SD, Zapata ML, Santillan NP and Hambrey MJ (2005) Impact of a rock avalanche on a moraine-dammed proglacial lake: Laguna Safuna Alta, Cordillera Blanca, Peru, *Earth Surf. Proc. Landf* 30:1251-1264.

Huggel C, Kääb A, Haeberli W, Teysseire P and Paul F (2002) Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps. *Can Geotech J* 39:316-330.

Huggel C, Kääb A, Haeberli W and Krummenacher B (2003) Regional-scale GIS-models for assessment of hazards from glacier lake outbursts: evaluation and application in the Swiss Alps. *Nat Hazard Earth Syst Sci* 3:647-662.

Huggel C, Haeberli W, Kääb A, Bieri D and Richardson F (2004) An assessment procedure for glacial hazards in the Swiss Alps. Canadian Geotechnical Journal 41:1068-1083.

Hungr O, Morgan GC and Kellerhals P (1984) Quantitative analysis of debris hazards for design of remedial measures, *Can. Geotech.J*. 21:663-677.

Hsu KJ(1975) Catastrophic debris streams (Sulzstroms) generated by rockfalls. *Geol Soc Am Bull* 86:129-140.

HidroAysén (2008) Estudio de Impacto Ambiental Proyecto HidroAysén. Available at http://www.e-seia.cl.

Iribarren Anacona P, Mackintosh A and Norton KP (2014) Hazardous processes and events from glacier and permafrost areas: lessons from the Chilean and Argentinean Andes. *Earth Surface Processes and Landforms (State of Science Paper).40:2-21.*

Kellerer-Pirklbauer A, Slupetzky H and Avian M (2012) Ice-avalanche impact landforms: The event in 2003 at the glacier Nördliches Bockkarkees, Hohe Tauern Range, Austria. Geografiska Annaler. *Geografiska Annaler: Series A, Physical Geography* 94:97-115. doi:10.1111/j.1468-0459.2011.00446.x.

Lari S, Frattini P and Crosta G B (2009) Integration of natural and technological risks in Lombardy, Italy, *Nat. Hazards Earth Syst. Sci*., 9, 2085-2106, doi:10.5194/nhess-9-2085-2009.

Lliboutry L, Arnao BM, Pautre A and Schneider B (1977) Glaciological problems set by the control of dangerous lakes in Cordillera Blanca, Peru. I. Historical failures of morainic dams, their causes and prevention. *Journal of Glaciology* 18(79): 239-254.

Loriaux TH, Casassa G (2013) Evolution of glacial lakes from the Northern Patagonian Icefield and terrestrial water storage in a sea-level rise context, *Global Planet. Change* 102:33-40.

Masiokas MH, Rivera A, Espizúa LE, Villalba R, Delgado S, Aravena JC(2009) Glacier fluctuations in extratropical South America during the past 1000 years. *Palaeogeography, Palaeoclimatology, Palaeoecology* 281: 242-268.

Masiokas MH, Luckman BH, Villalba R, Delgado S, Skvarca P and Ripalta A (2009) Little Ice Age fluctuations of small glaciers in the Monte Fitz Roy and Lago del

Desierto areas, south Patagonian Andes, Argentina. *Palaeogeogr Palaeoclimatol Palaeoecol* 281:351-362.

McKillop RJ and Clague JJ (2007) Statistical, remote sensing-based approach for estimating the probability of catastrophic drainage from moraine-dammed lakes in southwestern British Columbia. Global and Planetary Change 56:153-171.

Mergili M and Schneider JF (2011) Regional-scale analysis of lake outburst hazards in the southwestern Pamir, Tajikistan, based on remote sensing and GIS, Nat. Hazards Earth Syst. Sci. 11:1447-1462, doi:10.5194/nhess-11-1447-2011.

METI/ERSDAC, NASA/LPDAAC, USGS/EROS (2009) ASTER Global DEM validation summary report.

Muñoz M, Pérez L, Sanhueza R, Urrutia R and Rovira A (2006) Los paisajes del agua en la cuenca del Río Baker: bases conceptuales para su valoración integral. *Revista de Geografía Norte Grande* 36:31-48.

USGS., NASA., and LANDSAT 7 SCIENCE TEAM (2003) Preliminary assessment of the value of Landsat 7 ETM+ data following Scan Line Corrector malfunction.2003.Available at http://landsathandbook.gsfc.nasa.gov/pdfs/SLC_off_Scientific_Usability.pdf.

Nicoletti PG and Sorriso-Valvo M (1991) Geomorphic controls of the shape and mobility of rock avalanches. Geological Society of America Bulletin 103:1365-1373.

O'Connor JE, Hardison JH and Costa JE (2001) Debris flows from failures of Neoglacial-age moraine dams in the Three Sisters and Mount Jefferson Wilderness areas, Oregon, US Geological Survey, Reston (Virginia), 93 pp.

Osti R and Egashira S (2009) Hydrodynamic characteristics of the Tam Pokhari Glacial Lake outburst flood in the Mt. Everest region, Nepal. Hydrol Process 23:2943-55.

Paul F, Kääb A, Maisch M, Kellenberger T and Haeberli W (2002) The new remote sensing derived Swiss glacier inventory: I. Methods. Ann Glaciol 34:355-361.

Peduzzi P (2010) Landslides and vegetation cover in the 2005 North Pakistan earthquake: a GIS and statistical quantitative approach. Nat Hazards Earth Syst Sci 10:623-640.

Quincey DJ, Richardson SD, Luckman A, Lucas RM., Reynolds, J.M., Hambrey, M.J., Glasser, N.F. Early recognition of glacial lake hazards in the Himalaya using remote sensing datasets. Glob Planet Change 56(1-2):137-152, 2007.

Reuter HI and Nelson A (2008) Geomorphometry in ESRI packages. Hengl T and Reuter HI. (Eds), Geomorphometry: *Geomorphometry: Concepts, Software, Applications. Developments in Soil Science* 269-291 Elsevier B.V. ISSN 0166-2481.

Reynolds JM, Dolecki A and Portocarrero C (1998) Construction of a drainage tunnel as part of glacial lake hazard mitigation at Hualcán, Cordillera Blanca, Peru. In Geohazards in EngineeringGeology,Maund JG, Eddleston M (eds). Geological Society Special Publication (London), No. 15. Geological Society of London: London; 41-48.

Richardson SD and Reynolds JM (2000a) An overview of glacial hazards in the Himalayas. Quat Int 65/66(1):31-47.

Richardson SD and Reynolds JM (2000b) Degradation of ice-cored moraine dams: implications for hazard development, in: Debris- Covered Glaciers (Proceedings of a workshop held at Seattle, Washington, USA, September 2000), The Netherlands 187-197.

Rivas D (2014) Term report: Glacial lake outburst flood (GLOF).Palcacocha Lake, Peru. Available at: www.ce.utexas.edu/prof/maidment/giswr2012/TermPaper/Rivas.pdf [accessed: 28/04/2014].

Rivera A and Casassa G (2004) Ice elevation, areal, and frontal changes of glaciers from National Park Torres del Paine, Southern Patagonia Icefiled. *Artic, Antarctic and Alpine Research* 36(4): 379-389.

Saaty TL (1980) The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation, ISBN 0-07-054371-2, McGraw-Hill.

Saaty TL and Vargas LG (2001) Models, Methods, Concepts and Applications of the Analytic Hierarchy Process. Kluwer,Dordrecht.

Slingerland, R.L., and Voight, B (1979) Occurrences, properties and predictive models of landslide-generated impulse waves. Rockslides and avalanches, Vol. 2, B. Voight, ed. Elsevier, Amsterdam, 317-397.

Svoboda F and Paul F (2009) A new glacier inventory on southern Baffin Island, Canada, from ASTER data: I. Applied methods, challenges and solutions.Annals of Glaciology 50(53):11-21.

Tachikawa T, Kaku M, Iwasaki A, Gesch D, Oimoen M, Zhang Z, Danielson J, Krieger T, Curtis B, Haase J, Abrams M, Crippen R and Carabajal C (2011) ASTER Global Digital Elevation Model Version 2-Summary of Validation Results, The NASA Land Processes Distributed Active Archive Center and the Joint Japan – US ASTER Science 5 Team, available at: https://lpdaacaster.cr.usgs.gov/GDEM/Summary_GDEM2_validation_report_final.pdf (last access: 12 February 2014).

Tweed FS and Russell AJ (1999) Controls on the formation and sudden drainage of glacier-impounded lakes: implications for jökulhlaup characteristics. *Progress in Physical Geography* 23: 79-110.

Villalba R, Leiva JC, Rubullis S, Suarez J and Lenzano L (1990) Climate, Tree-Ring, and Glacial Fluctuations in the Río Frías Valley, Rio Negro, Argentina, *Arctic and Alpine Research*. 22:215-232.

Vince G (2010) Dams for Patagonia. *Newsfocus*. *Science* 329:382-385.

Wahl T (2004) Uncertainty of Predictions of Embankment Dam Breach Parameters. *Journal of Hydraulic Engineering* 130(5):389-397.

Walder JS and O'Connor JE (1997) Methods for predicting peak discharge of floods caused by failure of natural and constructed earthen dams: *Water Resources Research*., v. 33, p. 2337-2348.

Walder JS Watts P, Sorensen OE and Janssen K (2003) Tsunamis generated by subaerial mass flows, *J. Geophys. Res*., 108, 2236-2255.

Wang W, Yao T, Gao Y, Yang X and Kattel DB (2011) A first- order method to identify potentially dangerous glacial lakes in a region of the southeastern Tibetan Plateau, *Mountain Res. Develop*. 31:122-130.

Wang X, Liu S, Guo W and Xu J (2008) Assessment and simulation of glacier lake outburst floods for Longbasaba and Pida lakes, China, *Mountain Res. Develop*. 28:310-317.

Warren C, Benn D, Winchester V, Harrison S (2001) Buoyancy driven lacustrine calving, Glaciar Nef, Chilean Patagonia. *Journal of Glaciology* 47 (156), 135-146, 2001.

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

Xin W, Shiyin L, Wanqin G and Junli X (2008) Assessment and simulation of glacier lake outburst floods for Longbasaba and Pida Lakes, China. *Mt. Res. Dev*. 28 (3/4):310-317.

4 Reconstruction of a Glacial Lake Outburst Flood in the Engaño Valley, Chilean Patagonia: Lessons for GLOF risk management.

4.1 Abstract

Floods from moraine-dammed lake failures can have long standing effects on riverine landscapes but also in mountain communities due to the high intensity (i.e. great depth and high velocities) and damaging capacity of Glacial Lake Outburst Floods (GLOFs). GLOFs may increase in frequency as glaciers retreat and new lakes develop and there is an urgent need to better understand GLOF dynamics and the measures required to reduce their negative outcomes. In Patagonia at least 16 moraine-dammed lakes have failed in historic time, however, data about GLOFs dynamics and impacts in this region are limited. We reconstruct a GLOF that affected a small village in Chilean Patagonia in March 1977, by semi structured interviews, interpretation of satellite images and 2D hydraulic modelling. This provides insight into the GLOF dynamics and the planning issues that led to socioeconomic consequences, which included village relocation. Modelling shows that the water released by the GLOF was in the order of 12-13 x $10^6 m^3$ and the flood lasted for about ten hours, reaching a maximum depth of ~1.5 m in Bahía Murta Viejo, ~26 km from the failed lake. The lake had characteristics in common with failed lakes worldwide (e.g. the lake was in contact with a retreating glacier and was dammed by a narrow-steep moraine). The absence of land-use planning and the unawareness of the GLOF hazard contributed to the village flooding. The Río Engaño GLOF illustrates how small-scale and short-distance migration is a reasonable coping strategy in response to a natural hazard that may increase in frequency as atmospheric temperature rises and glaciers retreat.

4.2 Introduction

Moraine-dammed lake failures have been documented in glaciated areas worldwide. GLOFs can release millions of cubic metres of water in short time (minutes to hours) generating deep, high-velocity flows with significant erosive and transport capacity (Costa and Schuster. 1988; Breien et al. 2008). Thus, GLOFs can pose a severe hazard to mountain communities. The damaging capacity of GLOFs was dramatically demonstrated in the Peruvian Andes in 1941, when the Palcacocha Lake failed flooding the city of Huaraz killing ~6000 inhabitants (Lliboutry et al. 1977). GLOFs can be triggered by the impact of mass movements (Harrison et al. 2006) or ice avalanches (Vuichard and Zimmerman. 1987) into the lakes, by waves generated by calving or the floating of dead ice (Richardson and Reynolds 2000), or by overtopping as a consequence of intense or prolonged precipitation or increased ice/snow melting (Korup and Tweed, 2007). Floods from upstream lake failures can also cause outburst floods (Lliboutry et al. 1977).

The number and size of moraine-dammed lakes has increased worldwide in the last 40 years as a consequence of glacier retreat. This tendency has been observed for example in the Himalayas (Gardelle et al. 2011), tropical Andes (Ames, 1998) and Patagonia (Loriaux and Casassa. 2012). In Patagonia, at least 16 moraine-dammed lakes have failed in historic time (Iribarren Anacona et al. 2015) and one of these events is one of the largest GLOFs, in terms of flood volume, reported worldwide (Hauser 2000; Clague and Evans. 2000). However, GLOFs in Patagonia have affected mostly uninhabited valleys and thus have been underreported. The study of past GLOFs can shed light on flow dynamics and aid anticipating future GLOF behaviour (e.g. through the evaluation of numerical models or the development of empirical relationships). Hence, knowledge about past floods has both scientific and societal value (Baker, 2002). The study of past GLOFs may also aid unravelling planning and political issues affecting GLOF risk management (Carey et al. 2012).

Several studies have reconstructed GLOFs using stratigraphic and geomorphic evidence, numerical models or gauging data (e.g. Kershaw et al. 2005; Schneider et al. 2014). However, few studies have included eye-witnesses accounts, and when included, people’s experiences are only recorded to provide data about flood timing, extension or damage. Memories of GLOF events can also shed light on the perception of GLOF risk that ultimately may affect the community response during GLOFs (Gyawali and Dixit 1997; Carey et al. 2012). They also can inform about territorial planning practices and issues. We reconstruct the GLOF that affected Bahia Murta Village in March 1977, to provide insights in the dynamics of a GLOF in Western Patagonia, a region where few data about past GLOFs exist. We also analyse the people’s response to the GLOF and planning problems that led to the village's flooding and ultimate relocation. This information is used to delineate a GLOF risk management strategy. We suggest that an outburst susceptibility assessment and territorial planning should have prevented the GLOF damages.

4.3 Geographical setting

Bahia Murta is located at the north shore of the General Carrera Lake in Chilean Patagonia (Figure 4.1). The flooded village (known as "Bahia Murta Viejo") is located on a delta formed between the Engaño and Murta river outlets, about 26 km from the failed moraine-dammed lake. The village was settled from the 1930's onwards, supported by Chilean colonisation laws. Public facilities (i.e. school and a chapel) were built in the 1950's, and by 1977 Bahia Murta Viejo had about 130 inhabitants (El Diario de Aysén 1977a).

The Engaño Valley is flanked by the Andean mountain range with higher peaks in the Engaño Basin reaching 1950 m.a.s.l. The highest areas are generally covered by glaciers which descend to a lowest altitude of 750 m.a.s.l in the Engaño Basin. Glaciers in Patagonia generally have steep mass-balance gradients, are fast flowing and have high ablation rates (López et al. 2010). Most of the glaciers in Patagonia are receding (Davies and Glasser. 2012) as a consequence of twentieth century warming (Rosenblüth 1995) as well as decreasing precipitation in the last few decades in North-Central Patagonia (Garreaud et al. 2013).

Annual precipitation in the Engaño Basin varies from ~1400 (at 200 m.a.s.l) to more than 2000 mm in the highest parts of the catchment. There are no gauging data of the Engaño River, however, the mean river discharge is probably less than 50 m^3/s, with peaks in December and January associated with increased snow and ice melting. The Engaño valley has a low gradient along most of its length, however, the valley narrows and steepens in two bedrock gorges. The floodplain, as well as the valley sides, are forested. However, since the 1950's, large patches of forest have been cleared for pasturing or wood extraction.

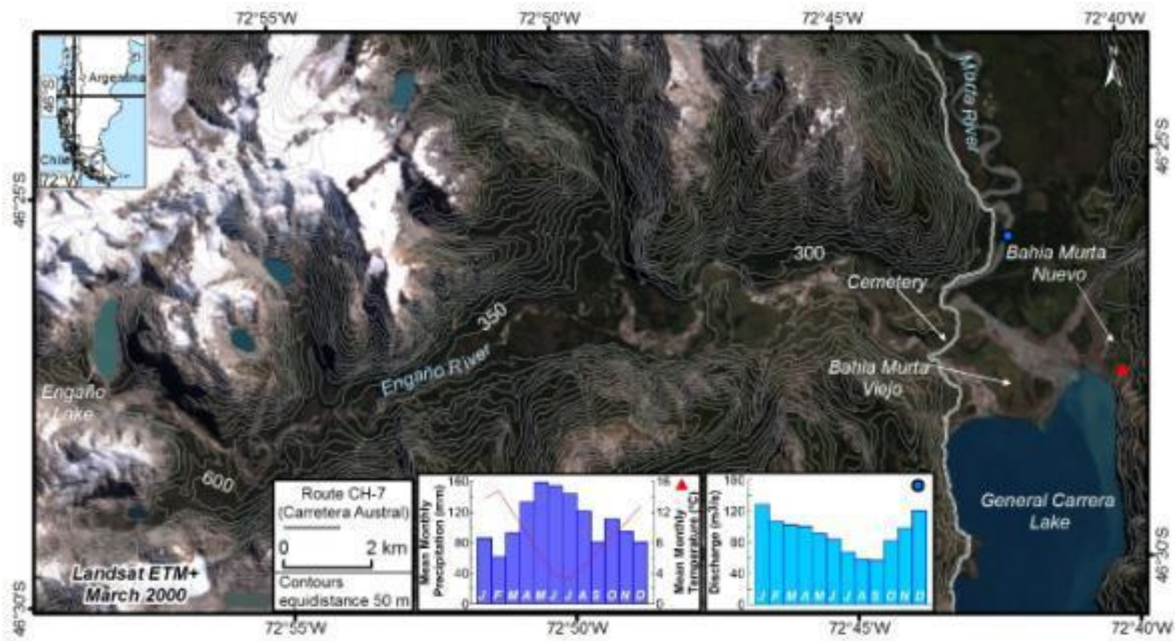

Figure 4.1. Geographical setting of the Engaño Lake and Bahía Murta Village. Discharge (1986-2013) at Murta River (a larger catchment adjacent to the Engaño) increases in the melting season. Precipitation (1993-2013) and temperature (1998-2013) data from the Bahía Murta meteorological station.

4.4 Methods and data

The Engaño GLOF was reconstructed by eye-witnesses accounts, newspaper reports, interpretation of aerial photographs and satellite images, and numerical modelling. The data and procedures followed to reconstruct the GLOF dynamics are described below.

4.4.1 Semi-structured interviews

In January 2014 we held semi-structured interviews with twelve Bahia Murta inhabitants who recalled their memories of the flood. Commonly, data about the time, duration and flood stage were given. In other cases, we asked the interviewees to recall these and other data including; planning actions, evacuation procedures and information about the village's history, including past floods and settlement. The interviews were conducted in the people's homes or in the street and were audio recorded. The first interviewees helped to locate eyewitnesses of the 1977 GLOF. Three interviewees were in Bahia Murta Viejo on the day of the flood, three were living in the Engaño Valley about 16 km from the lake, and two were in Bahia Murta Nuevo. The rest of the interviewees were Bahia Murta Viejo inhabitants whose houses or land were damaged by the flood, but were elsewhere when the GLOF occurred. Ten interviewees were adults and two were children in 1977.

4.4.2 Interpretation of aerial photographs and satellite images

The geomorphic and topographic setting of the Engaño Lake and its surroundings prior to the GLOF were analysed from aerial photographs of 1955 and a topographical map of 1975. The GLOF extension and its geomorphic effects were examined in a Landsat MSS image from February 1979 (60 m spatial resolution) and Google Earth Images. The analysis allowed identifying GLOF pre-conditioning and triggering factors (e.g. potential source of ice avalanches or mass movements) as well as describing the GLOF path (patches of stripped vegetation or sediment deposition).

4.4.3 GLOF modelling

The Río Engaño GLOF was reconstructed (flow extension, arrival time, depth and velocity) using the 2D capabilities of HEC-RAS 5.0 Beta which solves the Full 2D Saint Venant equations or the 2D Diffusion Wave equations using an implicit finite volume algorithm. A description of the model can be found in (HEC RAS 5 Beta Manual). The model set up included the definition of upstream and downstream boundary conditions, the creation of a grid with elevation data, the selection of Manning roughness values, and the definition of the model spatial domain.

The GLOF was modelled as an unsteady flow using simulated dam-breach hydrographs as an upstream boundary condition and the normal depth or energy slope (i.e. 0.001 m/m) as a downstream boundary condition. A base flow of 30 m^3/s was run for 72 hours to pre-wet the Engaño River channel until the water reached a steady state along the entire spatial domain. Manning coefficients for the channel (0.04 and 0.05) and floodplain (0.8 and 0.1) were derived from interpretation of satellite images and field photographs. These Manning values represent a realistic uncertainty range according to field observations. Only one Manning value was assigned to the floodplain and the channel in each simulation to simplify the model parameterisation.

Floods from failed dams commonly overtop river channels inundating floodplains and behaving as truly two-dimensional flows. Thus, 1D hydraulic models can be inappropriate for modelling such events (Hrodamka et al. 1985). 2D models are well suited for reconstructing the complex hydraulics of high-magnitude flows such as simultaneous channelised and sheet flows and divergent flow around obstructions (Carrivick 2006). Furthermore, 2D models usually have a better performance than 1D models in wide floodplains (Horritt and Bates, 2002) where detailed river cross sections are lacking. Thus a 2D model is warranted for simulating the Engaño Valley GLOF.

We used the 2D Diffusion Wave equations to simulate the Bahía Murta GLOF. HEC-RAS is more stable and requires less computational effort in solving the 2D Diffusion Wave than the Full 2D Saint Venant equations. Models that use the 2D Diffusion Wave equations may fail to reproduce local phenomena (e.g. run-up and bores) due to the omission of the inertial terms in the Saint Venant equations, however, they have previously proven adequate in simulating the overall dynamics of dam break floods over complex topography (Hrodamka et al. 1985; Prestininzi, 2008).

The SRTM v4 Digital Elevation Model (DEM) (3 arc seconds of spatial resolution equivalent to 80 metres in the study area; Rabus et al. 2003) and the ASTER GDEM2 (approximately 30 m of spatial resolution; Tachikawa et al. 2011) were used to model the flood. An inspection of the DEMs revealed that sinks exist within the Engaño River channel. These imperfections can modify water flow behaviour, reducing the accuracy of modelling results (Zhu et al. 2013). Thus, we applied the approach of Tarboton et al. (1991) to “hydrologically correct” the DEMs by filling the DEM sinks. This prevent, for example, the accumulation of water in spurious pixels which artificially delay the flood progression.

4.4.3.1 Outburst volume and dam breach hydrograph

As detailed topographic and geotechnical information is not available for the dam, and bathymetric data from Engaño Lake are lacking, we estimated the dam breach hydrograph and the failure time using empirical formulae. The outburst volume was previously estimated to be ~$7.3 \times 10^6 m^3$ using the same approach (Iribarren Anacona et al. 2014). Several simulations were run increasing and decreasing this reference value up to ~70%, which is the error margin of the empirical formula.

The breaching time was estimated with Froehlich's (1995) formula which is based on data from 63 dam breaches and has a smaller uncertainty range than other empirical approaches (Whal 2004)

$T = 0.00254 Vw^{0.53} hb^{-0.9}$

Where *T* correspond to the failure time in minutes, *Vw* is the volume of water above the breach invert and *hb* is the height of the breach. The height of the breach was measured using the ASTER GDEM2 data. We assumed a triangular shaped hydrograph lasting for the time calculated with the Froehlich (1995) formula. Resulting hydrographs have peak discharges surpassing 10.000 m^3/s (Figure 4.2). Although this value could be an overestimation, flow discharges tend to converge downstream, and the channel slope and flood volume dominate the flood behaviour (Ponce et al. 2003). Thus floods can still be simulated realistically in spite of the uncertainty of the peak discharge at the dam breach.

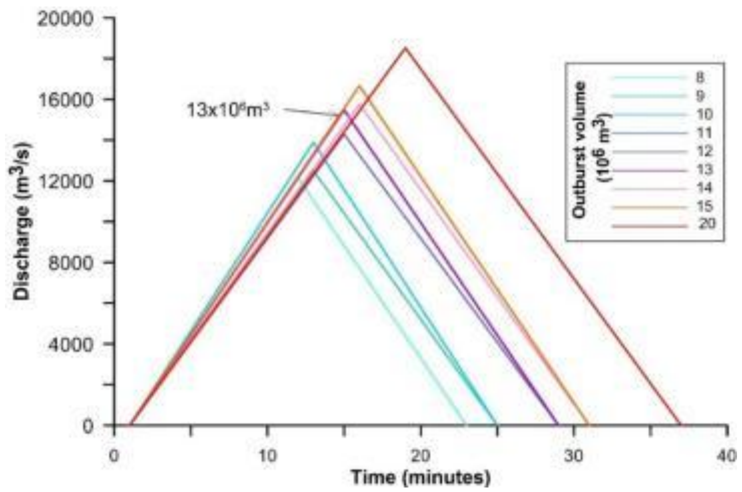

Figure 4.2. Breach hydrographs used as inputs to simulate the Engaño Lake 1977 outburst flood.

4.4.3.2 Sensitivity analysis

Several flood simulations were undertaken to obtain an optimal set of parameters to model the Engaño River GLOF. The simulation results were contrasted from eye-witness accounts and the interpretation of satellite images. Trials were performed using the SRTM and ASTER GDEM2 DEMs and different hydrograph volume and Manning values. Manning values ranging from 0.04 to 0.1 were tested since these values represent the range of roughness values of the Engaño channel and floodplain. A one second time step was used in each simulation.

4.5 Results

4.5.1 GLOF preconditioning and potential triggering factors

The characteristics of the Engaño Lake and its surrounding made it highly susceptible to outburst floods. The Engaño Lake had a surface area of 1.15 km^2 two years before the 1977 GLOF. However, the lake was considerably smaller in the 1950’s when a glacier occupied the lake basin. The glacier retreated about 1.5 km between 1955 and 1976 increasing the lake area (Figure 4.3). The Engaño Lake is surrounded by steep bedrock and ice-covered slopes prone to mass movement and ice/snow avalanching. The lake also was in contact with a retreating glacier at the time of failure and thus probably was exposed to glacier calving (Figure 4.4). Ice-avalanching and calving may have triggered waves capable of overtopping the dam, initiating the breaching process which was aided by the steep outlet slope (Iribarren Anacona et al. 2014). A reconnaissance flight carried out a few days after the GLOF showed the impact of ice into the lake (Diario de Aysén 1977b), which supports the ice avalanche or calving hypothesis. Both processes are enhanced by ice/snow melting which commonly peaks around midday or early afternoon (Kobayashi and Naruse 1987; Diolaiuti et al. 2005) when the GLOF probably started (see next section).

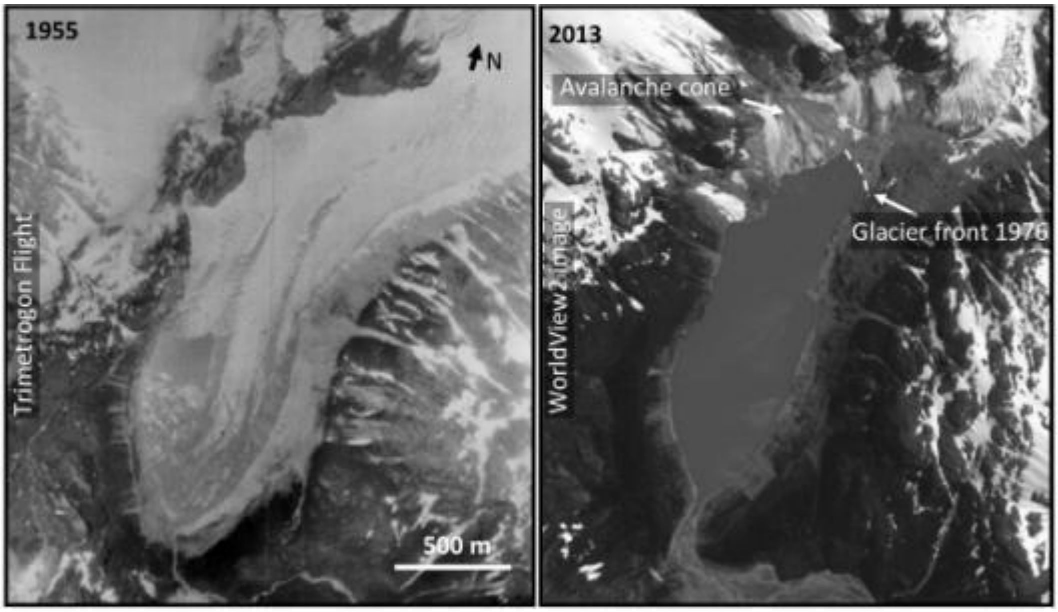

Figure 4.3. Glacier retreat and concomitant expansion of the Engaño Lake between 1955 and 2013. Icebergs are visible in the 1955 image indicating lake calving. The north lake shore was in contact with an avalanche cone prior to the 1977 GLOF.

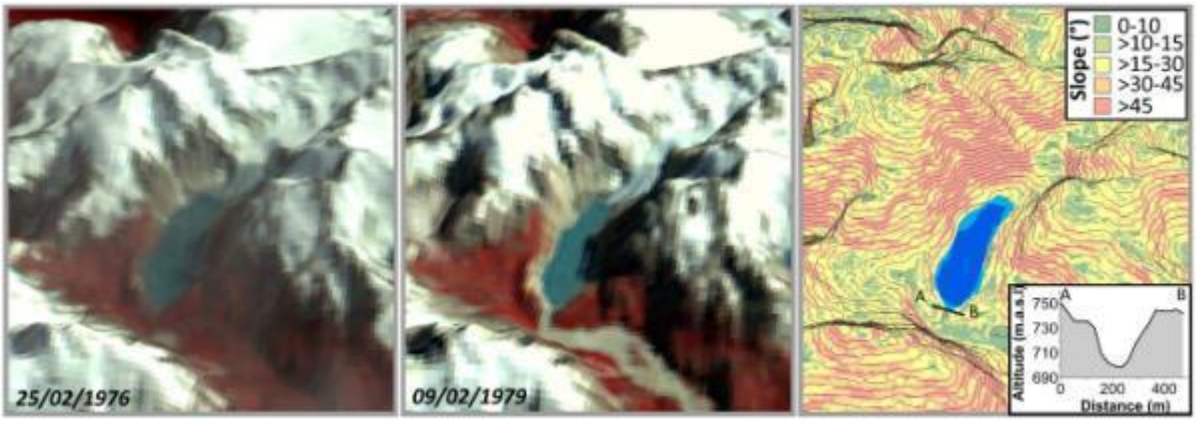

Figure 4.4. Engaño Lake prior and after the 1977 GLOF. The 1976 image shows that the lake was in contact with a glacier at the time of failure and the 1979 image shows striped vegetation patches along the GLOF path. High geomorphic activity can be inferred from steep (≥45°) ice and debris covered slopes around the lake. The graph inset in the lower right image shows the ~50 depth dam breach produced by the GLOF.

4.5.2 GLOF dynamics according to eyewitnesses accounts

The flood reached Bahia Murta Viejo at 6:30 PM on Friday 11, March 1977 (El Diario de Aysén 1977b). Eyewitnesses stated that the water level ranged between 0.5 and 1.5 metres in the village, and that the flood joined the Engaño and Murta rivers, isolating the area. Interviewees agreed that the flood lasted for 3 to 4 hours, although others stated that it continued, albeit receding, during the night. People returned to the village the next day at midday when the river had returned to its normal level.

The first eyewitness of the GLOF was on the river floodplain, 16 km from the Engaño Lake, upstream of one the river gorges and he recalled "*we saw trees floating on the river and heard a tremendous roar upstream"*. Another witness noted "w*hen we saw the floating trees, I said it's a rodado* [i.e. flood or landslide] *and we escaped to the hills*. *The water got dammed* [at the gorge] *and started to flood back forming swirls and trees were piled there* [at the gorge]*. The entire valley was flooded; the water reached the base of the hill and was at least 4 metres deep over the river terrace*" (Figure 4.5).

Figure 4.5. Engaño Valley viewed from East to West about 16 km from the failed lake. At least 4 metres of water were witnessed in this area. Note the forest covering the floodplain and buildings in the centre of the image. Buildings at the same location were destroyed by the 1977 GLOF.

The damming effect, caused by the obstruction of the gorge, was corroborated by Bahia Murta Nuevo inhabitants who stated "*someone that worked upstream, at the sawmill,* alerted *that the Engaño river was drying".* Backwater flooding was also observed in Bahia Murta Viejo where one of the inhabitants recalled "*I saw wood debris, of the height of a house, and snow entering the lake* [General Carrera], *the debris dammed the river mouth and the water came back flooding the village".* In spite of the transport of wood debris and fine sediments the event was described as a clear water flow (Newtonian flow) in the middle and lower river reaches.

4.5.3 GLOF modelling results

Notable differences were found in the flow path delineated using the ASTER GDEM2 and the SRTM DEM, especially in flat areas. In the ASTER GEDEM2 simulations the flow depth and velocity were similar in the channel and the floodplain, resulting in widespread-shallow flooding in the middle and lower reaches. The flooded area was 19% larger in the ASTER GDEM2 simulation (assuming an outburst volume of $13x10^6 m^3$) than in the SRTM results (Figure 4.6). In spite of the coarser resolution of the SRTM DEM, it better represents the differences between the channel and floodplain hydraulics in flat areas, having as expected, the channel larger velocities and depths than the floodplain. Thus, the SRTM DEM was used to assess the model sensitivity to changes in outburst volume and roughness values.

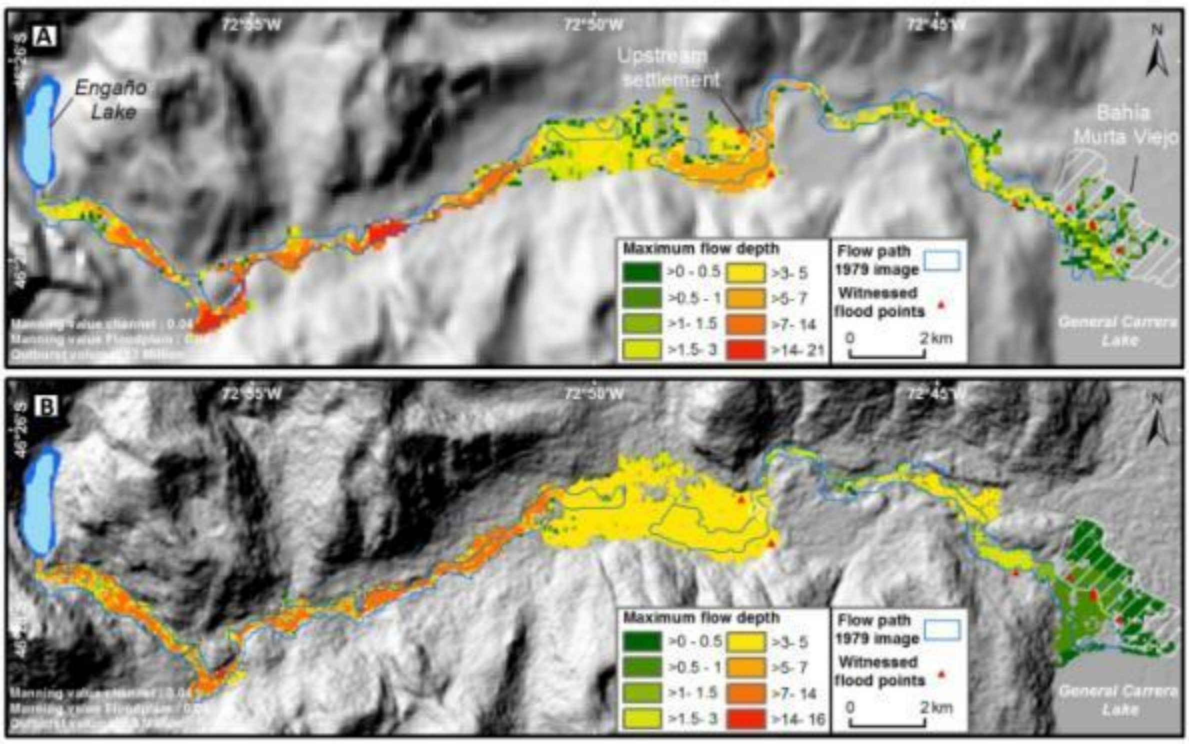

Figure 4.6 Flow extent and depth simulated using the SRTMv4 (a) and ASTER GDEM2 (b) DEMs. A larger area is flooded in the ASTER GDEM2 simulation although with a shallower flow. Note that in flat areas, the channel hydraulic is better defined in the SRTM DEM in spite its coarser resolution.

Flood stages and flooded areas pointed out by eyewitnesses were compared with flood simulations. Outburst volumes ranging from 12 to $13x10^6$ m^3 match with flow depths described by eyewitnesses in the Engaño Valley (at least 4 metres) and Bahia Murta Viejo (maximum of 1.5 metres) (Figure 4.7). Less voluminous outburst floods underestimate the maximum flow depth in the village´s location and larger volumes overestimate the flow depth in Engaño Valley. The flood extent, however, is similar in the 12 to $13x10^6$ m^3 scenarios (between 10.48 and 10.93 km^2).

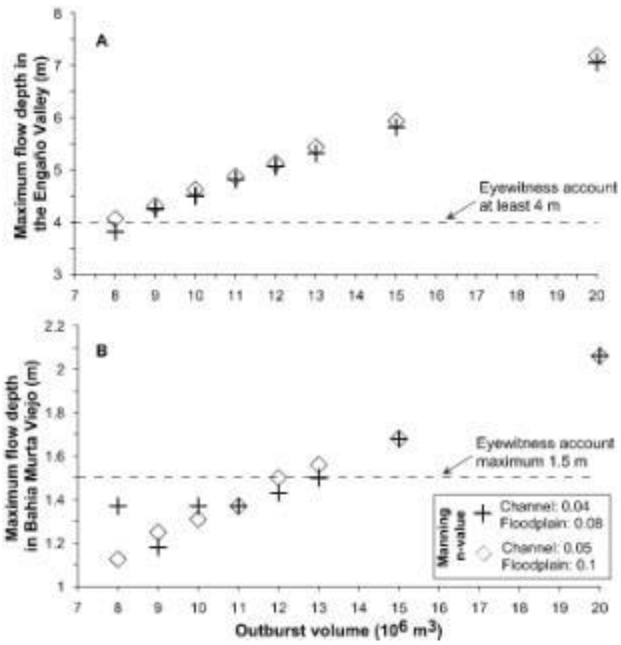

Figure 4.7 Maximum flow depth in the Engaño Valley (about 16 km from the Engaño Lake) and Bahía Murta Viejo under different flood scenarios. Outburst volumes from 12 to 13 million match with eyewitness accounts. Simulations run using the SRTM DEM.

The modelling results show that the flood reached Bahia Murta Viejo in 2 hours and 10 minutes and the flow had a mean velocity of 2.09 m/s. The flow velocity however changed markedly along the flow path increasing in valley constrictions to a maximum of 19 m/s and slowing to less than 1 m/s in wide floodplains (Figure 4.8). Hydraulic ponding, like that described by eyewitnesses, is well represented in the modelling results as an area with low flow velocities (≤1 m/s) and large depths (>4m) upstream the lower river gorge (Figure 4.9).

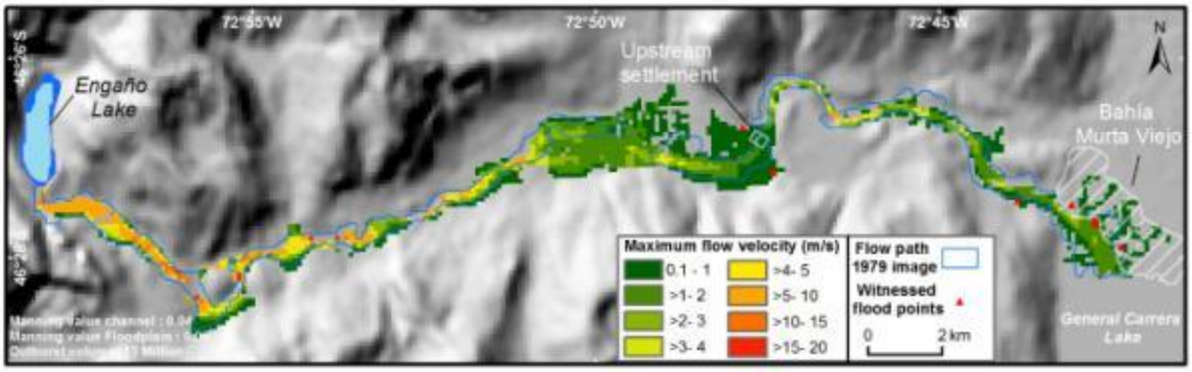

Figure 4.8 Maximum flow velocity along the Engaño Valley. Note that in Bahía Murta Viejo the simulated flow velocity is less than ≤ 1 m/s.

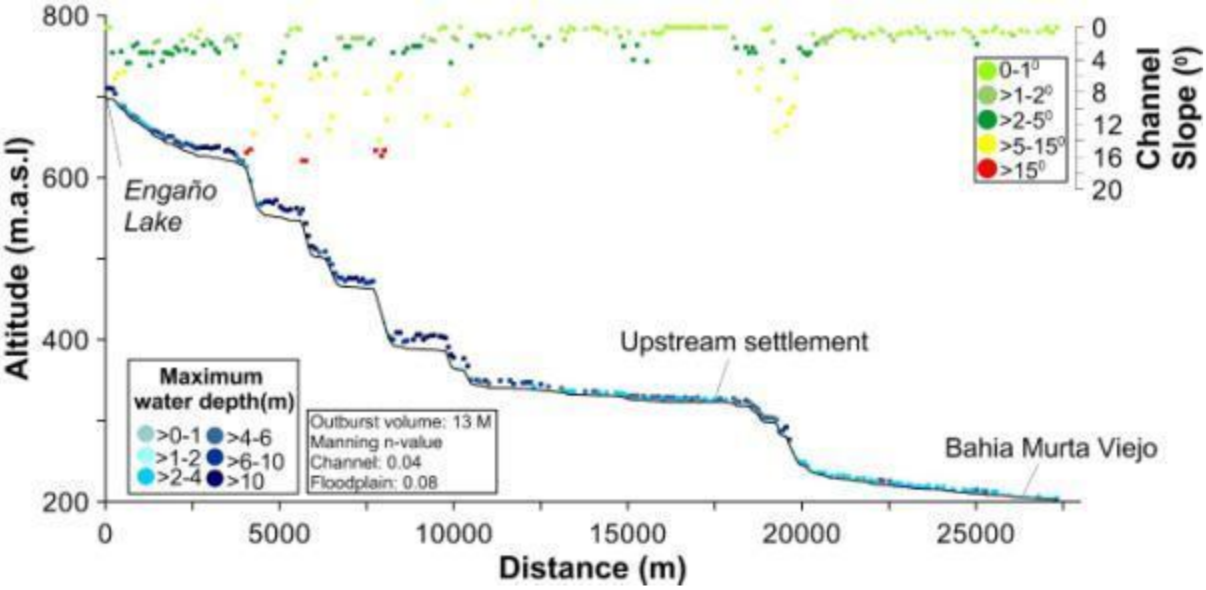

Figure 4.9 Topographic profile and steepness of the Engaño River channel. The slope decreases and the flow shallows 10 km from the Engaño Lake. This flat-wide area acted as a buffer dissipating the flood energy. Topographic data extracted every ~80 metres from the SRTM DEM.

According to our simulations, the flood lasted for at least 10 hours (assuming outburst volumes of 12 and 13x$10^6$$m^3$) in Bahía Murta Viejo and the peak discharge occurred one hour after the water reached the village (Figure 4.10). The receding limb of the hydrograph matches with the testimony of one of the two Bahía Murta inhabitants that remained in the village during the flood who stated (according to interviewees) that the water level lowered one hour after initiated the flood. The receding part of the flood occurred after nightfall, which may have limited the accuracy of eyewitnesses observation. Furthermore, the 3-4 hours stated by interviwees could correspond to the main flood wave and not to the return to the pre-flood water level.

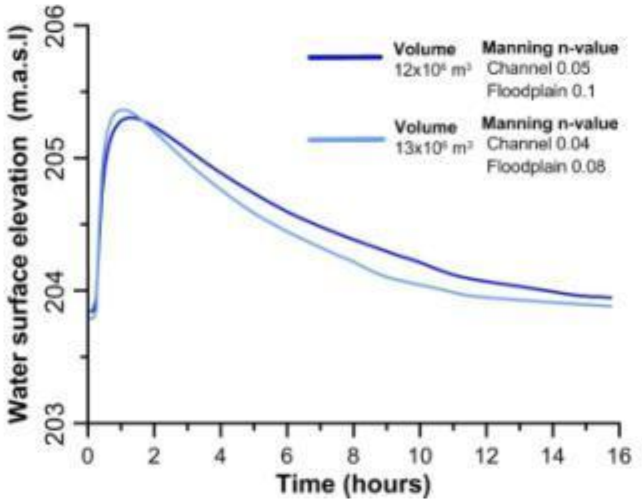

Figure 4.10. Flood stage and time at the Engaño River, close to Bahía Murta Viejo. In both scenarios the river returns to its pre-flood level in ~10 hours.

4.5.4 GLOF socioeconomic consequences

The buildings in Bahia Murta Viejo and the Engaño Valley were constructed of timber, however, only constructions located in the Engaño Valley suffered severe structural damage. These buildings were located in a valley section where the flood reached high intensities (>2 m^2/s) (Figure 4.11). Overall 22 houses were affected by the flood (El Diario de Aysén 1977c). According to eyewitnesses, in Bahia Murta Viejo houses were partially covered by mud, and one house was shifted from its foundations. However, most houses in Bahia Murta Viejo suffered only minor damage, which allowed full houses or parts thereof to be relocated months or years after the GLOF.

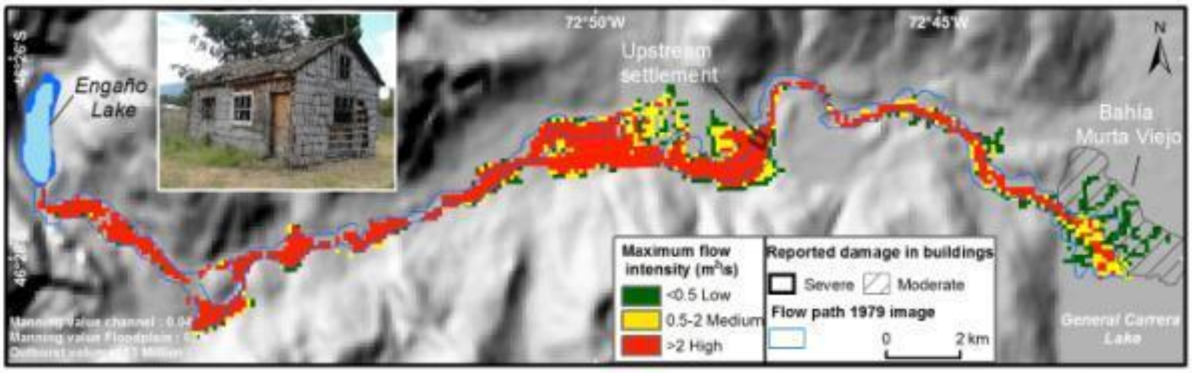

Figure 4.11. Simulated flow intensity and damages reported by eyewitnesses. Note the good correspondence between severely damaged houses (i.e. building destroyed or removed by the flood) and areas of high flow intensity, and houses lightly damaged (i.e. partially covered by mud) and low flow intensity. Flow intensity classes according to LAWA (2006). The inset photograph shows the type of wooden constructions existing in Bahia Murta at the time of the GLOF.

The GLOF however, had severe consequences for the subsistence economy of most of the families, since farm and forestry land were damaged, and livestock was lost. An interviewee stated "my family had 30 sheep and all of them died during the flood". Some damage was long lasting since mud-covered grassland hindered feeding of surviving livestock, some of whom were injured by wood debris. Furthermore, tree trunks several metres in length were piled around the village requiring clearance labour. The GLOF forced 53 adults and 73 children to leave their homes (El Diario de Aysén 1977a). Over the course of a few years, Bahia Murta Viejo inhabitants moved to Bahía Murta Nuevo. In fact, the regional government conducted topographic surveys in Bahia Murta Nuevo a few days after the GLOF, aiming to provide new land to the families affected by the flood (El Diario de Aysén, 1977d).

4.5.5 Lessons for GLOF risk management

The interviewees highlighted GLOF singularities, as well as technical and planning issues, that contributed to flood damage. Although this data is mostly anecdotal, it helps to point out measures that should be taken to prevent or mitigate negative outcomes in GLOF management.

4.5.5.1 Recognition of the hazard posed by glacial lakes

The recognition of the hazard posed by glacial lakes is essential for GLOF risk management. However, authorities and Bahia Murta inhabitants failed to recognise the threat posed by glacial lakes before the 1977 GLOF. In fact, most residents suspected that a volcanic eruption (the Hudson Volcano erupted in 1971 triggering lahars in a nearby valley) caused the flood. When interviewed, nevertheless, people knew that the failure of the Engaño Lake caused the 1977 flood, and some of them, recalled that GLOFs occurred later in Patagonia, showing an increasing awareness of GLOF hazards. Interviewees also mentioned possible triggers of the GLOF including mass movement impacts into the lake and the blockage of the lake outlet by icebergs. Increased awareness of GLOF hazards may have been further influenced by the media, which has intensively covered the episodic drainage of the ice-dammed lake Cachet 2 since 2008.

4.5.5.2 Effective risk communication

The effective communication of flood risk prior, during and after an emergency can significantly reduce flood damages. The GLOF risk communication failed before the 1977 event but succeeded during the emergency. According to one of the interviewees *"the other town was already planned* [Bahia Murta Nuevo], *there was a technical report* [pointing out the risk]*, the authorities knew about it, but the people weren´t told what the risk of staying was* [in Bahía Murta Viejo]". Although we were unable to confirm the existence of this report, the construction of a large school in Bahia Murta Nuevo in 1967, shows the authority's intention to promote settlement of this area, which is located in a higher and safer place. This decision, however, was at least partially influenced by the lobby of local residents with regional authorities due to the frequent floods affecting Bahía Murta Viejo, and not by the recognition of the GLOF hazard.

During the crisis, most of the Bahia Murta inhabitants were able to escape (crossing the Murta River on horseback, boating in the General Carrera Lake to Bahía Murta Nuevo, or running to the cemetery located in higher place) after being alerted about the coming flood. An interviewee stated *"someone rang the chapel bell alerting that a flood on the Engaño River was coming...in those years and even today we alert of an* *emergency by ringing the chapel bell"*. Other interviewe´s stated "*someone galloped through the village saying that a huge flood on the Engaño River was coming, but not everybody believed them"*. Although the communication of the risk was spontaneous, it was effective, allowing for the evacuation of the village. The success of this spontaneous response was aided by the relatively low velocity of the flood in the village, by the small number of inhabitants, and because the GLOF occurred during the day.

The last testimony highlights one of the singularities of GLOFs that should be taken into account in GLOF risk management programmes. GLOFs can occur without obvious meteorological triggers and thus with little warning. As the Engaño GLOF occurred on a sunny day, some people delayed the evacuation not believing that a flood-wave was approaching the village. In fact, some of Bahia Murta inhabitants moved towards the river to confirm that a flood was approaching.

4.6 Discussion

4.6.1 Outburst reconstruction and modelling

The Engaño Lake was highly susceptible to outburst floods before the 1977 GLOF. The lake was dammed by a high (~50 m) and steep (25°) moraine, was exposed to ice avalanche and mass movement impacts and was in contact with a retreating glacier, making calving activity likely. These characteristics were common to many other moraine-dammed lake failures in Patagonia (Iribarren Anacona et al 2014) and have been linked with GLOFs in other mountain ranges. Thus, an assessment of the lake outburst susceptibility could have identified the GLOF risk in the Engaño Valley and Bahía Murta village.

The retreat of the Engaño Glacier since the 1950's coincides with warmer temperatures registered in nearby weather stations on the second half of the twentieth century (see e.g. Rosenblüth 1995) and with generalised glacier retreat in Patagonia (Davies and Glasser. 2012). Calving glaciers, however, can have non-linear responses to climatic changes and may suffer rapid mass losses resulting in quick development of proglacial lakes (Benn et al., 2007). It is not know whether the Engaño Glacier experienced a gradual retreat between 1955 and 1977, or if the retreat accelerated before the GLOF.

As eyewitnesses suggest, the flow behaved as Newtonian flow (clear water flow) in the middle and lower reaches in spite of the transport of fine sediments and wood debris. Large blocks (several metres in diameter) were mobilised near the dam in the steepest valley reaches. The large GLOF discharge and water depths over 20 metres, however, suggest that these blocks could have been mobilised as bed load, due to the high shear stress exerted by the flow, and not by particle collision or floatation in a dense fluid which are characteristics of debris flows. Thus, the clear water flow approach used to model the Engaño GLOF seems reasonable.

The overall behaviour of the GLOF along the Engaño Valley was well simulated using the 2D capabilities of HEC-RAS 5, even using a relatively coarse (~80 m) DEM. The maximum water depth described by eyewitnesses in two different localities was coincident with flood simulation results obtained with reasonable values of terrain roughness and outburst volumes. Furthermore, flow intensity values coincide with reported damages on infrastructure in Bahia Murta and the Engaño Valley. Thus, useful data for quantitative GLOF hazard assessment can be readily obtained using the freely available HEC-RAS 5 (each simulation using the SRTM DEM was completed in about 1 hour in an Intel Core i5-4570, 8 GB RAM computer).

The accuracy of the simulated flow extent, however, is more difficult to evaluate since post GLOF topographic surveys or high resolution images are lacking. The flow path delineated over the 1979 Landsat image shows a good agreement with the flow simulation results in narrow reaches. However, this correspondence is less clear in floodplains. This can be explained because the GLOF intensity, as well as the geomorphic work done by the GLOF, decreases in flat areas were the flow disperses its energy leaving less geomorphic evidence. Thus, the GLOF path interpreted in the 1979 image is a minimum estimate, and only represents areas of striped vegetation and sediment entrainment or deposition, and not the entire flooded region.

Wood debris transport during the GLOF modified the flood behaviour and its damaging capacity. Eyewitnesses stated that log jams dammed or reduced the cross sectional area of narrow reaches generating backwater flooding. Furthermore, woody debris covered grass land around Bahía Murta Village requiring removal work, and injured livestock damaging inhabitant's livelihoods. The effects of wood debris in the GLOF dynamics is coincident with empirical evidence and modelling of floods in forested areas where it has been demonstrated that changes in the flood hazard (e.g. reduction in flood velocity and increase in water levels), as a consequence of wood transport occurs (see e.g. Mazzorana et al. 2009; Ruiz-Villanueva et al. 2013).

An important source of uncertainty in the modelling is the outburst volume used as input, due to the lack of bathymetric or gauging data to constrain our estimates. The outburst volume was estimated previously at about 7.36×10^6 m^3 using an empirical formula (Iribarren Anacona et al. 2014). Simulations run using this value underestimated the water depth in Bahía Murta Viejo and in an upstream settlement. Volumes from 12 to 13 million better match with eyewitness accounts. The difference between the empirical estimate and our modelling results, however, is in the range of error uncertainty of the empirical formula (~70%) and these values can be considered representative of the 1977 GLOF.

Another possible source of uncertainty in the simulations, which is difficult to quantify, is related to the accuracy of the co-registration of the DEM's and the satellite images used to assign the roughness values. It was noted that the channel interpreted in the Landsat images do not match perfectly with the channel location in the DEM's. This can also be linked to the horizontal accuracy of the SRTM DEM (±20 m; Rabus et al. 2003). Thus, small sections of the channel may have Manning values corresponding to the floodplain and vice versa. While this issue may affect the flow locally, the overall simulated flood behaviour is still reasonable. The modelling results show that the flow depths as well as the flood extent are mainly controlled by the outburst volume and secondarily by the roughness values. Roughness values, however, have a dominant control on the flood timing (Figure 4.12).

Flood data (e.g. flood depth and timing) recalled by eyewitnesses more than 30 years after the GLOF also are subject to error. However, the description of the event by several interviewees was consistent regarding the flood depth and duration and some of them have vivid memories of the GLOF event. However, the year of the GLOF was not always remembered by the interviewees. The maximum flood depth in Bahía Murta Viejo (1.5 m) was stated in a newspaper report few days after the GLOF substantiating eyewitness's statements (El Diario de Aysén 1977c). Memories of life threatening situations, such as the 1977 GLOF, are commonly held in the people's memory for long time (Pillemer 1998).

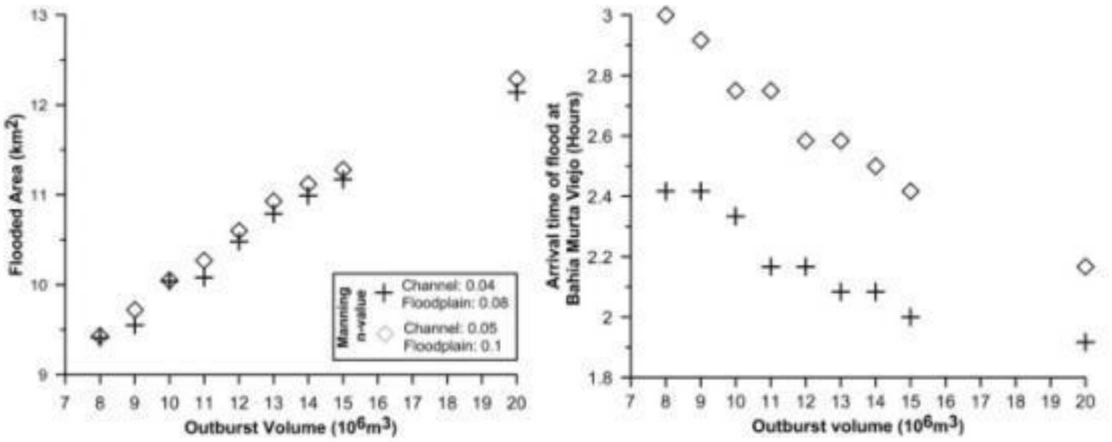

Figure 4.12 Changes in flood extent and flood timing under different scenarios of outburst volume and roughness values. Higher roughness values result in larger flooded areas and slower floods.

4.6.2 Outburst management

The flood of Bahía Murta Viejo during the 1977 GLOF revealed planning issues as well as forms of resilience in the local population. The village grew as an informal settlement under the umbrella of colonisation laws in Chile (see Peri Fagerstrom 1989 for a review of colonization laws in Chile). Thus, there was no territorial planning or hazard assessment before the village´s establishment. Bahía Murta Viejo inhabitants suffered repeatedly from floods especially by overflows of the Murta River. According to one of the interviewees, because the constant floods some inhabitants started lobbing with authorities to gain access to the land where Bahía Murta Nuevo is located. As a result of these efforts, a new school was built in Bahía Murta Nuevo in the mid-sixties and some people moved to this place. The 1977 GLOF, however, accelerated the relocation of the village including inhabitants that were reluctant to move before the GLOF.

The gradual short-distance migration from Bahía Murta Viejo to its current location is an example of a coping strategy to natural hazards observed in multiple geographical contexts (e.g. Laczko and Aghazarm. 2009). Local-scale migration is less expensive and involves less uncertainty than long-distance migration and thus is an attractive strategy to cope with natural hazard impacts (Findlay 2012). Nowadays, fluvial defences flank sections of the Engaño River aiming to protect the few people that still live in Bahía Murta Viejo and the Carretera Austral (opened in 1988), the main arterial road in Patagonia.

In spite of the socio-economic consequences of the Bahía Murta GLOF and that dozens of GLOFs have affected Patagonia, GLOF emergency management procedures remain reactive and have not been systematised. No measures have been taken to deal with GLOFs from moraine-dammed lakes and the identification of hazardous lakes has been made in only one basin (Iribarren Anacona et al. 2014). Experience in glaciated mountains worldwide show the type of procedures that can be taken to reduce the risk of GLOFs (Figure 4.13). These measures include the identification of hazardous lakes and GLOF modelling (Worni et al. 2012), GLOF awareness programmes (UNDP 2010), early warning systems, dam reinforcement, fluvial defence construction and preventive lake drainage (Kattelmann and Watanabe, 1997). The risk of GLOFs, however, cannot be completely eliminated unless lakes are fully drained. In fact, reinforced dams and partially drained lakes, have produced GLOFs (Carey et al. 2012). The unfeasibility of draining all the hazardous lakes urges for the development of integral approaches to reduce the GLOF hazard and risk. This includes soft (land use planning) and hard (geotechnical works) mitigation measures, in the frame of coordinated plans including actions before, during and after the emergency.

These approaches should be adapted to the local geographical context. Western Patagonia is characterised by sparsely inhabited areas and an isolated population (physically and technologically) (Muñoz et al. 2006). Thus radio messages may be more effective than cell phone messages or emails to warn the population about flood risk, since internet and cell phone coverage is limited. This was demonstrated in the success of a radio network implemented to warn the population about GLOFs from the ice-dammed Cachet 2 (El Divisadero 2009). On the other hand, monitoring changes in lake area, or identifying new hazardous lakes, could be better achieved using Synthetic Aperture Radar images (see e.g. Strozzi et al. 2012) rather than optical sensors due to the region's frequent cloud cover. Informal but effective emergency management actions were taken during the 1977 GLOF by Bahía Murta inhabitants, suggesting that the involvement of local population should increase the success of future GLOF management strategies.

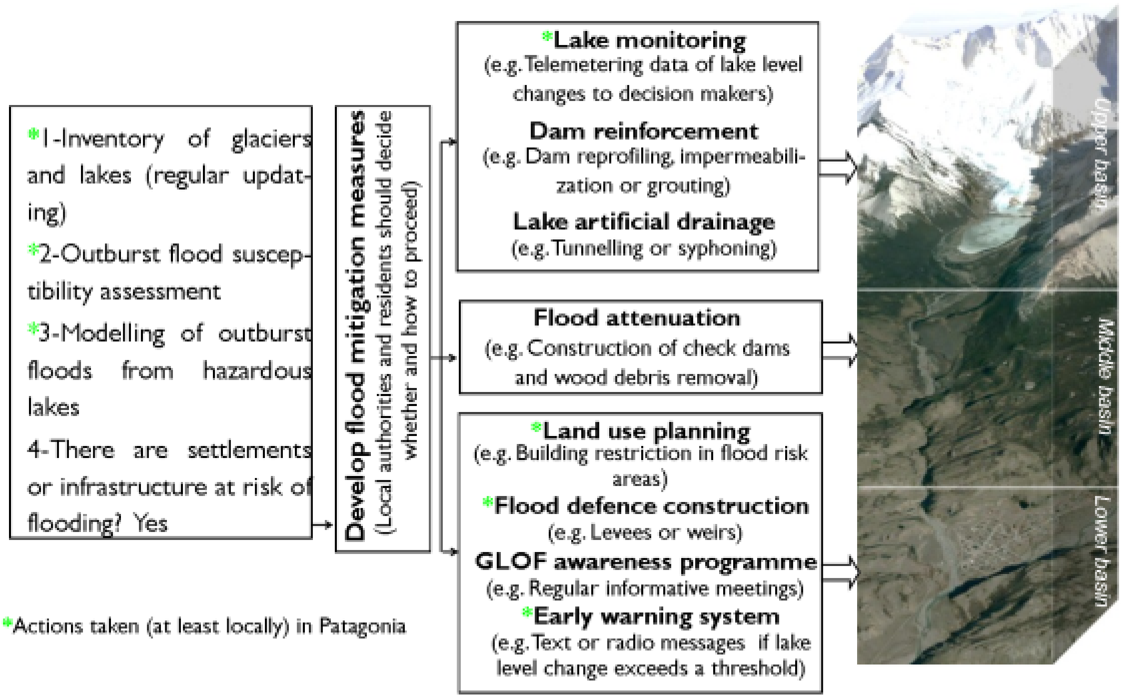

Figure 4.13 GLOF risk management procedures undertaken in mountain ranges worldwide. In Patagonia lake monitoring and an early warning system have been implemented only for the ice-dammed Lake Cachet 2.

4.7 Conclusions

We reconstructed the 1977 Engaño River GLOF, in the Chilean Patagonia, by means of eyewitness accounts, newspaper reports and a 2D hydraulic model. The HEC RAS 2D capabilities allowed a realistic representation of flood depth and intensity in different sections of the Engaño Valley, where a one dimensional model would have not achieved similar results due to the lack of cross sectional area on flat surfaces. The model allowed the extraction of valuable flow data (e.g. flow depth, velocity, intensity and arrival time) that can be used in GLOF hazard assessment. Flow characteristics described by eyewitnesses, such as hydraulic ponding upstream of valley constrictions, were well represented in the 2D flow simulations, in spite of the relatively coarse DEM used. However, GLOF risk management at local scale could benefit from a high resolution DEM which better represents smaller topographic features such as flood levees and bridges, which can modify the flood behaviour.

The failed moraine-dammed lake and its geographical setting before the GLOF had many common characteristics with failed dams in Patagonia and worldwide. Thus, the negative socioeconomic consequences of this GLOF could have been prevented or mitigated if a lake outburst susceptibility assessment, and flood mitigation measures, had been made. Bahía Murta Viejo, the village most affected by the GLOF, lacked flood mitigation measures in spite of frequent flooding. The 1977 GLOF, however, was larger than past floods and measures, such as levees, designed to protect against meteorological floods might have been insufficient for the GLOF, giving a false sense of security to the population.

The GLOF reconstruction highlighted particularities that have to be taken into account in GLOF awareness and risk management plans. GLOFs may occur in good weather conditions, thus with little warning, and GLOF behaviour (and damages) in forested land such as western Patagonia are linked not only with channel and floodplain hydraulics but also with wood debris entrainment and transport. Finally, the Río Engaño GLOF exemplifies that small-scale and short-distance migration is an effective coping strategy to a natural hazard that may increase in frequency if atmospheric temperature continues to rise.

4.8 References

Ames A (1998) A Documentation of Glacier Tongue Variations and Lake Development in the Cordillera Blanca, Peru. Zeitschrift für Gletscherkunde und Glazialgeologie 34(1):1-36

Baker VR, Webb RH, House PK (2002) The scientific and societal value of paleoflood hydrology in: P.K. House, R.H. Webb, V.R. Baker, D.R. Levish (Eds.), Ancient Floods, Modern Hazards: Principles and Applications of Paleoflood Hydrology, Water Science and Application, vol. 5, American Geophysical Union, Washington, D.C. (2002), pp. 1-19

Benn DI, Warren CR, Mottram RH (2007) Calving processes and the dynamics of calving glaciers. Earth-Science Reviews, 82:143–179.

Breien H, de Blasio FV, Elverhøi A, Høeg K (2008) Erosion and morphology of a debris flow caused by a glacial lake outburst flood, Western Norway. Landslides **5**: 271-280. DOI: 10.1007/s10346-008-0118-3.

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

Carrivick J (2006) Application of 2D hydrodynamic modelling to high-magnitude outburst floods: an example from Kverkfjöll, Iceland.Journal of Hydrology 321:187-199.

Clague JJ, Evans SG (2000) A review of catastrophic drainage of moraine-dammed lakes in British Columbia. Quaternary Science Reviews 19: 1763-1783. DOI: 10.1016/S0277-3791(00)00090-1.

Costa JE, Schuster RL (1988) The formation and failure of natural dams. Geological Society of America Bulletin 100:1054-1068.

Davies BJ, Glasser NF (2012) Accelerating shrinkage of Patagonian glaciers from the Little Ice Age (~AD 1870) to the present day. Journal of Glaciology**,** 58 (212):1063-1084.

Diolaiuti G, Smiraglia, C, Kirkbride MP, Benn DI, D'Agata C (2005) Calving processes and lake evolution at Miage Glacier (Mont Blanc, Italian Alps) Annals of Glaciology 40: 207-214.

Dussaillant A, Benito G, Buytaetr W, Carling P, Meier C, Espinoza F (2010) Repeated glacial-lake outburst floods in Patagonia: an increasing hazard? Natural Hazards 54:469-481.

El Diario de Aysén 1977a. Efectiva ayuda a damnificados. 15 Marzo 1977.

El Diario de Aysén 1977b. Auxilian a Pobladores en Murta. 14 Marzo 1977.

El Diario de Aysén 1977c. Fue arrasado Pueblo Viejo en General Carrera. 13 Marzo 1977.

El Diario de Aysén 1977d. Profesionales viajan llevando auxilio a pobladores damnificados. 16 Marzo 1977.

El Divisadero 2009. Listo proyecto Centinela que permitirá alertar a pobladores vaciamiento del lago Cachet 2. http://www.eldivisadero.cl/noticia-19892 (Last accessed 20/12/2014)

Findlay A (2012) Flooding and the scale of migration. Nature Climate Change, 2:401-402.

Froehlich DC (1995) Embankment dam breach parameters revisited. Water Resources Engineering, Proc. 1995 ASCE Conf. on Water Resources Engineering, New York, 887-891.

Gardelle J, Arnaud Y, Berthier E (2011) Contrasted evolution of glacial lake along the Hindu Kush Himalaya mountain range between 1990 and 2009. Global and Planetary Change **75**: 47-55. DOI: 10.1016/j.gloplacha.2010.10.003.

Garreaud R, Lopez P, Minvielle M, Rojas M (2013) Large-scale control on the Patagonian Climate, J. Climate, 26, 215-230, doi: 10.1175/JCLI-D-12-00001.1

Gyawali D, Dixit A (1997) How Distant is Nepali Science from Nepali Society? Lessons from the 1997 Tsho Rolpa GOLF Panic, Water Nepal, 5 (2): 5-43.

Harrison S, Glasser N, Winchester V, Haresign E, Warren CR, Jansson K. (2006) A glacial lake outburst flood associated with recent mountain glacier retreat, Patagonian Andes. Holocene 16: 611-620.

Hauser A (2000) Remociones en masa en Chile, 2nd edn, Boletín No. 59. Servicio Nacional de Geología y Minería: Santiago; 89.

Horritt MS, Bates PD (2002)Evaluation of 1D and 2D numerical models for predicting river flood inundation' Journal of Hydrology, vol 268, no. 1-4, PII S0022-1694(02)00121-X, pp. 87-99.

Hromadka TV, Berenbrock CE, Freckleton JR, Guymon GL (1985) A two-dimensional dam-break flood-plain model. Advances in Water Resources 8:7-14.

Iribarren Anacona P, Mackintosh A, Norton KP (2015) Hazardous processes and events from glacier and permafrost areas: lessons from the Chilean and Argentinean Andes. Earth Surf. Process. Landforms, 40: 2-21.

Iribarren Anacona P, Mackintosh A, Norton KP (2014) Moraine-dammed lake failures in Patagonia and assessment of outburst susceptibility in the Baker Basin, Nat. Hazards Earth Syst. Sci. Discuss. 2, 4765-4812, doi:10.5194/nhessd-2-4765-2014, 2014.

Kattelmann R, Watanabe T (1997) Draining Himalayan glacial lakes before they burst, In: G. H. Leavesley et al. (eds), Destructive Water: Water-Caused Natural Disasters, their Abatement and Control, Publication 239, International Association of Hydrological Sciences, Wallingford.

Kershaw JA, Clague JJ, Evans SG (2005) Geomorphic and sedimentological signature of a two-phase outburst flood from moraine-dammed Queen Bess Lake, British Columbia, Canada. Earth Surface Processes and Landforms **30**: 1-25. DOI:10.1002/esp.1122.

Kobayashi S, Naruse R (1987) Ice avalanches on Soler Glacier, Patagonia. Bulletin of Glacier Research 4: 87-90.

Korup O, Tweed F (2007) Ice, moraine and landslide dams in mountainous terrain. Quaternary Science Reviews **26**: 3406-3422. DOI:10.1016/j.quascirev.2007.10.012.

Laczko F, Aghazarm C (2009) Migration, Environment and Climate Change: Assessing the Evidence (International Organization for Migration, Geneva).

LAWA (2006) Empfehlungen der Länderarbeitsgemeinschaft Wasser (LAWA) zur Aufstellung von Hochwasser-Gefahrenkarten, unpublished.

Lliboutry L, Morales Arnao B, Pautre A, Schneider B (1977). Glaciological problems set by the control of dangerous lakes in Cordillera Blanca, Peru. I. Historical failures of morainic dams, their causes and prevention. Journal of Glaciology, 18: 239-254.

López P, Chevallier P, Favier V, Pouyaud B, Ordenes F, Oerlemans J (2010) A regional view of fluctuations in glacier length in southern South America, Global Planet. Change, 71:85-108.

Mazzorana B, Zischg A, Largiader A, Hübl J (2009) Hazard index maps for woody material recruitment and transport in alpine catchments. Natural Hazards and Earth System Science 9: 197-209.

Muñoz M, Pérez L, Sanhueza R, Urrutia R, Rovira A (2006) Los paisajes del agua en la cuenca del Río Baker: bases conceptuales para su valoración integral, Rev. Geogr.Norte Grande 36: 31–48.

Pillemer DB (1998) Momentous events, Vivid memories. Cambdrige: Harvard UP,1998. 256pp.ISBN 0-674-58205-5.

Peri Fagerstrom R (1989) Reseña de la colonización en Chile, Editorial Andrés Bello. Santiago Chile, 250 pp.

Ponce VM, Taher-Shamsi A, Shetty, AV (2003) Dam-breach flood wave propagation using dimensionless parameters. J. Hydraul. Eng. 12910, 777-782.

Prestininzi P (2008) Suitability of the diffusive model for dam break simulation: Application to a CADAM experiment." Journal of Hydrology, 361:172-185.

Rabus B, Eineder M, Roth A, Bamler R (2003) The shuttle radar topography mission—a new class of digital elevation models acquired by spaceborne radar. Journal of Photogrammetry and Remote Sensing, 57:241−262.

Richardson SD, Reynolds JM (2000) An Overview of Glacial Hazards in the Himalayas. Quaternary International 65-66:31-47

Rosenblüth B, Casassa G, Fuenzalida H (1995) Recent climatic changes in western Patagonia, Bull. Glacier Res. 13:127-132.

Ruiz Villanueva V, Castellet EB, Díez-Herrero A, Bodoque JM, Sánchez-Juny M (2013) Two dimensional modelling of large wood transport during flash floods. Earth Surface Processes and Landforms doi: 10.1002/esp.3456.

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

Strozzi T, Wiesmann A, Kääb A, Joshi S, Mool P (2012) Glacial lake mapping with very high resolution satellite SAR data Natural Hazards and Earth System Sciences, 12:2487-2498

Tachikawa T et al (2011) ASTER Global Digital Elevation Model Version 2 - Summary of Validation Results.(http://www.jspacesystems.or.jp/ersdac/GDEM/ver2Validation/Summary_GDEM2_validation_report_final.pdf)

Tarboton DG, Bras RL, Rodriguez-Iturbe I (1991) On the Extraction of Channel Networks from Digital Elevation Data," Hydrologic Processes, 5(1): 81-100.

UNDP/BCPR (2010) GLOF RISK Reduction through Community-based Approaches, Regional GLOF Risk Reduction Initiative in the Himalayas" published by UNDP and shared with regional partners.

Vuichard D, Zimmerman M (1987) The 1985 catastrophic drainage of a moraine-dammed lake, Khumbu Himal, Nepal: Cause and consequences. Mountain Research and Development **7**: 91-110.

Wahl TL (2004) Uncertainty of prediction of embankment dam breach parameters J. Hydraul. Eng. 130: 389-397

Worni R, Huggel C, Stoffel M (2012) Glacier lakes in the Indian Himalayas - glacier lake inventory, on-site assessment and modeling of critical glacier lakes. Science of the Total Environment. http://dx.doi.org/10.1016/j.scitotenv.2012.11.043

5 Dynamics of an outburst flood originating from a cold-based mountain glacier in the arid Andes of Chile.

5.1 Abstract

Ice-dammed lakes are common in glaciated areas, especially where dynamic temperate glaciers exist. Seasonal changes in glacier-bed adhesion and ice-conduit dynamics can trigger rapid lake drainage and voluminous outburst floods. Lakes dammed by high-altitude, cold-based glaciers, however, are less common and GLOFs from these glaciers have been rarely reported. Thus, data about the origin and failure mechanism of lakes dammed by mountain cold-based glaciers is needed. These data can help to assess the GLOF hazard where cold-based glaciers exist. We study a GLOF caused by the failure of a subglacial lake in the arid Andes of Chile in 1985, to provide insights in the lake's origin, failure mechanism and GLOF dynamics. To identify the factors that contributed to the lake formation and failure, we analysed satellite images, meteorological and topographic data. The GLOF dynamics were reconstructed using empirical (LAHARZ and MSF) and physical models (RAMMS) which were constrained with field data of flow extent, depth and velocity. We show that the failed lake formed under a cold-based glacier in a closed basin with a low slope (≤10°). Extreme (≥90th percentile) annual precipitation two-consecutive years before the GLOF contributed to the lake filling. The lake drained rapidly by mechanical collapse of the ice-dam (a non-tunnelled flood) reaching a peak discharge of 11000 m^3/s, although it decreased to ~1100 m^3/s at 105 km downstream. The flow behaved as debris flow and as an hyperconcentrated flow, although boulder bars also indicate the occurrence of Newtonian flow phase. The Manflas 1985 GLOF is a remarkable example of an infrequent but high-magnitude flood originating from a high-altitude, cold-based glacier.

5.2 Introduction

Glacial lakes are common in glaciated mountains worldwide and their number and size is increasing as a consequence of glacier retreat (Komori 2008; Gardelle et al., 2011). Lakes may be formed at the side, in front, within, or on the surface of a glacier, and related dam structures can be composed of ice, moraine or bedrock. Some of these lakes are unstable and have drained suddenly generating voluminous glacial lake outburst floods (GLOFs). Indeed, on a longer time scale, the release of huge volumes of freshwater (10^9 m^3) into the oceans by giant GLOFs during the Quaternary modulated ocean currents and influenced the Earth's climate (Andrews and Dunhill 2004). Historical GLOFs from ice-dammed lakes have reached high velocities (>10m/s) and peak discharges (10^5 m^3/s), mobilizing large volume of sediments ($10^4 m^3$), which exert long-term influence in riverine landscapes (Walder & Costa 1996; Korup and Tweed 2007). Sediment entrainment during GLOFs transforms floods into damaging debris flows, resulting in major disasters in densely inhabited mountains (Lliboutry 1977; Haeberli 1983; Carey 2005). This situation has prompted numerous studies of GLOFs to prevent or mitigate their socioeconomic consequences.

Outbursts of ice-dammed lakes occur through different mechanisms. These mechanisms are reviewed in Tweed & Russell (1999) and include: (a) the progressive enlargement of subglacial or englacial conduits as consequence of increases in water temperature or hydrostatic pressure, (b) ice-floatation (theoretically starts when the lake level exceeds the 90% of the ice-dam height) and the subglacial escape of floodwater, (c) breaching of the contact between the ice-dam and the rock-wall which allows subaerial drainage, (d) mechanical rupture of the dam and (e) overspill. The last mechanism is mostly observed in cold-based glaciers. Outbursts are common where lakes are dammed by dynamic temperate glaciers since changes in glacier thickness, bed adhesion and crevassing promote unstable hydrological conditions (Tweed & Russell 1999). However, outbursts from lakes dammed by polythermal and cold-based glaciers have also been recognised (Maag 1969; Wadham et al., 2001).

High-energy flows from failed dams exert extensive and long-term effects in fluvial systems. The geomorphic effectiveness of outburst floods is demonstrated by the erosion of consolidated river terraces and bedrock resulting in erosional gorges, cataracts, spillways and valley-fill aggradation (Cenderelli & Wohl 2003; Carrivick 2007). GLOFs commonly affect remote and ungauged rivers or destroy gauging stations. Thus, geomorphic features and paleostage indicators (e.g. silt lines) are used to reconstruct the flow hydraulics by using hydraulic equations, modelling and empirical relationships (see Webb & Jarrett 2002 for a review). These data provide insights into the flow dynamics and geomorphic work of GLOFS and are used to extend flood frequency data helping to improve flood hazard assessment (O'Connor & Webb 1988). Evidence of past flows (e.g. large imbricated boulders or high water marks) have both scientific and societal relevance, as flood reconstructions can be used to promote public awareness about floods (Baker 2008).

In the extratropical Andes (i.e. Andes of Chile and Argentina) GLOFs from ice-dammed lakes have been frequent, especially in Patagonia where dynamic glaciers impound large water bodies resulting in quasi-cyclic GLOFs (Stuefer et al 2007; Dusaillant et al 2009). In the central Chilean and Argentinean Andes, major GLOFs have resulted from episodic glacier advances and the temporary blockage of mountain streams (Peña & Klohn 1989; Fernández et al 1991). In the arid Andes, however, just one GLOF from an ice-dammed lake has been documented. The GLOF originated from the Río Seco de los Tronquitos Glacier (5200 m.a.s.l) and occurred in May 14 of 1985 (Peña & Escobar 1987). The GLOF caused extensive aggradation in the Manflas valley. Eyewitnesses' accounts indicate that flood waters destroyed infrastructure, agricultural lands and caused one fatality (Iribarren Anacona et al., 2015).

The Manflas GLOF is one of the few known GLOFs that originated from a high-altitude cold-based glacier worldwide. Furthermore, the affected valley has been developed since 1985, increasing the number of people and agricultural land exposed to future GLOFs. This makes it necessary to better understand the Manflas GLOF, and more broadly, the hazard associated with cold-based mountain glaciers. We expand the work developed by Peña and Escobar (1987) and, in the light of new research, hypothesise about the causes and mechanisms of the ice-dam formation and failure. We also reconstruct the GLOF dynamics and describe the geomorphic impacts of the GLOF. Finally, we investigate the utility of empirical and physical debris flow models in GLOF modelling and analyse the hazard posed by the glacier in its present state to the Manflas Valley.

5.3 Geographical setting

The Manflas Basin is located in the northern Andes of Chile, close to the Atacama Desert, in a region characterised by extreme arid conditions (Figure 4.1). In spite of its high altitude (catchment heads above 5000 m.a.s.l), glaciers are scarce and small (<5 km^2) in the arid Andes as a consequence of low precipitation (<400 mm/year) and high amounts of incoming shortwave radiation (Ginot et al., 2006; Nicholson et al., 2010). The 1985 GLOF originated from the Río Seco de los Tronquitos Glacier which is located at 5200 m.a.s.l.,and has an area of 1.16 km^2. High altitude glaciers in the Dry Andes are mostly cold-based, have low displacement rates (Ginot et al., 2006; Rabatel et al 2011) and range in thickness from few dozen to more than 100 metres (Rabatel et al., 2011). Glaciers in the region have shown a generalised down-wasting trend (Nicholson et al., 2009) and this tendency accelerated in late Twentieth century possibly due to precipitation decrease (Rabatel et al., 2011), although no systematic attempt has been made to attribute these glacier changes to different components of the climate forcing.

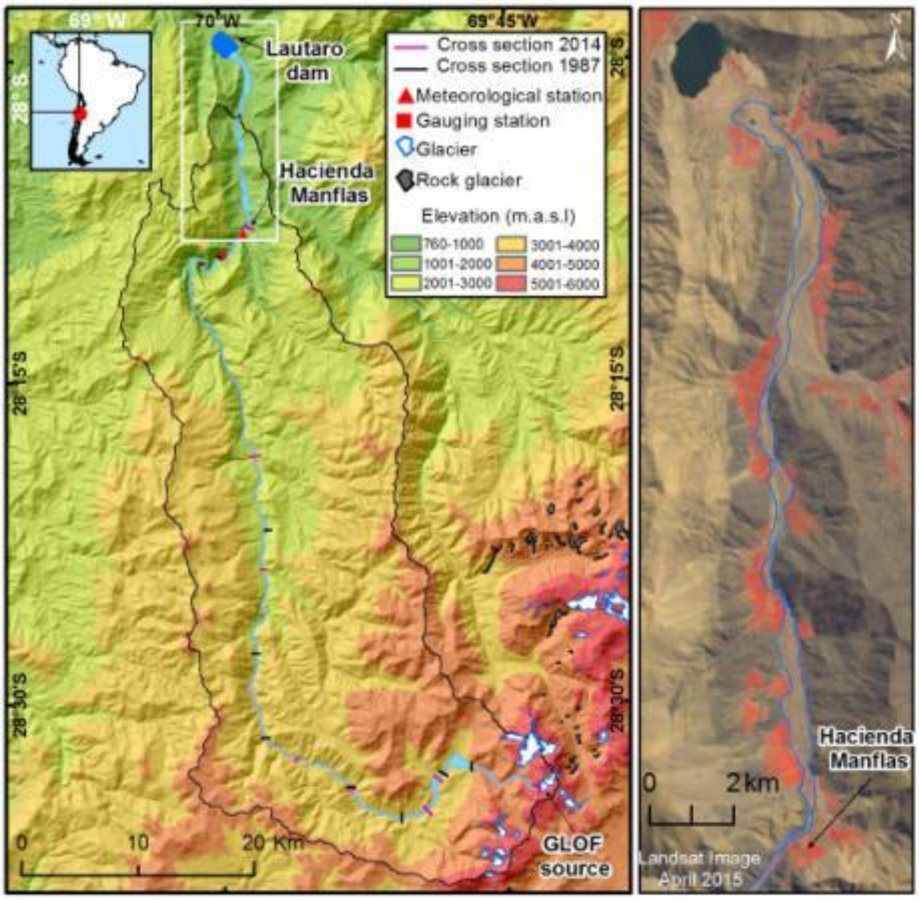

Figure 5.1 Manflas Valley and location of surveyed cross sections. The figure to the right shows grape plantation (red) in areas flooded by the 1985 GLOF.

The scarce precipitation in the Dry Andes results in rivers with low discharges. The discharge of the Manflas River is commonly less than 1m^3/s although values more than 6 m^3/s have been recorded and tehre is additional discharge in groundwater flow. These discharges are small, considering that the gauging station represents an area of 1180 km^2. Peak flows occur in summer, associated with snow melting, however, occasional winter rainstorms can also raise the river level. In small glaciated catchment heads, glacier melting also plays an important hydrological role (source of more than 20% of the discharge) (Gascoin et al 2011). The Manflas Valley is flanked by coluvial and fluvial deposits although bedrock gorges also are present in its middle and lower reaches. The valley hosts large wetlands in its upper reaches and is covered by coarse sediments along its extension. The valley floor and slopes, in areas with altitudes <1500 m.a.s.l, are occupied by grape plantations and associated infrastructure. The main settlement in the Manflas Valley, upstream Lautaro Dam, is Hacienda Manflas. It has about 150 permanent residents; however, this number increases by a factor of three in the grape harvesting season (December to March).

5.4 Methods

5.4.1 Subglacial lake formation and ice-dam failure mechanism

Data about the Río Seco de los Tronquitos Glacier and its surroundings, predating the 1985 GLOF, are scarce, or from indirect sources (e.g. meteorological data). Thus, we can only hypothesise about the factors that contributed to the subglacial lake formation and the ice-dam failure mechanism. We analysed aerial photographs and topographic data to identify features that could have favoured the lake formation (e.g. crevasses or a flat glacier surface). The glacier subglacial topography also was inferred. We used an assumed glacier basal shear (Paterson, 1994) to estimate the glacier thickness (*H*) and derive the subglacial topography:

$$H = t/p*g\sin\alpha$$

where *t* is the basal shear stress (assumed here as $1x10^5$ Pa), *p* is the ice density (917 kg m^{-3}), g is the acceleration due to gravity (9.81 m s^{-2}) and *α* is the glacier slope. The formulation assumes that the glacier is flowing by plastic deformation and that the ice movement is primarily horizontal, a reasonable assumption for a cold-based glacier. The thickness estimates were contrasted with visual inspections and topographic surveys carried out on the glacier by Peña and Escobar (1987) two years after the GLOF, showing a good agreement.

Meteorological data were also analysed since they can provide clues about potential GLOF triggering factors (e.g. heat peaks and increasing ice/snow melting), the lake-water source and the time needed to accumulate the water into the lake. Temperature data were extrapolated from the Lautaro station (27° 58'-70° 00'; 1110 m.a.s.l) to analyse the temperature on the glacier (28°33'-69°42'; 5200 m.a.s.l) prior to the GLOF. We assumed a temperature lapse rate of 0.6 °C/100m. The precipitation was extrapolated from the Hacienda Manflas station (28º 08'-69º 58';1410 m.a.s.l) based on a comparison with the Hijmans et al (2005) data, which indicates precipitation to be ~5 times larger on the glacier than on the Hacienda

Manflas. For the calculation of extreme values and return periods, the 30-year climatological reference period of 1981-2010 was used.

There is no volcanic activity close to the glacier (see Stern et al 2007). However, according to local inhabitants, warm water springs (likely fault related) occur at ~3000 m.a.s.l in the Manflas Valley, potentially suggestive of geothermal heat fluxes in the upper catchment, which may have conditioned the GLOF. We visually inspected thermal bands of satellite images to identify sources of geothermal heat near the glacier (see e.g. Pieri and Abrams 2005). A Landsat TM image (day time; 120 m of spatial resolution) from a date close to the outburst flood was analysed as well as two nocturnal images from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER; 90 metres of spatial resolution). Only ASTER images from summer and captured before 2008 were analysed to avoid areas covered by snow and because the ASTER scanner has been defective since April 2008 (ASTER Science office, 2009). Thermal infrared bands of Landsat images in Digital Numbers were first converted to radiance and then to brightness-temperature following standard procedures (see Sobrino et al., 2004). The Surface Kinetic Temperature product of ASTER (see Gillespie et al., 1998) was used to obtain the night time surface temperature of the glacier and its surroundings.

5.4.2 Mapping of GLOF path and geomorphic impact

We mapped the GLOF path using a Landsat TM image taken three days after the GLOF. The GLOF imprint was clearly visible since vegetation patches were covered by mud and the GLOF path appeared as a wet-brown area along the valley. Aerial photographs predating the GLOF aided to clearly distinguish the forms shaped by the 1985 flood from past (although minor) flood features. The mapping was complemented by field surveys carried out in March 1987 (Peña and Escobar 1987) and December 2013 where flow depth, velocity and discharge were estimated. We also described the deposits' stratigraphy (sediment size, sorting and texture) in sections exposed by flood erosion along the flow path.

The 1985 GLOF was larger than any historical flood in the Manflas valley, and it caused remarkable impacts on the landscape, especially in the riparian vegetation. We quantified the changes produced by the GLOF in the vegetation coverage along the GLOF path. We mapped the vegetation prior and after the GLOF using the Normalized Difference Vegetation Index (NDVI), which is a good indicator of the vegetation coverage and health (Carlson and Ripley 1997). We used Landsat TM and ETM+ images for this purpose. Images were converted from digital numbers to radiance, corrected atmospherically using the dark object subtraction method (Chavez 1988), and converted to reflectance values before the NDVI calculation. The pre-GLOF image (March 1985) was compared to a March 2003 image since both dates follow over-average annual precipitation and thus vegetation status was preceded by similar meteorological conditions.

5.4.3 GLOF dynamics and modelling

Several physical and empirical models have been used to reconstruct GLOF dynamics (e.g. Wetsoby et al., 2014). Here we use one physical and two empirical models to reconstruct the Manflas GLOF path, velocity and depth and assess qualitatively their usefulness in GLOF hazard analysis. These models provide potential constraints on the size of the event, its bounding parameters, and the possibility to model impact of future events. Digital Elevation Models (DEMs) used to simulate the GLOF were hydrologically corrected (see Tarboton et al., 1991) to prevent spurious pixels affecting the flood progression.

5.4.3.1 GLOF Modelling with RAMMS

The Manflas GLOF was simulated using the numerical simulation model RAMMS (Rapid Mass Movement Simulation; Christen et al., 2010) version 1.6.The model results were constrained with data of flood velocity inferred from measurements made in the field two years after the GLOF by Peña and Escobar (1987) and estimates of flood depth from geomorphological features mapped in 2013. RAMMS employs a finite-volume scheme to solve the 2-D shallow water equations and describes a debris flow as a hydraulic-based depth-average continuum model (Hussin et al., 2012). RAMMS uses a Voellmy rheological approach to simulate debris flows where the basal resistance to the flow is accounted by a dry-Coulomb friction coefficient (μ) and a velocity dependent turbulent coefficient (ξ) (Bartelt et al 1999). The model equations and model applications can be found in Bartelt et al., (1999) and Hussin et al., (2012).

To set up a simulation of a debris flow in RAMMS the model grid size, friction parameters, flow density as well as an input hydrograph or a release block must be defined. Trials were performed using a model grid size of 90 m using the SRTMv4 Digital Elevation Model and 30 m which is the ASTER_GDEM2 DEM resolution. Typically, flows modelled with RAMMS using coarse DEMs (grids >= 30 m) have tended to underestimate flow run outs due to DEM artefacts (Buhler et al., 2011). We simulated the Manflas GLOF using the SRTM DEM and simulations failed to reach Lautaro Dam even using low (0.001) μ values (and a stopping criteria of 10% of the total mass momentum), which is one of the main controlling factors of the flow run out (Barbolini et al., 2000). Thus the ASTER_GDEM2 DEM was preferred for modelling the Manflas GLOF.

The friction parameter ξ was set as 500 m/s^2 which is a common turbulent coefficient for debris flows (Hussin et al., 2012; Quan Luna et al., 2014). We run simulations changing μ until the flow reached Lautaro Dam. Only simulations with values of $\mu <= 0.001$ had the run out of the 1985 GLOF and thus we used this value in the GLOF reconstruction. The same set of friction parameters were used in the entire model domain. The density of the flow was set to 2000 kg/m^3, which is an average value between typical solid grain and fluid grain properties of debris flows (see Iverson 1997). Finally, we used as a model input a hypothetical breach triangular hydrograph with a volume of $5x10^6 m^3$ and a peak discharge of 11000 m^3/s following Peña and Escobar (1987). Each simulation was completed in ~20 hours in an Intel Core i5-4570, 8 GB RAM computer.

5.4.3.2 GLOF Modelling with LAHARZ

LAHARZ is a widely-used model designed to predict lahar inundation zones based on the empirical relationship between lahars' volume, cross sectional and planimetric areas (Iverson et al., 1998; Shilling 1998). LAHARZ was originally written in Arcinfo Macro Language (AML) and calibrated with data from 27 lahars ranging in volume from 10 m^3 up to $4x10^9$ m^3 (Iverson et al., 1998). The model has been used to predict pyroclastic flows and surges (Widiwijayanti et al., 2009), non-volcanic debris flows (e.g. Oramas Dorta et al., 2007; Magirl et al., 2010) and rock avalanches (Griswold and Iverson 2008) by modifying the model governing equations. Iverson et al., (1998) derived the following equations that relate the volume (V), maximum cross-sectional area (A) and total planimetric area (B) of lahars:

Equation 2: $A = 0.05V^{2/3}$

Equation 3: $B= 200V^{2/3}$

The Manflas GLOF was a highly sediment-charged flow with an estimated volume of $5x10^6 m^3$ at Lautaro Dam (Peña and Escobar 1987). Thus, GLOF characteristics resemble that of the lahars used to calibrate LAHARZ. We modelled the Manflas GLOF using the default parameters of LAHARZ, however, the flow run-out was largely underestimated (only ~25% of the GLOF path was flooded). Accordingly, we modified the constant (0.05) of equation 2 using data of the GLOF cross-sectional area (Peña and Escobar 1987). The average cross-sectional area of the Manflas GLOF was 466 m^2 and thus we changed the 0.05 constant to 0.01. As we lacked field data to calibrate equation 3, the constant (200) in equation 3 was iteratively modified until the GLOF reached the Lautaro Dam. As LAHARZ calculates the cross-sectional area in which a specified lahar volume accommodates, it is possible to derive the flow depth in each DEM pixel. We used the Castruccio and Clavero (2015) AML code to retrieve the flow depth in LAHARZ simulations.

5.4.3.3 GLOF Modelling with MSF

The Modified Single Flow Direction Model or MSF (Huggel et al., 2003) was conceived to describe the movement of a debris flow or other mass movement downslope, following the steepest descent path with a maximum deviation of 45° degrees. It has the advantage that it can be easily implemented in GIS platforms using standard tools (see Gruber et al., 2008) and has proved to adequately delineate mass movement paths. The run out of the mass movement is determined by an empirical friction angle or Heim coefficient (Hsu 1975) which in case of debris flows is generally set as 0.19 (ratio between the height and distance travelled by the mass movement). We set the friction angle to 0.04 for allowing the GLOF reaching the Lautaro Dam. This low friction angle probably reflects the transition of the debris flow to a less dense flow capable of covering a larger distance.

5.5 Results and discussion

5.5.1 Subglacial lake formation

5.5.1.1 Conditioning factors

We analysed aerial imagery and topographic data predating the 1985 GLOF to identify factors that contributed to the lake formation. Our analysis shows that the geometry of the basin and the glacier favored the lake development. The basin's drainage converged towards the place where the lake formed, thus encouraging water accumulation. Furthermore, the glacier basin had a steep-slope (≥20°) upstream, and downstream from the more gentle surface (≥5° and ≤10°) where the lake developed. The inferred subglacial topography shows this gentle area has a local overdeepening which favoured water accumulation. Although, no crevasses were evident in 1984 aerial photographs (CH 60 Flight; Photo: 023199 at scale 1:60.000), the high tensile stress (inferred from the glacier steep-slope) upstream of the lake probably induced crevasse formation that helped meltwater routing from the surface to the bed (Figure 5.2). Our findings coincide with studies (Frey et al., 2010; Linsbauer et al., 2012) that show a relationship between flat glacier surfaces, adjacent steepening of topography, local overdeepenings and the formation of glacial lakes.

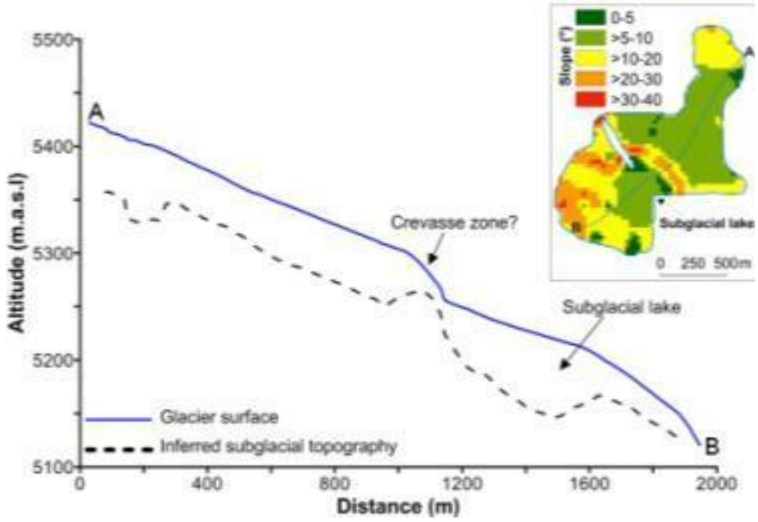

Figure 5.2 Topographic profile and inferred bedrock topography of the Río Seco de los Tronquitos Glacier. The subglacial lake developed in a relatively flat area downstream a break in slope. Topographic data from the IGM 1:50.000 map of 1955.

5.5.1.2 Water origin and routing

The lake water could have had two origins; ice melting induced by geothermal influence at the glacier base or infiltration of water from snow/ice melting at the surface (ice melting by frictional sliding was not considered since the glacier base is most likely below the melting point; Figure 5.3a). To test the first hyphothesis, we analysed bibliography and satellite imagery. There is no volcanic activity close to the glacier (Stern et al., 2007) and nocturnal satellite imagery shows negative temperatures on the glacier and its surroundings (Figure 5.4). Although we lack direct temperature data at the glacier bed, sources of geothermal heat under the glacier are unlikely (geothermal areas in valleys are often associated with faults and are not located in valley heads) and no indications were found during the 1987 field work. It is much more likely that the subglacial lake formed by meltwater infiltration.

Different processes can explain the routing of supraglacial meltwater to the base of cold glaciers. Vincent et al., (2010a) suggest that supraglacial lakes, formed in years with negative glacier mass balance, can evolve into subglacial lakes if several years of positive glacier mass-balance occur covering the lake with thick snow layers. Glaciers in the arid Andes have waxed and waned since the 1950s (Nicholson et al., 2009) and cartography from the 1950s at scale 1:50.000 do not depict a supraglacial lake. Furthermore, aerial imagery from 1984 and satellite images from 1985 do not show a supraglacial lake. We thus suspect that the model of lake formation offered by Vincent et al., (2010) does not fit with evidence from the Río Seco de Los Tronquitos glacier.

Gulley et al., (2009) suggest that supraglacial conduits can develop into englacial conduits and reach the base of cold glaciers by the cut and closure mechanism. This is the erosion of a supraglacial channel by viscous dissipation, the closure of the channel by drift snow, ice-blocks or ice creep, and the vadose incision of the channel to the glacier hydrological base level. One of the premises of the cut and closure mechanism is that the ablation rate must be lower than the rate of channel incision (Gulley et al., 2009). Thus, large drainage areas and steep surfaces are required to sustain this process. The drainage area of the failed subglacial lake at Río Seco de Los Tronquitos glacier is small (2.67 km^2), hence high discharges upstream the subglacial lake are unlikely. Thus, the routing of supraglacial water to the base of the glacier is unlikely to reflect the cutting and closure mechanism.

Water can also infiltrate to the bottom of cold glaciers through crevasses. Although crevasses are relatively uncommon in cold-based glaciers, they exist in favourable topographic conditions, such as steep slopes near ice divides (Campbell et al., 2013). Because the low rate of deformation of cold-based glaciers, crevasses can remain open for years allowing water channelization. Scambos et al., (2000) show that crevasses can propagate to the glacier base by hydro-fracturing if they are water filled. In cold-based glaciers, this mechanism is more efficient if the ice has previously been warmed by refreezing events, and latent heat release (Boon and

Sharp, 2003). Thus crevasses could have helped to route meltwater to the glacier base since the steep glacier-slope upstream of the lake could have had fractures that evolved into englacial conduits. Glacial conduits were observed on the upper part of ice-walls surrounding the glacial lake corroborating that water infiltration helped to fill the lake (Figure 5.5). However, lateral water influxes may also have contributed to form the lake as water was seen flowing on slope-glacier margins. As part of the lake was in contact with an unglaciated wall to the east, drainage through this slope could have warmed up water promoting the formation of glacial conduits.

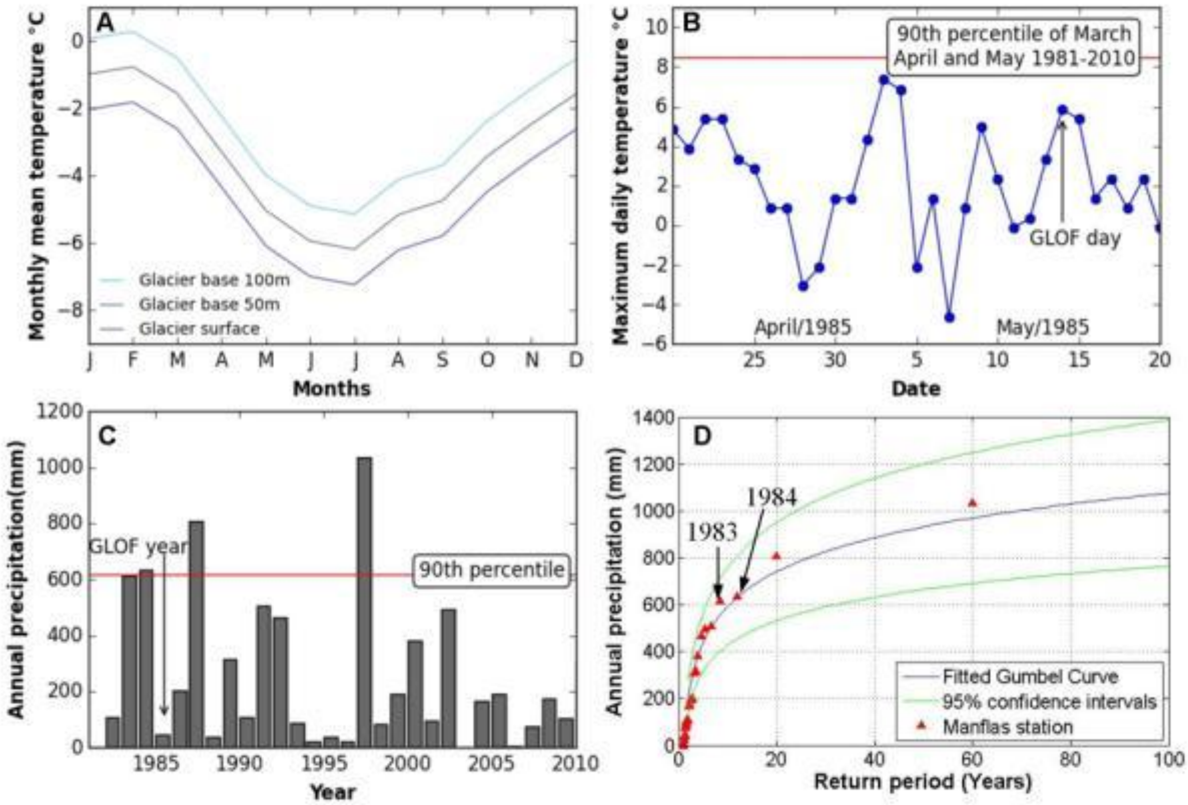

Figure 5.3 A) Estimated temperature at the Río Seco de los Tronquitos Glacier surface (5200 m.a.s.l) and base. Temperature at the glacier base (assuming maximum thickness of 50 and 100 metres) is most the year below the melting point. B) Maximum daily temperatures were above 0 °C at the glacier surface days before the GLOF although these were not extreme events. C-D) No precipitation was registered days prior to the 1985 GLOF. However, 1983 and 1984 were exceptionally rainy years with return periods between 8 and 12 years.

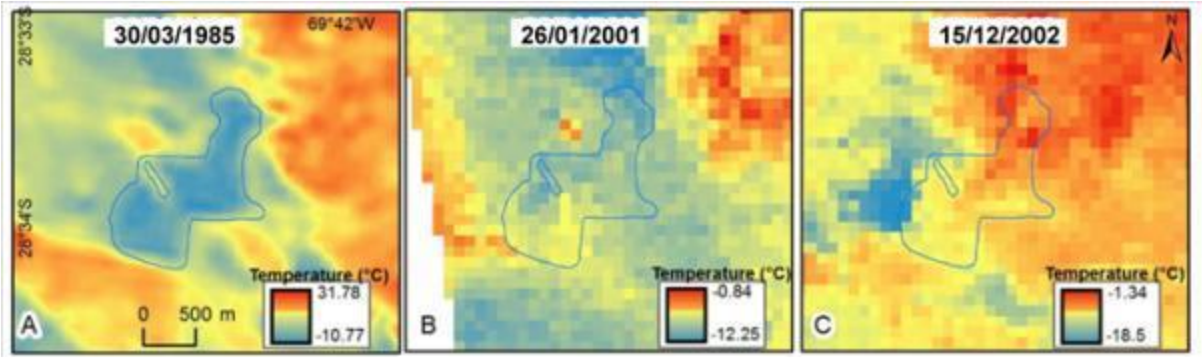

Figure 5.4 Temperature of the Río Seco de Los Tronquitos Glacier and its surroundings. No hot-spots are visible in the day time Landsat TM image (A). Temperature patterns in (A) are explained by slope orientation and the presence of ice. In the night time Aster images (B and C) no clear temperature patterns are visible. However, the 2001 image (B) shows a 'hot spot' north of the glacier with temperatures 4°C larger than the background, which can be explained by the presence of a small pond visible in Google Earth Images.

5.5.1.3 Time to lake formation

The average annual precipitation in the period 1981-2010 at Manflas Station was 48.8 mm and precipitation at the glacier basin is 5 times larger according to Hijmans et al., (2003) dataset. However, sublimation on glaciers is more important than melting by a factor of 4.3 in the arid Andes (see table 3 in MacDonell et al., 2013) and thus a small percentage of annual precipitation is transformed to liquid water and could have infiltrated to form the lake. Considering the data above, the time required to accumulate $4x10^6 m^3$ of water in the glacier basin (2.67 km^2) is ~32 years. This period extends to ~66 years if precipitation is extrapolated based on Tropical Rainfall Measuring Mission (TRMM) data (period 1998-2009; Bookhagen in review), which indicates that precipitation at the glacier basin is only 2.43 times larger than precipitation at the Manflas station. TRMM data usually underestimates precipitation (see e.g. Javanmard et al., 2010) and thus this should be considered a minimum value. Thus, although the data we used are extrapolated and hence somewhat uncertain, our results suggest that the lake required several decades to form due to low precipitation and high sublimation rates in the arid Andes. However, extreme annual precipitation (above the 90^{th} percentile) before the GLOF (Figure 5.3) contributed to fill the lake until the ice-dam reached an unstable state.

5.5.2 Ice-dam failure mechanism

The high discharge (11000 m^3/s) estimated at the base of the glacier by Peña and Escobar (1987), suggest an abrupt failure of the subglacial lake. The rapid opening of subglacial conduits by thermal erosion seems unlikely since floods require a high amount of energy to melt cold-ice (the ice has to be warmed to the melting point) and form efficient drainage systems in cold glaciers. The ice-dam mechanical collapse, as a consequence of the high hydrostatic pressure exerted by the lake, is a more likely mechanism to explain the ice-dam failure. The probable presence of ice/snow masses in the flood deposit (inferred from a post GLOF Landsat Image) attest for ice breaking during the flood. We compared the estimated peak discharge near the glacier front with discharges obtained from empirical formulae and the results also support the hypothesis of an abrupt dam failure (Table 5-1) as suggested by Peña and Escobar (1987).

The empirical formula, however, underestimates the peak discharge by one order of magnitude. Two mechanisms may help explain this high peak discharge. The collapse of the lake roof during the GLOF could have increased the energy of the draining process by creating impulse waves in a confined space (Figure 5.5). Ice-blocks may also have blocked the drainage path which then released the dammed water in a catastrophic way, as described by Ballantyne and McCann (1980).

Table 5-1 Peak discharge at the glacier base estimated using empirical formula. All the approaches underestimate the Manflas peak discharge (11000 m^3/s). V = lake volume in $m^3 x10^6$; Tw = empirical time constant ranging from 0.001 to 0.002 s.

Formula	Peak discharge (m^3/s)	Failure mechanism	Reference
$75\ V^{0.67}$	~220	Ice-tunnel flood	Clague and Matthews (1973)
$46V^{0.66}$	~130	Ice-tunnel flood	Walder and Costa (1996)
V/Tw	2500-5000	Non-tunnel flood	Haeberli (1983)
$1100V^{0.44}$	~2200	Non-tunnel flood	Walder and Costa (1996)

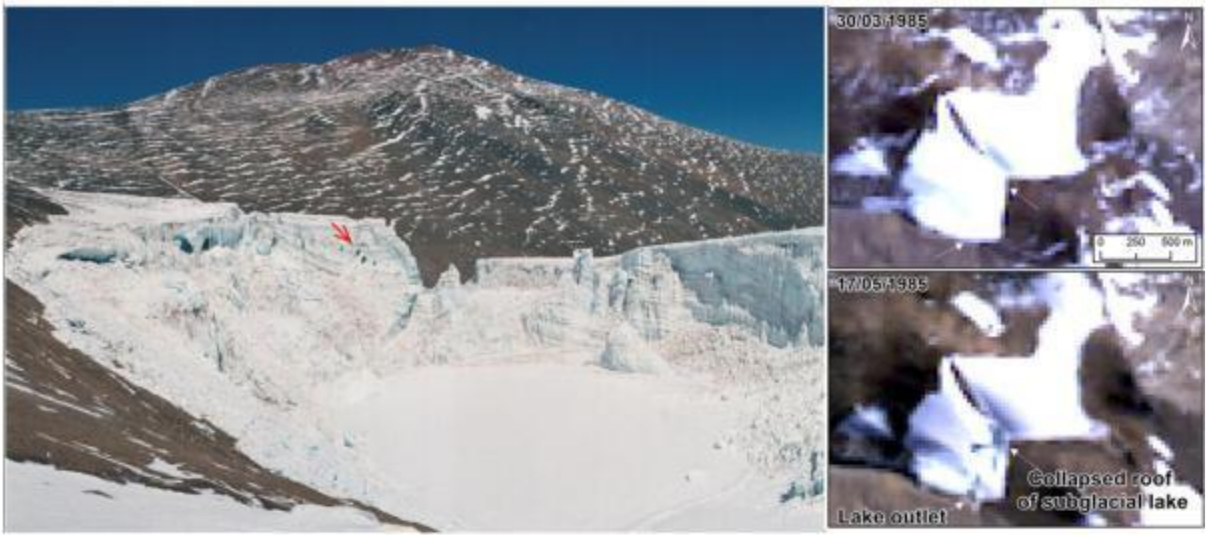

Figure 5.5 Ice-amphitheatre and the remainder of the subglacial lake in 1987.The amphitheatre formed as the roof of the subglacial lake collapsed leaving ~70 m high walls. Landsat images (to the right) show that the roof failed during or a short time after (maximum 3 days) the GLOF. The red arrow show ice conduits. Left photograph by Fernando Escobar.

The GLOF occurred on the 14th of May and according to eyewitnesses reached Hacienda Manflas (located ~95 km from the lake) at midnight. Assuming an average flow velocity of 7 m/s (see Peña and Escobar 1987) it can be estimated that the ice-dam collapsed in the early evening (about 8 PM). Thus, glacier and snow melting during the day could have increased the water pressure over the ice-dam triggering the failure. The dam collapse could have been aided by the sealing of englacial or subglacial conduits in the middle of autumn.

5.5.3 GLOF path and geomorphic impact

The Manflas GLOF travelled ~110 km from the Rio Seco de los Tronquitos Glacier (5200 m.a.s.l) to the Lautaro Dam (1110 m.a.s.l), on an average slope of 2°. The path-slope, however, was ≥20° in upper reaches and bedrock gorges, and decreased downstream. The high-energy flow surged several metres over hill-slopes in perpendicular river bends, covering slopes with a ~50 cm thick sheet of fine sediments, pebbles and boulders. Backwater flooding also occurred in the upper reaches as is attested by sheets of fine sediments in the upstream Manflas tributaries.

The flow had a remarkable transport capacity since rocks up to ~3 metres in diameter were mobilised even in lower reaches more than 40 km from the flood origin. Flood deposits suggest that the Manflas GLOF rheology varied in short distances and temporally as the sediment availability and channel hydraulics changed (Figure 5.6). Massive diamictons of matrix supported boulders and pebbles attest for rapid deposition rates in a high-energy environment (Rushmer 2006) and similar facies have been attributed to debris flows (Costa 1988). Clast-supported boulder bars, with imbricated clasts, also indicate deposition in a turbulent fluidal flow (i.e. Newtonian or clear water flow; Figure 5.6) (Fay 2002; Carling 2013).

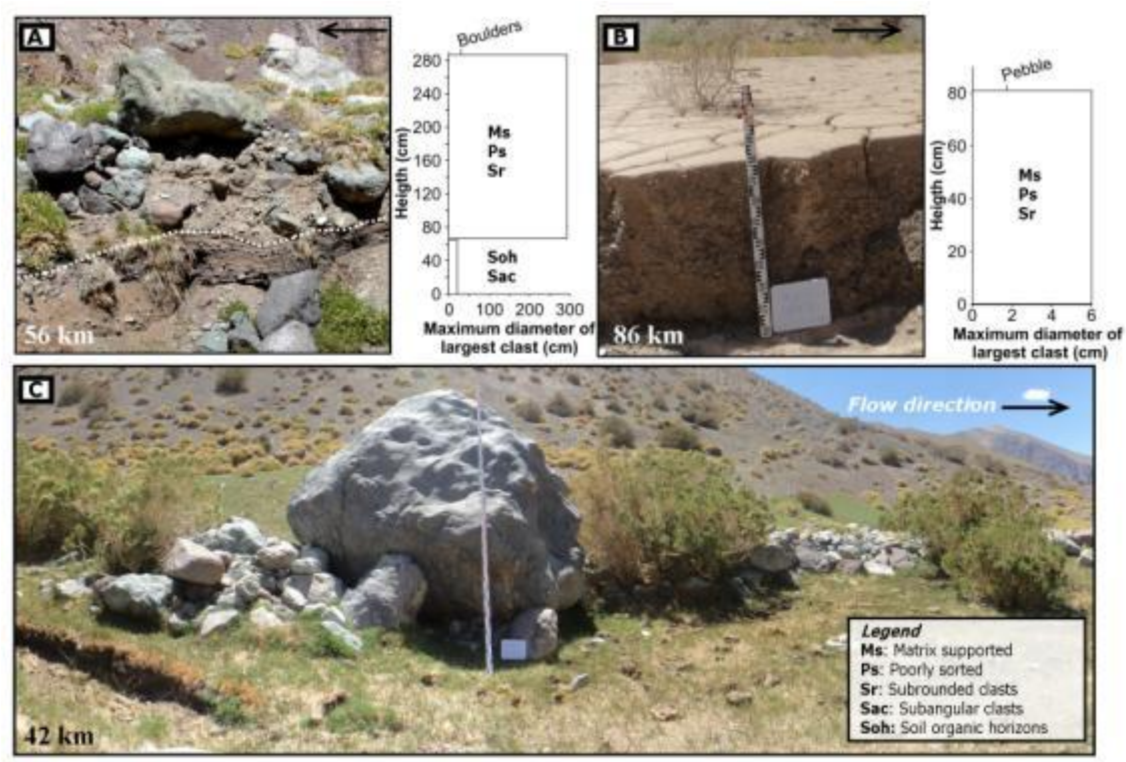

Figure 5.6 Deposits and forms created by the Manflas GLOF. The flow changed spatially and temporarily from a debris flow (a) carrying blocks up to 3 m in diameter, to a clayey hyper-concentrated flow (b). Flood bars (c) with imbricated boulders also indicate the occurrence of a high-energy Newtonian flow phase. Numbers on the left bottom corner of the photographs indicate the distance downstream from the glacier.

The occurrence of a high-energy sediment-laden flow is also confirmed by eyewitness accounts. One of the eyewitness of the Manflas GLOF was interviewed in 2013 and recalled "*what alerted us about the flood was a tremor*…*things started to shake over the table*…*we thought it was an earthquake*…*but then, by the mud smell, we realised that it was a flood*". The roar produced by the flow was confirmed by press reports (Diario Atacama 1985). The tremor described is comparable with an earthquake with a Mercalli intensity of IV (light) to V (moderate). Ground vibrations are commonly produced by debris flows due to the collision and friction between rocks and the channel bed (Huang et al., 2007). The eyewitness, whose home was 400 m to the east of the GLOF path, also recalled that the flow reached Hacienda Manflas at midnight and lasted for about 2 hours, although the receding limb lasted 24 hours according to Peña and Escobar (1987); Figure 5.7.

Figure 5.7 Receding stage of Manflas GLOF seen from Hacienda Manflas on the morning of the 15th of May 1985. Note the sediment-charged and turbulent flow and the flow traces to the left of the image. A partially destroyed building (left) illustrates the high-flow intensity. Photo by Juan D'Etigny.

The GLOF incorporated shrubs within the moving mass and ~4.8 km^2 of vegetated areas were covered with sediments or damaged. The damage to vegetation is still evident in the arid Manflas Valley since the amount of biomass, especially on the upper reaches (≥2500 m.a.s.l), decreased after the GLOF (Figure 5.8). Wetlands in the upper reaches were covered by GLOF deposits accounting for most of the vegetation decrease.

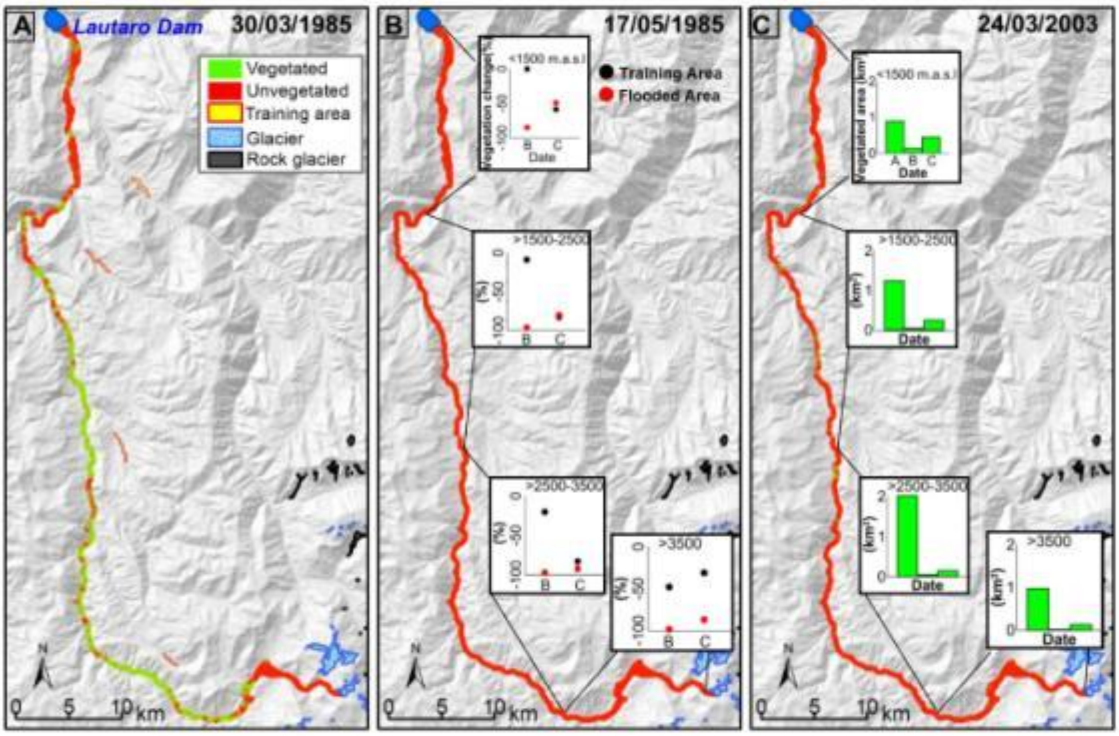

Figure 5.8 Panels A – C illustrate the damage to vegetation along the Manflas GLOF path, based on mapping using the Normalized Difference Vegetation Index with a threshold value of ≥ 0.2 to distinguish vegetated areas. The GLOF path width is exaggerated for representation purposes. Plots in Panel B give the percentage change in vegetation between May 1985 and March 2003 relative to conditions before the GLOF (March 1985). Plots in Panel C give the total vegetation coverage (in km^2) for all three dates. Most vegetation was lost in the upper reaches (>2500 m.a.s.l), where wetlands were covered by sediments. It is noted that vegetation coverage also diminished outside the GLOF path (i.e. training areas in B) although to a minor extent.

Images predating the 1985 GLOF show a debris accumulation similar to the one formed by the 1985 GLOF in the upper section of the Manflas Valley.These deposits extended up to 10km downstream the Río Seco de los Tronquitos Glacier. Furthermore, in 1987 old flow traces, containing vegetation debris, were observed in river bends, above the fresh-flow marks of the 1985 GLOF. This evidence suggest that a large flood, probably a GLOF, affected the Manflas Valley before 1985. However, there are no historic records of this event.

5.5.4 GLOF dynamics and modelling

Peña and Escobar (1987) surveyed eight cross sections along the Manflas GLOF path to estimate flow data using indirect methods as the Manflas gauging station was destroyed by the GLOF (Diario Atacama 1985).The GLOF peak discharge and velocity were estimated using the slope-area method and the Manning formula respectively.

The maximum peak discharge occurred at the glacier terminus and was estimated at 11000 m^3/s (assuming that a critical height occurred in the transition from the glacier to the river channel), whereas this value decreased to 1100 m^3/s at Hacienda Manflas, 90 km downstream (Peña and Escobar 1987). The GLOF velocity was higher in the upper reaches with values up to 12 m/s, however velocity decreased to 4 m/s at Hacienda Manflas (Peña and Escobar 1987). This value (~4 m/s) was coincident with velocities estimated comparing flood arrival times at Salto del Toro and Hacienda Manflas (Peña and Escobar 1987). The flow depth varied from more than 7 metres in constricted reaches to about 2 metres in lower valley sections.

5.5.4.1 GLOF path geometry

The geometry of the Manflas GLOF path is complex since phenomena such as slope surges and backwater flooding occurred as the GLOF traversed valley constrictions and confluences. The overall flow geometry was well represented in the MSF, LAHARZ and RAMMS simulations (Figure 5.9). However, the total flooded area, as well as the area correctly delimited (i.e. areas flooded by the 1985 GLOF and flooded in the simulation) differ markedly between models (Table 5-2).

RAMMS correctly reproduced phenomena such as slope surges (overbank flow) and backwater flooding which were not represented in LAHARZ simulations. However, RAMMS largely overestimated the flooded area and an unrealistic overspill (the flow surged to an adjacent valley) was simulated ~43 km from the glacier. The three models were sensitive to the DEM resolution and a coarser DEM resulted in larger flooded areas in MSF and LAHARZ simulations. A coarser DEM, however, caused the debris flow simulated by RAMMS to starve and stop before reaching Lautaro Dam.

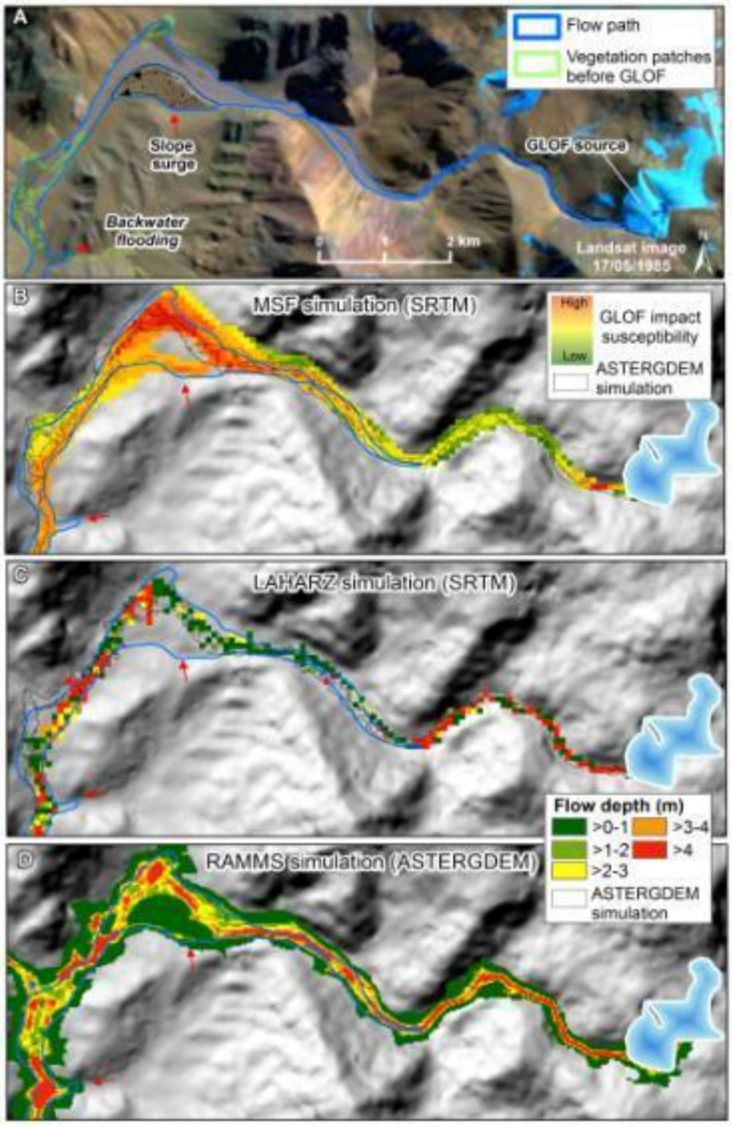

Figure 5.9 GLOF modelling using MSF, LAHARZ and RAMMS and different DEMs. The MSF results match with the GLOF path including overbank flow (SRTM simulation). However, MSF and LAHARZ can not recreate flow features such as backwater flooding. RAMMS although overestimated the flooded area, correctly simulated slope surges and backwater flooding. The LAHARZ and RAMMS simulation were ran assuming a GLOF volume of $5x10^6 m^3$.

Our results are in agreement with previous back analyses and modelling of small debris flows with RAMMS which have found large overestimations of flooded areas (> 1000%; Cesca and D'Agostino 2008). Similar studies also reported local discrepancies between the simulated flow geometry and mapped (observed) debris flows (Hussin et al., 2012) stressing the difficulties in calibrating models and simulating sediment-charged flows. Divergent imprints of flooded areas simulated with different DEMs also were reported by Huggel et al., (2008) using LAHARZ and MSF. The authors highlighted that a finer DEM resolution did not necessarily add precision to the model results, which is corroborated in this study. In our case, this could be due to the noisy nature of ASTER GDEM (Slater et al., 2011).

Table 5-2 Comparison between flooded area interpreted in Landsat TM image and model simulations. Percentages in the first three columns indicates the deviation of simulations from the areas intepreted in the landsat image. Percentages in the fourth column indicates the matching between simulated and flooded areas.

Flow model and DEM	Total flooded Area km^2	False positive km^2	False negative km^2	Correctly classified km^2
MSF ASTER_GDEM 2	9.28 (-36%)	2.66 (28%)	7.94 (85%)	6.61 (45%)
MSF SRTM	20.7 (42%)	10.83 (52%)	4.69 (22%)	9.86 (67%)
LAHARZ ASTER_GDEM 2	13.5 (7%)	4.38 (32%)	5.44 (40%)	9.11 (68%)
LAHARZ SRTM	17.48 (20%)	7.55 (43%)	4.64(26%)	9.91 (62%)
RAMMS ASTER_GDEM 2	46.14 (217%)	35.54(77%)	0.18(0.3%)	14.37(98%)
Flooded Area interpreted in 1985 Landsat TM image = 14.55 (km^2)				

The channel and flood plain interpreted in Landsat images do not always coincide with the steepest descent path of the DEMs highlighting possible co-registration biases. Thus, co-registration biases, model assumptions (e.g. the GLOF volume remains constant in LAHARZ simulations) and DEMs artifacts may explain the deviation between observed and simulated GLOF paths. The deviations of MSF and LAHARZ, however, should be understood within the framework of the model objectives since they where designed to provide preliminary hazard assessments when time or resources for site-specific analyses are unavailable, and not to provide definitive hazard-zone boundaries (Iverson et al., 1998; Huggel et al., 2003; Wilcock et al., 2003). RAMMS deviations may have been reduced by using a DEM with a smaller spatial resolution, through a detailed sensitivity analysis (see e.g. Hussin et al., 2012), or incorporating friction parameters or density data measured in the field. However this is out of the scope of this study.

5.5.4.2 -Comparison of GLOF field data and model results

Velocity and flow depths estimated in the field were compared with RAMMS and LAHARZ simulations. Flow depths obtained with both models decrease markedly 30 km upstream of Lautaro Dam coinciding with valley widening and a slope decrease (Figure 5.10). The simulated flow patterns match well with flow data that indicates a decrease in both discharge and flow depth downstream. However, simulation results differ from field data (Table 5-3 and 5-4) with RAMMS having a slighter better performance than LAHARZ (RMSE values of 2.38 m and 2.44 m respectively). However, the good performance of the LAHARZ model is remarkable considering that each simulation lasted only a few minutes in comparison with the ~20 hours required for the RAMMS simulations.

Differences in flow depths estimated in the field and RAMMS simulations range from 16% to 128%. Large deviations (32% to 95%) also have been found reconstructing small (e.g. few kilometres of run out) debris flows using medium and high resolution DEMs (Hussin et al., 2012; Cesca and D'Agostino 2008). The deviation of debris flow simulations and the mapped (observed) GLOF can be explained by several factors, among them: erroneous model assumptions, difficulties in setting model parameters and DEMs pitfalls. Future work can test RAMMS performance in simulating large debris flows over long distances using spatially variable friction parameters, different rates of sediment entrainment or using as a GLOF input a block release.

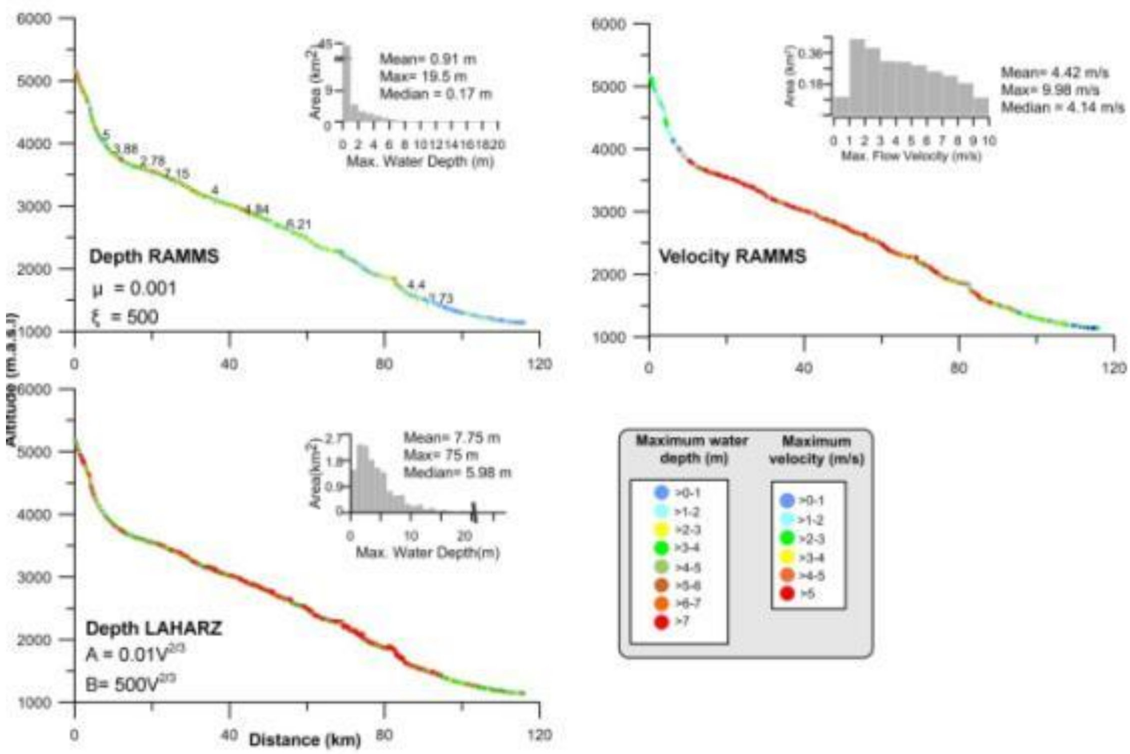

Figure 5.10 Maximum water depth and velocity estimated with LAHARZ and RAMMS assuming a GLOF volume of $5x10^6 m^3/s$. Profiles represent values along the Manflas River channel while histograms show the statistics of the total flooded area. In RAMMS most of the flooded area has depths < 1m.

Table 5-3 In situ estimated flow depths and simulated depths with RAMMS and LAHARZ

Distance from glacier (km)	Estimated depth (m)	RAMMS	LAHARZ
8.4	5	5.8(16%)	9.4(88%)
12.6	3.88	5.15(32%)	3(-22%)
20.3	2.78	6.36(128%)	4.2(52%)
26.6	7.15	5.04(-29%)	4.8(-31%)
36.7	4	2.2(-45%)	3.23(-19%)
45.3	4.84	5.8(19%)	5.25(8%)
58.2	6.21	1.54(-75%)	5.6(-8%)
88.2	4.4	2.71(-38%)	5(15%)
91.1	2.73	1.03(-72%)	7.7(183%)

Table 5-4 Estimated flow velocities and simulated flow velocities with RAMMS

Distance from glacier (km)	Estimated velocity (m/s) (sourced from Peña and Escobar 1987)	Velocity RAMMS (m/s)
0.73	12	2.4(-79%)
13.67	10	7.8(-21%)
17.76	6.2	7.1(15%)
26.36	7.2	5.5(-22%)
32.98	5.3	8.9(68%)
54.43	6.9	6.7(-1.5%)
65.68	7.2	5(-29%)
95.44	4.1	2.1(-47%)

5.5.5 GLOF hazard and management

Aerial photographs from the late 1990s and satellite images from 2008 shows that an ice-dammed lake with a frozen surface again exists on the Río Seco de los Tronquitos Glacier (Figure 5.11). The remanent of the failed glacial lake had a depth of ~20 metres (measured with a weight tied to a rope) in 1987. However, the lake dimensions probably have changed since this date.

The volume of water accumulated on the glacier is likely less than the water drained in the 1985 GLOF since glaciers had thinned in the arid Andes (Rabatel et al., 2011). Thus, the magnitude (in terms of volume) of a hypothetical future GLOF could be lower than the 1985 event. This assumption, however, should be corroborated by geophysical soundings to establish the current lake bathymetry. This task is urgently required since sustained negative glacier mass balance in the region (Nicholson et al., 2010; Rabatel et al.,2011) may weaken the ice-dam increasing the likelihood of a new GLOF.

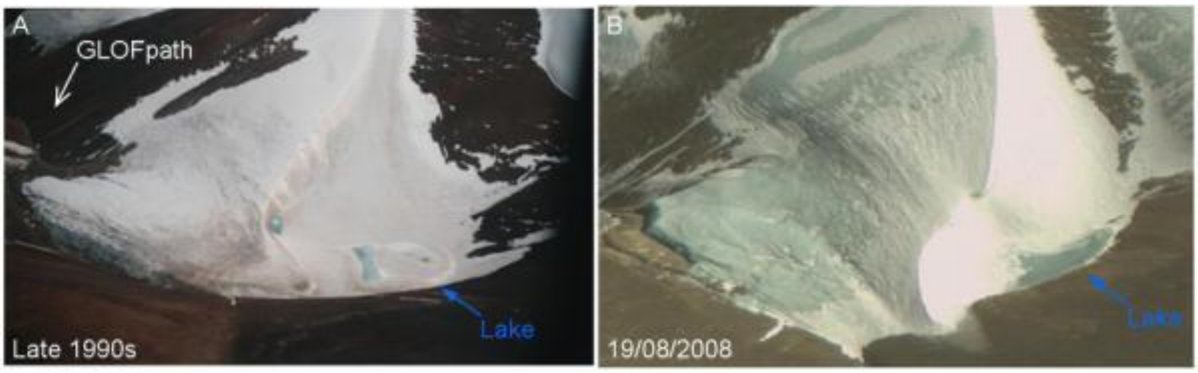

Figure 5.11 Río Seco de los Tronquitos Glacier and ice-dammed lake. A) Photograph by Fernando Escobar and B) satellite image sourced form Google Earth.

Although infrastructure and agricultural land is located more than 100 km from the lake, GLOFs can still endanger these areas as was demonstrated by the 1985 GLOF. Negative consequences from a GLOF, however, can be reduced using several approaches. Due to the long distance between populated areas and the GLOF source, an early warning system (e.g. telemetering geophone or gauging data to decision makers) could be used to alert of a coming flood hours in advance allowing for the evacuation of areas at risk in the Manflas Valley. Even very rapid flows (≥10 m/s) will take at least 2 hours to reach zones located 100 km from the lake. This time could also be used to drain the Lautaro Dam (storage capacity $25x10^6m^3$ according to a 2007 bathymetric survey; drainage capacity 75 m^3/s) if required, to accommodate the GLOF waters. An early warning system requires the formulation of protocols (e.g. when and where to evacuate), a GLOF awareness program, and full engagement of the local community and stakeholders.

Infrastructure along the Manflas Valley can by protected by levees, although such barriers may be onerous since they should be designed to resist the impact pressure of infrequent debris flows or highly sediment-charged flows. Damages due to GLOFs, however, cannot be completely eliminated with structural measures and early warning systems. Only lake drainage can eliminate the GLOF risk. A successful experience of an ice-dammed lake being artificially drained is described in Vincent et al., (2010b) where siphons and explosives were used to drain a lake in the French Alps. The described soft and hard GLOF risk reduction measures should be assessed in the frame of their economic, technical, legal, cultural and ecological feasibility.

5.6 Conclusions

We studied an extraordinary GLOF originating from a small cold-based mountain glacier in the arid Andes of Chile. We assessed the mechanisms that may have caused the ice-dam formation and failure. We then used empirical and physical debris flow models to reconstruct the GLOF dynamics and analysed the hazard posed by the glacier and the ice-dammed lake to the Manflas Valley.

The ice-dammed lake formed in a closed subglacial basin after two years of extreme annual precipitation. The mechanism of how water infiltrated to the glacier bed is unknown. However, we postulate that crevasses could have routed water to the glacier bed aided by hydrofracturing and that geothermal heat was unlikely to have contributed to lake formation. Our analysis support early findings indicating that the ice-dam failed catastrophically, producing a non-tunnelled flow.

The GLOF ($4\text{-}5 \times 10^6 m^3$) travelled > 100 km, producing slope surges and depositing massive diamictons, which attest to the rapid (≥ 4 m/s) and sediment-laden nature of the flow. However, a Newtonian flow phase was also identified, revealing the complex flow dynamics that ensued from changing channel geometry and sediment availability. The GLOF modified the channel geometry but also decreased the vegetation coverage along the Manflas Valley, showing the GLOF's long-term impact in the arid mountain landscape.

Data of GLOF extent, depth and velocity were compared to GLOF simulations with empirical (MSF and LAHARZ) and physical (RAMMS) models. Large discrepancies between simulated and estimated GLOF characteristics were found. Empirical models, although less demanding than physical models in terms of input requirements and computational time, fail in reproducing flow features such as backwater and overbank flooding, and thereby underestimate the flood hazard. However, the parameterization of physical debris flow models is difficult; especially over long distances (dozens of kilometres) due to changes in the channel hydraulics and sediment characteristics.

Our results indicate that data from empirical and physical models should be carefully analysed if they are intended to be used in land use planning and decision making. Debris flow simulations can be affected by a variety of factors including model assumptions (e.g. the rheology of the expected flow) and inputs (e.g. hydrograph shape and friction coefficients) although other problems such as bias in the co-registration of DEMs and images used to draw hazard and risk maps can also by significant. Thus, model uncertainties, their limitations, and the spatial scale at which the model outputs can be used should be clearly communicated to stakeholders.

Satellite images from 2008 show an ice-dammed lake is now present on the east side of the Río Seco de los Tronquitos Glacier. Recent glacier retreat and thinning may have weakened the ice-dam, increasing the likelihood of a new GLOF. Thus, it is urgent to carry out geophysical soundings to measure the lake bathymetry and dam dimensions in order to assess the current outburst flood hazard. Finally, the Manflas GLOF demonstrates that slow-flowing cold-based glaciers can represent a threat to inhabited areas since they can be the source of voluminous, although infrequent, GLOFs.

5.7 References

Andrews JT, Dunhill G (2004) Early to mid-Holocene Atlantic water influx and deglacial meltwater events, Beaufort Sea slope, Arctic Ocean. *Quaternary Research* 61:14-21.

Baker VR (2008) Paleoflood hydrology: origin, progress, prospects. *Geomorphology* 101(1-2):1-13

Ballantyne CK, McCann SB (1980) Short-lived damming of a high-arctic ice-marginal stream, Ellesmere Island, N.W.T., Canada. *Journal of Glaciology* 25:487-491

Barbolini M, Gruber U, Keylock CJ, Naaim M, and Savi F (2000) Application of statistical and hydraulic-continuum dense-snow avalanche models to five real European sites, *Cold Reg. Sci. Technol*., 31:133-149, doi:10.1016/S0165-232X(00)00008-2, 2000.

Bartelt P, Salm B, Gruber U (1999) Calculating dense-snow avalanche runout using a voellmy-fluid model with active/passive longitudinal straining.*Journal of Glaciology* 45 (150): 242-254

Boon S, Sharp M (2003) The role of hydrologically-driven ice fracture in drainage system evolution on an Arctic glacier. *Geophys. Res. Lett*., 30(18) DOI10.1029/2003GL018034

Bookhagen B (in review) High resolution spatiotemporal distribution of rainfall seasonality and extreme events based on a 12-year TRMM time series, in review.

Buhler Y, Christen M, Kowalski J, Bartelt P(2011) Sensitivity ¨of snow avalanche simulations to digital elevation model quality and resolution, *Ann. Glaciol*., (52): 72-80.

Campbell S, Roy S, Kreutz K, Arcone S, Koons P, Osterberg E (2013) Strain Rate Estimates for Crevasse formation at an Alpine Ice Divide: Mount Hunter, Alaska. *Annals of Glaciology*: 54(63):200-208

Carey M (2005) Living and dying with glaciers: people's historical vulnerability to avalanches and outburst floods in Peru. *Global Planet. Change* 47:122-124

Carling, Paul (2013) Freshwater megaflood sedimentation: What can we learn about generic processes?. *Earth-Science Reviews* 125: 87-113

Carlson TN, Ripley DA (1997) On the relation between NDVI, fractional vegetation cover, and leaf area index. *Remote Sensing of Environment* 62:241−252

Carrasco JC, Quintana J, Casassa G (2005) Changes of the 0° C isotherm and the equilibrium line altitude in central Chile during the last quarter of the 20th century. *Hydrol. Sci. J*., 50 (6):933-948

Carrivick JL (2007) Hydrodynamics and geomorphic work of jökulhlaups (glacial outburst floods) from Kverkfjöll volcano, Iceland. *Hydrological Processes* 21:725-740

Cenderelli DA, Wohl EE (2003) Flow hydraulics and geomorphic effects of glacial-lake outburst floods in the Mount Everest region, Nepal. *Earth Surface Processes and Landforms* 28:385-407

Cesca M, D'Agostino V (2008). Comparison between Flo-2D and RAMMS in debris flow modelling: a case study in the Dolomites. Int. Conference on monitoring, simulation, prevention and remediation of dense and debris flow II, D. De Wrachien, C.A. Brebbia e M.A. Lenzi (eds.), pp 197-206, WITpress Southampton (ISBN 987-1-84564-118-4; ISSN 1746-4471).

Chavez PS (1988) An improved dark-object subtraction technique for atmospheric scattering correction of multispectral data, *Remote Sensing of Environment* 24:459-479

Christen, M., Kowalski, J., and Bartelt, P (2010) RAMMS: Numerical simulation of dense snow avalanches in three-dimensional terrain. *Cold Reg. Sci. Technol*., 63:1-14

Clague JJ, Mathews WH (1973) The magnitude of Jökulhlaups. *Journal of Glaciology* 12: 501-504

Diario de Atacama (1985) Aluvión de dos metros por quebrada de Manflas. Page 07, Saturday 18 May 1985.

Dussaillant A, Benito G, Buytaert W, Carling P, Meier C, Espinoza F(2009) Repeated glacial-lake outburst floods in Patagonia: an increasing hazard? *Natural Hazards* 54: 469-481

Fay H (2002) Formation of ice block obstacle marks during the November 1996 glacier outburst flood (jökulhlaup), Skeiðarársandur, southern Iceland. In: Martini, I.P., Baker, V.R., Garzón, G. (Eds.), Flood and Megaflood Processes and Deposits: Recent and Ancient Examples. IAS Special Publication, 32, pp. 85-97

Fernández P, Fornero L, Maza J, Yañez H (1991) Simulation of flood waves from outburst of glacier dammed lake. *Journal Hydraulic Engineering* 117: 42-53

Frey H, Haeberli W, Linsbauer A, Huggel C, Paul F (2010) A multi-level strategy for anticipating future glacier lake formation and associated hazard potentials, *Nat. Hazards Earth Syst. Sci*.,10, 339–352, doi:10.5194/nhess-10-339-2010.

Gardelle J, Arnaud Y, Berthier E (2011) Contrasted evolution of glacial lakes along the Hindu Kush Himalaya mountain range between 1990 and 2009. *Global Planet. Change* 75:47-55 doi:10.1016/j.gloplacha.2010.10.003

Gascoin S, Kinnard C, Ponce R, Lhermitte S, MacDonell S, Rabatel A (2011) Glacier contribution to streamflow in two headwaters of the Huasco River, Dry Andes of Chile, *The Cryosphere*, 5, 1099-1113, doi:10.5194/tc-5-1099-2011

Gillespie AR, Matsunaga T, Rokugawa S,Hook SJ (1998)Temperature and Emissivity Separation from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Images. IEEE Trans. *Geosci. Remote Sens*. 36, 1113–1126.

Ginot P,Kull C, Schotterer U, Schwikowski M, Gäggeler HW (2006) Glacier mass balance reconstruction by sublimation induced enrichment of chemical species on Cerro Tapado (Chilean Andes), *Clim.Past*, 2:21-30

Griswold JP, Iverson RM(2008) Mobility statistics and automated hazard mapping of debris flows and rock avalanches. USGS Scientific Investigations Rep. No. 2007-5276, USGS, Cascades Volcano Observatory, U.S. Dept. of the Interior, at http://pubs.usgs.gov/ sir/2007/5276/.

Gruber S,Huggel C, Pike R(2008) Modelling mass movements and landslide susceptibility using geomorphometry, in: Geomorphometry: Geomorphometry: Concepts, Software, Applications, edited by: Hengl, T. and Reuter, H. I., Developments in Soil Science, Vol. 33, Elsevier B.V. ISSN 0166-2481, doi:10.1016/S0166-2481(08)00023-8, 2008

Gulley JD, Benn DI, Muller D, Luckman A (2009) A cut-andclosure origin for englacial conduits in uncrevassed regions of polythermal glaciers. *Journal of Glaciology* 55(189):66-80, doi:10.3189/002214309788608930

Haeberli W (1983) Frequency and characteristics of glacier floods in the Swiss Alps. Annals of Glaciology 4:85-90

Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A (2005) Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology* 25(15): 1965-1978

Huang, C.-J., H.-Y. Yin, C.-Y. Chen, C.-H. Yeh, and C.-L. Wang (2007), Ground vibrations produced by rock motions and debris flows, *J. Geophys. Res*., 112, F02014, doi:10.1029/2005JF000437.

Hussin HY, Quan Kuna B, van Westen CJ, Christen M, Malet JP, van Asch TW (2012) Parameterization of a numerical 2-D debris flow model with entrainment: a case study of the Faucon catchment, Southern French Alps. *Nat Hazard Earth Syst* 12:3075-3090

Huggel C, Schneider D, Miranda PJ, Delgado Granados H and Kääb A (2008) Evaluation of ASTER and SRTM DEM data for lahar modeling: a case study on lahars from Popocatepetl Volcano, Mexico. *Journal of Volcanology and Geothermal Research* 170:99-110

Iribarren Anacona, P, Mackintosh A, Norton KP (2015). Hazardous processes and events from glacier and permafrost areas: lessons from the Chilean and Argentinean Andes. *Earth Surface Processes and Landforms*, 40(1):2-21

Iverson RM (1997) The physics of debris flows, Rev. Geophys., (35):245–296.

Iverson RM, Schilling SP, Vallance JW (1998) Objective delineation of lahar inundation hazard zones. *Geol Soc Am Bull* 110(8):972-984

Javanmard S, Yatagai A, Nodzu M.I, BodaghJamali J, Kawamoto H (2010)Comparing high-resolution gridded precipitation data with satellite rainfall estimates of TRMM 3B42 over Iran. *Advanced Geosciences* 25:119-125

Komori J (2008) Recent expansions of glacial lakes in the Bhutan Himalayas. *Quaternary International* 184:177-186

Linsbauer A, Paul, F, Haeberli W(2012)Modeling glacier thickness distribution and bed topography over entire mountain ranges with GlabTop: application of a fast and robust approach,*J. Geophys. Res*., 117, F03007, doi:10.1029/2011JF002313, 2012. 4820, 4821, 4822

Lliboutry L, Morales B, Pautre A, Schneider B (1977) Glaciological problems set by the control of dangerous lakes in Cordillera Blanca, Peru. I: Historical failure of morainic dams, their causes and prevention. *Journal of Glaciology* 18:239-254

Maag H (1969) Ice dammed lakes and marginal glacial drainage on Axel Heiberg Island, Canadian Arctic Archipelago. Axel Heiberg Island Research Reports, McGill University, Montreal. Jacobsen-McGill Arctic Research Expedition 1959-1962

MacDonell S, Kinnard C, Mölg T, Nicholson L, Abermann J (2013) Meteorological drivers of ablation processes on a cold glacier in the semi-arid Andes of Chile.*The Cryosphere* 7 (5): 1513-1526

Magirl CS, Griffiths PG, Webb RH (2010) Analyzing debris flows with the statistically calibrated empirical model LAHARZ in southeastern Arizona, USA. *Geomorphology* 119:111-124

Nicholson L Marín J, Lopez D, Rabatel A, Bown F, Rivera A (2010) Glacier inventory of the upper Huasco valley, Norte Chico, Chile: glacier characteristics, glacier change and comparison with central Chile, *Ann. Glaciol*., 50:111-118

O'Connor JE, Webb RH (1988) Hydraulic modeling for paleoflood analysis. In: Flood Geomorphology (ed. by V. R. Baker, R. C. Kochel & P. C. Patton), 393-402. John Wiley & Sons Inc., New York, USA.

Oramas Dorta D, Toyos G, Oppenheimer C, Pareschi MT, Sulpizio R, Zanchetta G (2007) Empirical modelling of the May 1998 small debris flows in Sarno (Italy) using LAHARZ. *Nat Hazards* 40:381-396

Paterson WSB (1994) The physics of glaciers. 3rd edition, Pergamon Press, Oxford: 480 pp.

Peña H, Klohn W. 1989. Non-meteorological flood disasters in Chile. In Hydrology of Disasters, Starosolszky O,Melder OM (eds). James & James: London; 243-258

Peña H, Escobar F (1987) Análisis del aluvión de mayo de 1985 del río Manflas, cuenca del río Copiapó,Publicación Interna Estudios Hidrológicos 87/3. Ministerio de Obras Públicas, Dirección General de Aguas:Santiago; 14p.

Pieri DC, Abrams MJ (2005) ASTER observations of thermal anomalies preceding the April 2003 eruption of Chikurachki Volcano, Kurile Islands, Russia, *Remote Sens. Environ*., 99:84-94

Quan Luna B, Blahut J, Kappes M, Oguzhan Akbas S, Malet JP, Remaitre A Van Asch T, and Jaboyedoff M (2014) Methods for debris flow hazard and risk assessment. In Mountain Risks: from prediction to management and governance. Advances in Natural and Technological Hazards Research. 3:133-177.Springer

Rabatel A, Castebrunet H, Favier V, Nicholson L, Kinnard C (2011) Glacier changes in the Pascua-Lama region, Chilean Andes (29_ S): recent mass balance and 50 yr surface area variations.*The Cryosphere* 5:1029-1041 doi:10.5194/tc-5-1029-2011

Rushmer EL (2006) Sedimentological and geomorphological impacts of the jökulhlaup (glacial outburst flood) in January 2002 at Kverkfjöll, northern Iceland.*Geografiska Annaler*, 88A:43-53

Scambos TA, Hulbe CL, Fahnestock MA (2000) The link between climate warming and break-up of ice shelves in the Antarctic Peninsula. *Journal of Glaciology* 46:516 - 530

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

Schilling S (1998) LAHARZ: GIS programs for automated mapping of lahar-inundations hazard zones. US Geological Survey Open-File Report 98-638

Schilling S (2014) Laharz_py: GIS tools for automated mapping of lahar inundation hazard zones. US Geological Survey Open-File Report 2014-1073

Slater JA, Heady B, Kroenung G, Curtis W Haase J, Hoegemann D, Shockley C, Tracy K (2011) Global assessment of the new ASTER global digital elevation model, *Photogrammetric Engineering & Remote Sensing*, 77(4):335–349

Sobrino JA, Jiménez-Muñoz JC, Paolini l.2004.Land surface temperature retrieval from LANDSAT TM 5 Remote Sensing of Environment, 90 (4):434-440

Stern CR, Moreno H, López-Escober L, Clavero JE, Lara LE, Naranjo JA, Parada MA, Skewes MA (2007). Chilean Volcanoes. In The Geology of Chile (Moreno, E; Gibbons, W.; editors), Geologic Society of London Press Chapter 5: 149-180. London, UK.

Stuefer M, Rott H, Skvarca P (2007) Glaciar Perito Moreno, Patagonia: climate sensitivities and glacier characteristics preceding the 2003/04 and 2005/06 damming events. *Journal of Glaciology* 53(180): 3-16

Tarboton DG, Bras RL, Rodriguez-Iturbe I (1991) On the extraction of channel networks from digital elevation data. *Hydrol. Process*. 5 (1), 81–100.

Tweed FS, Russell AJ (1999) Controls on the formation and sudden drainage of glacier-impounded lakes: implications for jo¨kulhlaup characteristics. *Progress in Physical Geography* 23:79-110

Vincent C, Auclair S, Le Meur E (2010a) Outburst flood hazard for glacier-dammed Lac de ochemelon, France. *J. Glaciol*., 56(195) :91-100 (doi: 10.3189/002214310791190857)

Vincent C, Garambois S, Thibert E, Lefebvre E, Le Meur E, Six D (2010b) Origin of the outburst flood from Tete Rousse glacier in 1892 (Mont Blanc area, France). *Journal of Glaciology* 56:688-698.

Wadham JL, Hodgkins R, Cooper RJ, Tranter M (2001) Evidence for seasonal subglacial outburst events at a polythermal glacier, Finsterwalderbreen, Svalbard. *Hydrological Processes* 15: 2259-2280. DOI: 10.1002/hyp.178

Walder JS, Costa JE (1996) Outburst floods from glacier-dammed lakes: the effect of mode of lake drainage on flood magnitude. *Earth Surface Processes and Landforms* 21:701-723

Webb RH, Jarrett RD (2002) One-dimensional estimation techniques for discharges of paleofloods and historical floods: Ancient Floods, Modern Hazards: Principles and Applications of Paleoflood Hydrology, AGU's Water Science and Application Series, vol. 5, p. 111-125.

Widiwijayanti C, Voight B, Hidayat D, Schilling SP (2009) Objective rapid delineation of areas at risk from block-and-ash pyroclastic flows and surges. *Bull Volcanol* 71:687-703

Wilcock PR,Schmidt JC, Wolman MG, Dietrich WE, DeWitt D, Doyle MW, Grant GE, Iverson RM,Montgomery DR, Pierson TC, Schilling SP, Wilson RC (2003) When models meet managers: examples from geomorphology P.R. Wilcock, R.M. Iverson (Eds.), Prediction in Geomorphology, AGU, Washington, DC. 27–40

Worni R, Huggel C, Stoffel M, Pulgarin B (2012) Challenges of modeling current very large lahars at Nevado del Huila, Colombia. *Bull Volcanol* 74:309-324

6 Thesis summary and conclusions

This chapter summarises the thesis findings and discusses future research directions. In the first section, I discuss the conclusions of the thesis in light of the objectives presented in chapter 2. The second section discusses research directions that can help fill the knowledge gaps identified in this thesis.

Objective 1. Provide a synthesis of the geomorphic and hydrologic processes and hazards originating in glacial and permafrost areas in the extratropical Andes in historic time.

I carried out the first review of hazardous processes and events originating from glacier and permafrost areas in the extratropical Andes. Bibliographic analysis and the interpretation of satellite images reveal differences in the distribution, frequency and magnitude of hazardous processes affecting this region. The number and magnitude of hazardous events increases from north to south as the glacier-covered areas become larger. Indeed, 27 of 31 glacial lakes known to have failed in the extratropical Andes were located in heavily-glacierized Patagonia. Furthermore, the largest GLOF ($5000x10^6$ m^3) in Patagonia was three orders of magnitude larger than the most voluminous GLOF in the arid Andes. In other words, I observe a direct relationship between the number and dimension of GLOFs and the size of the glacier-covered area.

The type of hazardous events also changes along the extratropical Andes. In the arid Andes, where slow-flowing, high altitude cold-based glaciers exist; hazardous events from glacier and permafrost areas have been scarce, although the collapse of rock glaciers and an exceptional GLOF from a sub-glacial lake were recorded. In the central Andes, GLOFs resulting from river blockage by surging glaciers have been documented as well as multiphase mass movements originating in permafrost areas. High-altitude valleys in the central Andes are exploited economically by tourism, mining and hydropower production. Thus, events such as rock-falls from rock glacier fronts and the slow-movement of ice-rich permafrost forms also have caused economic damage. In Patagonia, lahars from ice-capped volcanoes and GLOFs have been common. The large number of GLOFs in Patagonia is linked with the highly-dynamic nature of temperate glaciers which can experience rapid (monthly to yearly) changes in area resulting in the development of unstable moraine and ice-dammed lakes. Damages from GLOFs, however, have been limited in Patagonia due to the scarce population, in spite of the enormous magnitude of GLOFs, which include one the largest (~$200 \times 10^6 m^3$) moraine-dammed lake failures known worldwide.

In most cases the triggering mechanism of mass movements and GLOFs remain uncertain due to the lack of meteorological data and the uncertain date of the events. However, it is known that extreme meteorological conditions (e.g. high temperatures, enhanced snowmelt and intense precipitation) have been linked with GLOFs and mass movements involving glacier-ice and permafrost. In spite of the active seismicity of the extratropical Andes (especially north of 46º S); earthquakes have not been associated with hazardous events in glacier and permafrost areas. Thus, extreme meteorological events and long-term climate changes are the main conditioning and triggering factors of hazardous processes originating in glaciated areas in the extratropical Andes.

Objective 2: Characterise and create an inventory of failed glacial lakes and their surroundings in the extratropical Andes, in order to develop a method to assess the outburst flood susceptibility of glacial lakes in this region.

As GLOFs are frequent in the extratropical Andes (more than 100 have been documented since the eighteenth century), I investigated failed moraine-dammed lakes in Patagonia with the objective of identifying common characteristics of failed (and thus of hazardous) lakes and their surroundings. To achieve this objective, I carried out a multi-temporal analysis of satellite images. Lakes dammed by temperate glaciers are inherently unstable, hence the analyses focused on moraine-dammed lakes. The morphometry of failed moraine-dammed lakes vary in Patagonia. Indeed, the size of failed lakes spans three orders of magnitude (from 0.01 to 1.87 km^2). Larger (dozens of km^2) moraine-dammed lakes also exist in this region; however these lakes have not failed in historic time. It is postulated that the stability of these, comparatively, larger lakes is related to several factors. Larger glacial lakes are commonly located far from currently glaciated areas and thus are less prone to ice avalanche impacts. Furthermore, large lakes usually date to the LIA or before (attested by dams covered by mature forest). Thus, these lakes have had a long period of adjustment to new climatic and hydrological conditions. This adjustment could have included pre historic GLOFs which served to reduce the hazard posed by breaching and lowering the height of moraine dams. Finally, small lakes can have quick responses to increases in water influx which can result in dam overflows. Thus, data in Patagonia suggests that relatively small and recently formed lakes are more susceptible to GLOFs.

Although failed moraine-dammed lakes differ in size, the lakes share several common characteristics. My analysis shows that 13 of 16 moraine-dammed lakes known to have failed in Patagonia were in contact with retreating glaciers at the time of failure. Furthermore, most of these lakes have moderate (≥8°) to steep (≥15°) outlet slopes. It is argued that the high susceptibility to GLOFs of lakes in contact with glaciers can be explained by three factors. First, these lakes are subject to glacier calving which can cause waves able to overtop and breach dams. Second, icebergs from glacier calving can obstruct lake outlets raising the lake level producing overflows. Finally, the area and volume of these lakes can grow quickly (because of glacier retreat) dramatically changing the basin's hydrology. Hence, it is certain that lakes in contact with glaciers have a higher GLOF susceptibility than more distant lakes.

The internal composition of dams (e.g. sediment structure and the presence of ice) greatly affects the dam stability and the GLOF hazard. However, these characteristics can only by assessed by detailed and costly field studies. Our analysis, however, shows that morphometric data, which can be measured by remote sensing methods and GIS techniques, can be used to identify hazardous lakes. These data include the glacier-lake contact status, the lake outlet slope, the identification of mass movement and ice-avalanche paths, and the lake area. A method to estimate the outburst susceptibility of glacial lakes was developed based on image classification techniques, flow routine algorithms and the Analytic Hierarchy Process method (and the variables mentioned above). The outburst susceptibility of hundreds of glacial lakes was estimated in the Baker Basin (used as pilot area to test the proposed method) and dozens of glacial lakes were classified with high or very high outburst susceptibility. It was shown that remote sensing and

GIS techniques can be used to readily identify hazardous glacial lakes at a regional-scale. Furthermore it was demonstrated that hazardous lakes are not unusual in Patagonia; ~ 7% of 386 lakes in the Baker Basin were classified as potentially hazardous.

Objective 3: To unravel the GLOF dynamics in geographically contrasting environments in the extratropical Andes and test empirical and physical flow models in GLOF simulation

Although the dynamics of individual GLOFs are unique (since they depend on local factors such as lake bathymetry and GLOF triggering mechanism), GLOF inventories and case studies suggest that generalisations can be made regarding the GLOF dynamics in the arid Andes and western Patagonia. GLOFs in both geographic settings were studied by means of geomorphic interpretation of satellite images and field analysis. Eyewitnesses accounts and newspaper reports were also used to develop an understanding of GLOF behaviour.

GLOFs in the high arid (and central) Andes commonly are sediment-charged flows which behave as debris or hyperconcentrated flows. Floods within these high-relief basins with steep, unvegetated slopes result in rapid flows with extreme erosive and transport capacity. By contrast in Patagonia, channel slopes favoring debris flow development commonly occur within less than 5 kilometres from glacial lakes, and GLOFs tend to behave as difussive and rapidly attenuating flows running over gentle valleys. Also, large lakes exist in middle-basins in Patagonia which help to attenuate GLOFs (reducing GLOF velocity and delaying floods). GLOFs in western Patagonia are also affected by wooden debris entrainment which reduces channel cross-sectional area, increasing flood level and reducing flood velocity. Hence GLOF dynamics appear to vary along the extratropical Andes responding to the region's geographic and glaciological diversity.

Physical (HEC-RAS and RAMMS) and empirical (MSF and Laharz) flow models were used to simulate (and reconstruct) GLOFs in the arid Andes and in western Patagonia. A Newtonian (clear water) flow was simulated in Patagonia using the 2D capabilities of HEC-RAS 5 Beta. It is shown that this model can reproduce complex GLOF dynamics such as hydraulic ponding upstream of valley constrictions. Furthermore, HEC-RAS 5 Beta accuratelly reproduced GLOF timing and water levels. The efficiency (GLOFs were simulated in less than two hours using 30 to 80 m resolution DEMs) and physical basis of HEC-RAS 5 Beta makes this model suitable for GLOF simulations and GLOF hazard and risk studies in Patagonia and similar geographic settings where large Newtonian flows occur.

It was demonstrated that GLOF simulations run with empirical models have drawbacks (e.g. models were not developed to simulate flow features such as backwater flooding or slope surges, understimating areas at risk of flooding) which limits their usefulness in hazard assessments. However, these models require fewer inputs and use less computational time than physical models and may provide useful preliminary risk assesments in some cases. More complete physical models such as RAMMS no doubt provide more quantitative hazard and risk assessments. However, these models are difficult to set up, and are not capable of accurately simulating all types of floods. For example in this study, the RAMMS model was unable to accurately simulate voluminous debris flows over large distances.

6.1 Limitations and future research directions

The overall aim of this thesis was to gain a better understanding of the nature of hazards originating in glacier and permafrost areas in the extratropical Andes and in particular on GLOFs dynamics and hazards. To accomplish this task, I carried out a review of the hazardous processes and events originating in glacier and permafrost areas in the Chilean and Argentinean Andes in historic time. Furthermore, I characterised failed moraine-dammed lakes in Patagonia and developed a method for assessing the outburst susceptibility of glacial lakes. Finally, I reconstructed GLOFs in the arid Andes and western Patagonia with a suite of methods including GLOFs modelling, photo interpretation and semi-structured interviews. This study filled knowledge gaps and forms a more informed basis for future assessments and policies regarding glacier and permafrost hazards in the extratropical Andes. The thesis, however, has certain limitations that could be addressed in future research.

One of the limitations of this research is the broad-scale analysis of the meteorological conditions that could have conditioned or triggered GLOFs or mass movements involving glacier-ice or permafrost. An in-depth analysis of the meteorological conditions that preceded GLOFs and mass movements, could lead to the identification of GLOF and landslide triggering thresholds, data useful for developing early warning systems. The lack of meteorological stations in remote glaciated areas, however, has inhibited this type of analysis. This issue can be potentially solved analysing global meteorological datasets. The usefulness of these datasets (e.g. Tropical Rainfall Measurement Mission TRMM) in characterising meteorological conditions associated with landslides has been explored in different mountain ranges but remains to be tested in GLOF and landslide studies in the extratropical Andes.

The method developed to assess the outburst susceptibility of glacial lakes allows an objective categorisation of hundreds of lakes using publicly available datasets. Although useful, this analysis has temporal limitations since the geometry of glacier close or in contact with glacial lakes can change in few months or years modifying the lake's outburst susceptibility. Furthermore, new lakes could form over short spaces of time. Thus, periodic assessments (e.g. on an annual basis) of the outburst susceptibility of glacial lakes are required. This task could be done using the method developed to classify the outburst susceptibility in the Baker Basin. However, this periodic duty could be aided by the automation (e.g. writing a script tool to assesses GLOF susceptibility) of the procedures which will reduce processing times. Furthermore, the thesis focused in existing glacial lakes. Methods developed to identify areas where glacial lakes can form (e.g. slope overdeepenings and gentle glacier surfaces) can be used to anticipate the formation of emerging hazardous lakes.

Finally, the reconstruction of past GLOFs in different geographic settings helps to understand the GLOFs dynamics in contrasting geomorphic environments. Indeed, it was demonstrated that sediment-laden flows are common in GLOFs occurring in the arid and central Andes, while voluminous clear water floods with abundant wood transport commonly affects the western Patagonian Andes. Furthermore, the advantages and drawbacks of physical and empirical models (e.g. the ability of physical models to reproduce complex flow behaviour such as backwater flooding) used to simulate GLOFs were indentified. This knowledge can aid in the selection of models to simulate GLOFs in different regions of the extratropical Andes. Future studies can build upon this knowledge to develop GLOFs hazard and risk analysis in inhabited valleys or areas with riverine infrastructure.

7 Appendices

7.1 Rationale behind the choice of models to simulate GLOFs

Several physical and empirical models can be used to simulate GLOFs (Table appendix 1). The model of choice depends on the scale and scope of analysis, the type of flow (clear-water flow or debris flow) and the data available to parameterise simulations (e.g. flow density and roughness coefficients) or to evaluate the model results (e.g. depth, extent and velocity of past events). Other factors such as the availability of the model (i.e. commercial software or freely distributed code) and the model computational requirements are also considered when selecting a model for GLOF simulations. Newtonian and Non-Newtonian physical models provide quantitative outputs (e.g. flow velocity and depth), however, these are demanding in terms of computing time and input requirements. Empirically models are easy to implement but just provide qualitative outputs to be used at regional-scale.

In the thesis I used two empirical and two physical models to simulate GLOFs. The selected empirical models (where flooded areas are defined based on statistical analyses of past events) were the Modified Single Flow Model (MSF) of Huggel et al., (2003) and LAHARZ of Schilling (1998). Both models are described in chapter 5. These models were selected since the models were developed to simulate sediment-laden flows, such as the GLOF that occurred in the Manflas Valley in 1985. Furthermore, MSF and LAHARZ have proven to be useful in preliminary hazard assessments, require few input data (a DEM and estimated GLOF volume and flow angle of reach) and are easy to implement in GIS platforms. Other empirical models have been used to simulate GLOFs such as r.randowalk (Mergili et al., 2015) and MC-LCP (Watson et al., 2016); however, the model outputs (delineating areas likely to be affected by floods) are also qualitative.

The physical models chosen to simulate GLOFs were RAMMS, developed by Christen et al., (2010) and HEC-RAS 5 of the U.S Corps of Engineers (2015). Other models also have been used to simulate GLOFs but most models are based on the same governing equations (i.e. St Venant equations in clear water flows and the

Voellmy or Bingham rheologies in debris flows). RAMMS was selected to simulate the Manflas GLOF since it is able to simulate non-Newtonian flows and has been successfully used to reproduce the flow dynamics of rain-induced debris flows (Hussin et al., 2012) and GLOFs (Schneider et al., 2014). RAMMS is a commercial software; however, it can be used for a week free of charge.

HEC-RAS 5 was used to simulate the Río Engaño GLOF in Patagonia since the model was developed to simulate clear-water or Newtonian flows. Due to the large volume of water released by GLOFs in Patagonia and the rapid decrease in slope from glacier lakes (see chapters 2 and 3), GLOFs rarely develop into debris flows and thus can be reproduced using Newtonian models. HEC-RAS is a freely distributed software and has been used since the 1980's having a large community of users which have tested the model in different settings (e.g. Osti and Egashira 2009; Wang et al., 2015). RAMMS and HEC-RAS 5 are two dimensional models and thus are able to reproduce complex GLOF behaviour such as unconfined flows, flows around obstructions and hydraulic jumps (Carrivick 2006). The models' ability to simulate complex flow behaviour, their successful use in GLOF studies, and their friendly user interfaces were model attributes taken into account selecting these models to simulate the Manflas and Río Engaño GLOFs.

Table appendix 1 summarises attributes of some empirically and physically-based models used (or that can be used) to simulate GLOFs, and provides references where further model details can be found. Some physical models can be used to simulate the breach of dams; however, they require input data that are not mentioned in the table (e.g. dam geometry and gran size distribution). Furthermore, empirical models such as r.randomwalk (Mergili et al., 2015) use different inputs (e.g. GLOF volume or angle of reach) that can be selected by the user. Physical models are more complex to set up than empirical models, as is demonstrated by the larger number of required inputs, however, these models provide quantitative data (e.g impact pressures) that can be used in flood risk and hazard assessments. Thus, physical model should be preferentially used to carry out high-resolution simulations for territorial planning. Due to the uncertainties underlying both, physical and empirical models, model outputs should be treated with care to provide realistic information to stakeholders. Where possible, models should be thoroughly evaluated with field data.

Table appendix 1: Characteristics of models used (or that can be used) to simulate GLOFs

Model	Type			Minimum inputs requirements					Setting parameters				Dimension		Others				
	Empirical	Newtonian	Non-Newtonian	DEM	Cross sections	Hydrograph (or peak discharge)	Downstream boundary condition	GLOF volume	Manning coefficient	Flow density	Rheological parameters	Angle of reach	One	Two	Breach simulation	freely distributed	Commercial software	Key GLOF studies	Source
HEC-RAS		X		X	X	X	X		X				X	X	X	X		a	US Corp of Engineers
IBER		X		X	X	X	X		X				X	X	X	X		b	IBER (2010)
SOBEK		X		X	X	X	X		X				X	X	X		X	c	Delft Hydraulics
BASEMENT		X		X	X	X	X		X				X	X	X		X	d	Faeh et al., (2012)
FLOW-2D			X	X	X	X				X	X		X	X	X	X		e	O'Brien et al., (1993)
RAMMS			X	X		X				X	X			X		X		f	Christen et al., (2010)
r.avaflow			X	X							X			X			X	-	Mergilli et al.,(2012)
LAHARZ	X			X				X			X			X		X		-	Schilling (1998)
MSF	X			X								X		X		X		g	Huggel et al., (2003)
MC-LCP LC	X			X					X					X		X		h	Watson et al., (2016)
r.randomwalk	X			X		X		X				X		X		X		i	Mergili et al., (2015)

a) Osti and Egashira (2009); b) Schneider et al., (2014); c) Carrivick (2006); d) Worni et al., (2012); e) Mergili et al., (2011); f) Schneider et al (2014); g) Huggel et al., (2003); h) Watson et al., (2016); i) Mergili et al., (2015).

References

Carrivick JL (2006) Application of 2D hydrodynamic modelling to high-magnitude outburst floods: an example from Kverkfjöll, Iceland. J. Hydrol. 321, 187–199.

Huggel C, Kääb A, Haeberli W, Krummenacher B (2003) Regional-scale GIS models for assessment of hazards from glacier lake outbursts: evaluation and application in the Swiss Alps. Nat. Hazards Earth Syst. Sci. 3 (6), 647–662.

Hussin HY, Quan Kuna B, van Westen CJ, Christen M, Malet JP, van Asch TW (2012) Parameterization of a numerical 2-D debris flow model with entrainment: a case study of the Faucon catchment, Southern French 744 Alps. Nat Hazard Earth Syst 12:3075-3090

Faeh R, Mueller R, Rousselot P, Veprek R, Vetsch D, Volz C, Vonwiller L, Farshi D (2012) BASEMENT-Basic Simulation Environment for Computation of Environmental Flow and Natural Hazard Simulation. VAW Mitellung, ETH Zurich (www.basement.ethz.ch. [Accessed 27 July 2016]).

Mergili M, Schneider D, Worni R, Schneider JF (2011) Glacial Lake Outburst Floods (GLOFs): challenges in prediction and modeling. In: Genevois, R., Hamilton, D. L., Prestininzi, A. (eds.): Proceedings of the 5th International Conference on Debris-Flow Hazards Mitigation: Mechanics, Prediction and Assessment, Padua, Italy, June 14-17, 2011. Italian Journal of Engineering Geology and Environment - Book: 973-982.

Mergili M, Schratz K, Ostermann A, Fellin W (2012) Physically-based modelling of granular flows with Open Source GIS. Natural Hazards and Earth System Sciences 12: 187-200. doi:10.5194/nhess-12-187-2012

Mergili M, Krenn J, Chu HJ (2015) r.randomwalk v1, a multi-functional conceptual tool for mass movement routing. Geoscientific Model Development 8: 4027-4043. doi:10.5194/gmd-8-4027-2015

O'Brien JS, Julien PY, Fullerton WT (1993) Two-dimensional water flood and mudflow simulation. J. Hydraul. Eng. ASCE 119, 244–261

Osti R, Egashira S (2009) Hydrodynamic characteristics of the Tam Pokhari glacial lake outburst flood in the Mt. Everest region, Nepal. Hydrol. Process. 23, 2943–2955.

Schilling S (1998) LAHARZ: GIS programs for automated mapping of lahar-inundations hazard zones. US Geological Survey Open-File Report 98-638

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

SOBEK (2013) http://www.deltaressystems.com/hydro/product/108282/sobek-suite (Accessed 27 July 2016).

Wang W, Gao Y, Iribarren Anacona P, Lei Y, Xiang Y, Zhang G, Shengai L, Lu A (2015) Integrated hazard assessment of Cirenmaco glacial lake in Zhangzangbo valley, Central Himalayas. Geomorphology DOI: 10.1016/j.geomorph.2015.08.013

Watson C, Carrivick J, Quincey D (2016) An improved method to represent DEM uncertainty in glacial lake outburst flood propagation using stochastic simulations. Journal of Hydrology: 529-3; 1373–1389.

7.2 Semi-structured interviews guide

1-How long have you been living in Bahia Murta and what do you do for living?

2-Do you know where Bahía Murta was originally located and when it was moved to its actual location?

3-How many people lived there at this time?

4-Do you know why the village was relocated?

5- Was the decision to relocate the village taken by the villagers or by regional authorities?

6-How long did the relocation process last and what was it like?

7-What do you remember about the flood that affected Bahía Murta in 1977?

8-Do you remember which areas were reached by the flood?

9-What was the maximum height of the flood in these areas?

10-Was there any damage to the village's houses or rural properties?

11-Can you recognize any flood evidence nowadays?

12-Do you remember at what time the flood started and what the meteorological conditions during this day or the previous days were?

13-Do you know if the flood transported any debris?

14-How long did the flood last?

15-Do you know what caused the flood?

16-What did the people do during the flood and the subsequent hours/days?

17-Do you remember other floods of the same or larger magnitude in the Engaño Valley?

18-Has there been any flood control measure applied since then?

7.3 Transcripts of interviews of chapter 4

Interviewees agreed to be named in published works; however, we omitted their names and changed names recalled in interviews to protect the interviewee's confidentiality.

Interview 1.

Cuando reventó, cuando se destapó la laguna, según cuentan los que estaban aquí, allá en esa parte ese rodao, allá hay un salto, este río tiene un salto, y es angosto igual, y dicen que ahí se devolvió el agua pa tras, y empezó a subir su nivel, y al subir su nivel por ejemplo en el cerro así, una vez que reventó bajó toda esa palizaa, todos los palos. Entonces dicen que cuando la vieron que venía por aquí, dicen que venía así. Para esto todo lo que está en la costa del río, este campo da hasta el río, teníamos nosotros unas casa donde hacíamos queso, corrales, no quedó nada nha nha nha.

Aquí al frente estaba la población del otro vecino, don Eugenio Barrientos, está la población al laito allá de esa loma. Él tenía su casa allá, no quedó nah, quedó una sola casa vieja al medio de los palos ahí. (*Cuantas casas habían?*) Eran galpones, casas, huerta todo, todo, de eso no quedó nada. Porque ahí como digo ya venía con madera, con palos, mucho palo.

Entonces la creciente pegó allá po, en esa parte y una vez que pegó allá, vino a pegar acá, ahí donde está el puente pa allá, se dio una vuelta, la de la carretera, y ahí agarró pal pueblo viejo.

Yo estaba pal Baker, nosotros escuchamos por la radio, la radio Santa María, Patagonia, no me acuerdo como se llamaba la que había en ese tiempo, y dijeron inundación en Murta no se sabe, el desborde de un río, una laguna, chuuta dije, no se sabe si hay damnificados, nada, están saliendo aviones. En ese tiempo estaba la cancha al otro lado y todo. Había un aeropuerto grande, tiene 600 y tanto metros de pista. Del Baker nos demoramos tres días no más en llegar.

El año 60 no sé cuándo, dicen que llovió todo un mes y toda la noche y estos ríos casi se juntaron ahí en la casa de la señora Carolina, casi se juntan, ahí han de haber como 100 metros un poquito más de diferencia, y el pueblo estaba ahí abajo, entonces el pueblo estaba ahí al medio. Entonces ya empezaron con que el pueblo no podía seguir. Claro porque antiguamente, cuando estaban los Carmona, una familia que llegaron años atrás, que tuvieron aserradero, el 57 el 60 por ahí, esos tuvieron poblaciones ahí en la costa del lago, hicieron muelle, y este río ya se salía, este río como le decía pegaba allí.

(Usted cuando llegó aquí 3 días después se notaba la crecida?). Pfff, todo esto pa allá lleno de palo, hasta donde dan lo faldeos así palos, y lo que había aquí se lo llevo todo, cerco, todo todo, cuando llegamo a la casa allá, (*por esta parte pasó?)* bañó todo todo, no ve que allá pegó en el cerro allá, …allá donde se ven esos palo amontonaos, eso traía el río, pero el río llego hasta arriba. Ahí salió un buey que estaba allá arriba leejo, se vino entre los palos, apareció, todo embarrao. Ahí donde está esa mata de caña, hay unos palos grandes, hay uno palo encimaos, todo eso quedó del río. Allá en el pueblo viejo, resacas grandes así, más grandes que el cerco pero laarga, y quedó tanto barro, una casa movió po, hasta el medio de la calle, la suerte de que fue de día, como a las 3 de la tarde, dicen que vinieron a avisar de adentro que venía saliendo el mar. Pensaba que era el mar no ve que cuando vió esa cuestión de agua, la vió que venía el agua, y se vino a avisar allá, y el otro gritando por este lado, no se animó a venir por la costa, venia por aquí por arriba, tocaron la campana allá en el pueblo y que viene saliendo una creciente el Engaño el mar viene saliendo, pero

del otro lado dicen que lo vieron. Y se vinieron uno en vote acá. Porque antes el pueblito el único movimiento que tenia, la gente que tenia caballo cruzaba a caballo.

No y la gente, hay un cementerio arriba de este cerro, arrancó para acá para el cementerio la altura, y algunos que alcanzaron, que se les hizo, ya con el miedo, de que no iban a alcanzar a pasar para acá, arrancaron pal bote se fueron pal otro lado, un solo hombrecito quedó en el pueblo, un enfermito mental, y a ese lo pillaron al otro día, vivía en un galpón, había puesto una tabla arriba, y ese fue el único que quedó en el pueblo, ya claro la gente cuando subió ahí vio esto, pucha dijeron no va aquedar ni una casa (*cuanta gente había en el pueblo ?)* tienen que haber habido unas 15 familias. Claro es que toda la gente del campo tenía casita ahí, no si ahí había una iglesia, mi mamá el fundadora, el santuario de santa rosa. … En esos años se tocaba la campana cualquier, cosa, había que correr a la iglesia. Se pedía ayuda, a veces se quebraba un trabajador en el campo. Se tocaba la campana se sabía que algo había pasado. Ya salían unos de a caballo…

Antes la escuelita estaba en el pueblo viejo, (*el pueblo ya se había cambiado para el otro lado cuando fue la inundación?).* Después, habían casas si, allí al otro lado habían casas ya de la gente, por ejemplo los pobladores, del otro lado tenían sitios, y otros que se habían estado trasladando, por el trabajo de la escuela, había gente que se había contratado en la escuela, cocinera, auxiliar, y pa la creciente, ya dijeron que no, que se tenía que trasladar la gente pa allá y iban a entregar sitios y todo eso, y después se trasladaban las casas, si las casas quedaron buenas, quedaron llenas de barro, como 70 centímetros, pero se limpiaron, una casa creo que se llevó (del pueblo) en la población de ahí de don Eugenio quedo un pedacito de casa no más….

Don Benancio tenía campo al lado de eso rodados, y dice que andaba en el campo y de repente sonaba y sonaba, un ruido raro, siempre suenan los rodados, cuando caen esos rodados al fondo allá se siente un ruido paca, uno dice están cayendo rodados pa dentro, uno está acostumbrado, y la gente tampoco se dio cuenta del río, que este río como le digo, cruzaba a las 10 de la mañana al pueblo y a las dos de la tarde ya cruzaba a nado, por eso decían que se llama Engaño, porque engañaba a la gente, cuando iba lo pasaba bajito… Nadie se dio cuenta que estaba tan bajo el río en pleno verano, no si dicen que tenía tantita agua así no más, y nadie se daba cuenta porque estaba tan bajo, se daban cuenta decían porque el río está bajo, pero nadie iba a mirar pa dentro…

(*Y cuanto duró la crecida?)* Duró como 4 horas, fue como a las tres de la tarde y como a las 6 ya había pasado todo. Pasó todo de un viaje pa allá…Lo único que quedó toda la palizada, que agarró por la costa (*rivera del río*), pedazos de casa, y cuanta macana, quedó hecho trinchera de palos, y el pueblo tapao en barro y agua, la gente no se animó a bajar después del cementerio porque podía venir otro golpe de agua,.. no nosotros cuando nos vinimos, de Tranquilo pa ya hay una parte que se llama la playa de los Martinez, pasa del camino , no ve que no había carretera nada, puro camino de caballo, pero había uno dos metros de altura de madera, el lago esa playa hace así una vuelta larga, debe de ser como de aquí al cementerio la playa o más larga, ahí está la capilla de mármol, en una esquinita, entonces el viento llevo todo eso, amontonó amontonó, ahí habían carros, pedazos de casa, nosotros dijimos la gente se habrá ahogado, porque después que salimos de allá del Baker no tuvimos ni un contacto más por radio. Nosotros volvimos, si pensamos que no había quedado na, las casas los animales, nosotros teníamos ovejas, vacas, gallinas de todo…

Estaba bueno el día, un día de sol era, si fue que el tranque que tenia la laguna no aguantó más, después lo fueron a ver dicen que había un rodado que había caído del otro lado con madera, palos, entonces, tapó la salida, entonces al acumular tanta agua, el peso lo hizo aflojar, y ahí empezó a agarra palos, arboles que pilló, palos secos…

Ahí había un palo de tres cuatro metros, no quedó ninguno y los arboles, quedaron todo así (*inclinados mostrando la dirección de la corriente*) y ahora como está el renuevo de cipres chiquitito, volvió a salir que era cipresal, y hay harto renuevo…

Interview 2

Esa vez cuando hubo esa creciente yo, ahí estábamos con un peón estábamos haciendo un galponcito, de canoga, yo arrendaba un pedazo de tierra, y una tarde de repente, empezaron a pasar árboles, árboles en el río, árboles que iban pa bajo, los iba levantando el agua, y bueno y que pasa un tremendo ruido pa dentro, y yo le digo que es eso raro, mira los arboles como van ahí, y le dije al muchacho que trabajaba conmigo, y claro era la creciente que se venía, había reventado adentro, en el río engaño, o sea la laguna del engaño, porque justo la laguna sale de ahí, de esa como abertura que se ve allá, sale de acá del lado norte, ahí hay una laguna adentro, y esa fue que cayó un rodado, en la boca de la laguna, entonces se tapo y, entonces de repente salió el agua y se llenó todo este bajo de agua, (*esas casas que se ven, estaban con agua también?)* desparecieron, esas son nuevas casas, ve esa cuestión café que hay, hay un árbol, al lado se ve una casita, esa casa del finado Nicolas Castro, entonces ellos vivían ahí, tenían como 30 ovejitas, tenían vacas y resulta que cuando vino la creciente, las ovejitas se murieron, las 30 ovejas, se murieron todas ahogadas ahí, pero el agua subió como algo de siquiera cuatro metros sobre la barranca del río, porque se lleno todo hasta allá hasta el cerro de agua, y ellos se subieron arriba de ese cerro montoso, y ahí pasaron la noche. Onda el agua.

Y yo había comprado unas chivas, treinta chivitas, y ahí abajito teníamos un campamento, y tenía una tropilla de caballos encerrada en un corral, el corral tenía como 20 caballos, entonces cuando …vimos cuando el agua venia trayendo palos, entonces el perrito que tenía yo …yo le gritaba al muchacho que venía la creciente, venia algo raro, entonces el perro en vez de sacar las chivas pa arriba las trajo pa bajo, y ahí se ahogaron…Una yegua se la llevo el río.

No había tanto árbol verde como ahora….Y fíjese que la señora hacia queso, la dueña de la casa, hacia queso y tenía mucho queso guardado en la casa, una cuestión que se llama salandra, que es de caña así se pone el queso a secar, entonces cuando vino la inundación, la casa la levantó el agua, y ahí los quesos se perdieron casi todos, se dio vuelta aquí..(*quién bajo a avisar al valle*?) La gente se dio cuenta, la gente del pueblo viejo…(*cuando duró la crecida*?). Duró, esto sería como a las 5 de la tarde, duró hasta el otro día, bajando agua, bajando palos, pero ya en retroceso, como le dijera, no venia tanto palo…

Así que nosotros con el muchacho que trabajaba conmigo, fuimos en la noche pa bajo, dijimos vamos a ver la gente, a ver la familia, el pueblo viejo, el pueblo nuevo, no sabíamos que había ocurrido palla po, llegamos estaba sumamente inundado, casi a mi altura, que está ahí en la entra del lago, está el viejito, en esos años vivían los dos viejitos, ahora no queda ninguno vivo, está el hijo, y llegamos en la noche, y estaban arriba en un cerrito, estaban acampaos, y habían arrancado de la casa, así que arrancaron al cerrito, nosotros con el muchacho, nos fuimos, usted sabe en esos tiempos yo era jovencito, caminador, y fuimos en la misma noche pal la, pa los faldeos arriba, y como sonaba el rio, se veía que iba la creciente pa bajo, nosotros no bajamos abajo,(*en la noche seguía sonando?*)Claro, llevaba palos, ya a eso de las 10 de la noche ya oscuro nosotros salimos pa ir a ver la demás gente…Algunos habían arrancado pal cementerio otros en bote pal pueblo nuevo, por lago, y después la creciente pasó y llego hasta el río Murta…(*cuantas familias habían el en pueblo?)* Habían unas 10 familias, en el pueblo nuevo había más gente ya estaba poblado, casitas nuevas…

Bueno después aquí a mí se me murieron un par de vacas, se ahogaron en el río acá, pero esta cuestión se apreciaba bien, porque acá salió un chorro de agua, que va por la orilla del cerro, de cerro a cerro pura agua…(*dicen que arriba hay un salto*?).Si hay como le dijera una angostura, ahí paso el río, se retaco atrás porque se lleno de palos la angostura, el río retrocedió una parte allá…que se llama el parrillal

Ese era un día de sol, una tarde bonita, estábamos preparando ahí para cortar pasto… ve esos palos, ese era un tremendo montón de palos..

(*Se trasladaron casas*?) Entonces se hacía sobre basa, palos por debajo, y ahí le colocaban tambores..el mismo año…se las llevaron enteras…y para llevarlas al río con bueyes..6, 8. Y pa eso se hacía una fiesta po, el dueño de la casa se rajaba con una vaquilla, con vino y todo eso, que no iba a pagar si no tenia plata…como 20 carneros a otra familia..y yo tenía un solo carnero encerrado ahí, un carnero de mala clase, así ordinario, yo le voy a contar como yo hablo no más, ese se salvó.. y yo tenía como 100 ovejas en otro lado, después encontramos al carnero con esas ovejas…la casa de don Barria también quedo dentro, la movió.. el otro día en la mañana ya empezaron votes a llegar, a ver que pasaba, por si había muerto alguna persona..Otra cosa que se salvó es la capilla, la pura iglesia, con un montón de madera al lado, pero no la votó, claro si se inundó, pero no la votó el agua…

Después se supo, sobrevoló un avión, un helicóptero, y vieron que era la laguna la que había reventado… se llama la laguna del Río Engaño.

Interview 3

De arriba de una lomita se veía el río que llegó al lago, empezaron a salir palos, y comentamos de que, que había sido, después empezó a salir la gente en vote, para allá para el pueblo nuevo, claro un vote cargao, la gente arrancó así sin cosas, y algunos arrancaron pal lado del cementerio, por la orilla del Murta pa arriba, se quedaron en la noche... la gente volvió al otro día estaba lleno de barro… no se podía andar, ahí en ese lugar donde paso el río porque quedó todo, con barro, la iglesia le llego el agua pero quedó ahí no más, no la movió nada.

Interview 4

Yo vendí allá por la creciente, compramos acá (*en Pueblo Nuevo*), yo tenía miedo po, cuando crecían los ríos era un ruido, ahora mi viejito falleció así que me quedé sola, (*como a qué hora fue la crecida?)* en la tarde, en la tarde yo había ido a lavar, no ve que esos años no habían lavadoras nada, había que lavar a la orilla del rio, entonces fui a lavar y de repente, fui con todos mis chicos, no tan lejos el río de aquí a aquí, y ahí cuando estaba la, había caldeado agua pa lavar, y de repente venían los palos así, tocando unos con otros, un rodado dije yo, y nada po, venia el agua por fuera, por detrás de la casa po, y arrancamos con los chicos, pa arriba de un cerro, ahí amanecimos en la noche, haciendo fuego, sin nada sin comer, sin ninguna cosa, toda la noche, (*cuanto niños había?*) eran 5, y dos sobrinos, claro arrancamos no nos dio tiempo pa salir a la casa nada, tuvimos que irnos de ahí no más, sin ninguna cosa, tuvimos que amanecer ahí toda la noche, nos sacaron con lazo, el agua inundó todo, como un lago, nos dio vuelta la casa, las ovejas todo lo llevó, los animalitos que habían, había subido quizás cuantos metros si llego arriba de los arboles, así tan alto como ese árbol, tocaba el agua arriba, todavía están en los árboles las señas donde tocaban los palos. (*Y ese día había llovido?).* Había llovido un poquito en la noche, pero estaba bajito el río… una laguna, una laguna que tapó con los témpanos, y esa laguna después se destapó, y se vino de un viaje el agua, (*cuanto duró la crecida*?) no un rato no más, ya empezó a bajar, después ya al otro día, ya no había nada había puro barro, puro barro, fue como a las 4, si po tuvimos que disparar para que no nos llevara la creciente, duraría unas tres cuatro horas no más, y de repente empezó a bajar así, así que quedamos sin ninguna cosa, y volvimos otra vez para allá, y nos vinimos para acá, nos fueron a buscar, pasaron en la barcaza, en un barco pasaron, pa ca pa este pueblo de acá, yo me fui ahí arriba donde mi suegra, ahí estuvimos, aquí arriba, (*y que pasó en el pueblo viejo*?) ahí no fue tanto, si igual pero, nosotros fuimos los más, los que sufrimos más arriba, claro la casa todo perdimos, en esos años no había ayuda, ninguna cosa, había que arreglárselas como, como era no más, ninguna cosa, el gobierno, nosotros creíamos que se había tapado la laguna nomás... En esos tiempos era a puro caballo, ahora están regalaos, tienen vehículo hasta allá mismo, antes había que pasar en vote allá, para traer los chicos a la escuela, mi viejito tenía que pasar con pilcheros con harina pal otro lado del río, antes crecía grande, ahora ni crece la porquería de río, no sé porque crecía tanto antes…vendimos allá compramos acá con mi viejito, porque el ya estaba enfermo ya sufría mucho reumatismo, no hace un año que falleció...(*ahora hay harto bosque arriba en el valle*?) no quedó nada, pura pampa quedó, ahora puro monte esa cuestión, si yo el otro día anduve donde la Rosario mi hermana, cuantos años ya po, nació todo el renuevo otra vez… (*me imagino como estaban de asustados ese día*) después cuando entraba a llover, parecía que dejaba todo listo la ropa a los chicos, todo para arrancar, por si volvía a repetirse, así que no me quedé tranquila hasta cuando nos vinimos paca recién, y acá estamos tranquilos, me dio susto esa cuestión…claro más encima estaba mi hermana, y nosotros, siete chicos, como 10, 11 habíamos, entre todos, tuvieron que sacarnos con lazo, las bardas arriba, del otro lado, para que pudiéramos hacer pie, no había a otra parte donde salir, así que nos ponían lazos y los agarrábamos nosotros, un avión anduvo mirando, si estábamos vivos o no, paso un avión pa vernos no más e hicimos señas, pa que nos fueran a buscar por el otro lado.. si po algunos conversan ni parecido como es po, sienten conversar pero, ni es como es, claro si por ahí han grabado, pero ni parece como es, yo sé todo como fue po.. ahí nos mandaron a sacar, pero salimos así con lazo, fue harta gente, (*para donde se cargó el río ahí*?) pa ca pa donde está mi hermana, ahí se tapó pue, han ido a los baños?, ahí en los baños se tapó, y empezó a volver pa atrás el agua, de puro palo, entonces empezó a hacer remolinos, así , se empezó a llenar, todo de agua, los palos se ganaron ahí, huu, yo me acuerdo de todo, como si fuera hoy, capas que si era en la noche nos ahogamos ahí, no quedamos ni uno, los chicos, salvar los chicos, milagro de dios lo que nos toco pasarlo, si no nos ahogamos todos, porque en la noche oscura quién va a saber…

Interview 5

Como el 70 parece que fue po, cuando se inundó el pueblo al otro lado (*Pueblo Viejo*), yo llegué el 66 aquí al otro lado (Pueblo Viejo), después cuando se inundó el pueblo, se mudaron todos pa este lado, ya la gente no quisieron que viviera , porque quedó la ceniza, así de alto el barro, claro y la cocina, toda llena de mugre, las camas todas llenas de barro, de ahí nos cambiamos a este lado, (*y cuando se cambió?*), de ahí no pudimos ir más pa allá po, claro nos trajeron a este lado, toda la gente…había que vandear en bote, por el lago si, y en carro por el río, cuando estaba bajo, si pa traer las cosas, (*y quien arreglo para que se vinieran*?), cada uno había que arreglarse pero igual nos ayudaban la gente, las autoridades, nos dijeron que ahí no podíamos vivir más porque no iba a ser más pueblo, se iba a terminar el pueblo, por la cuestión de la inundación…yo estaba tendiendo la ropa, mi ropa afuera, y en eso llega un caballero y dice se viene una tremenda creciente del río engaño, una revancha dijo, hay que arrancar, y nadie le creíamos, así que cuando de repente yo salgo a mirar y veo que está pasando una resaca, de palos pa abajo, témpanos, de nieve entreveraos en el río, y se hizo un tranque a la entrada del lago si ahí fue que empezó a rebalsar para el pueblo, el agua, donde se hizo ese tanque ahí, a la entrada del lago, así que ahí tuvimos que arrancar a la buena de dios sin ni una cosa, con lo puesto, toda la gente, (y para donde arrancó?) para este lado, tuvimos que ahí unos en bote, otros en la anca de caballo, los que tenían caballo, y así , si se inundó todo el pueblo, en un rato, llegamos hasta la orilla del lago, y había vote, ahí los trasladaban en vote, habían como dos votes no más, claro tuvo que hacer mas viajes, como el río acá venia entrando arriba donde está el paso de los caballos, ahí venia entrando la revancha, pero acá abajo todavía no, alcanzó a salir la gente, otros que escaparon para el cerro de la virgen, allá se fueron toda la demás gente, por allá se escaparon el resto, arrancaron pa allá, (*se quedaron en la noche ahí*?) toda la noche, y los de acá no sabíamos nada de ellos, no sabíamos que pasaba, si a mí me faltaban dos chicos, los mas chiquitos que eran así no más, se lo llevaron la misma gente que arrancaron, pa allá, los llevaron, los tenían allá en el cerro la virgen arriba, ahí en el cerro se fueron a acumular todos, la gente el resto, y otros arrancamos pa este lado, así que después era porque no sabíamos donde habían ido los hijos, si habían quedado metidos en el lago, o los había llevado la corriente, no sabíamos nada así que después, nos vinieron a avisar como a las 12 de la noche, que ya bandearon el río pa ca, a nado algunos que los chicos estaban allá con la demás gente, porque arranqué yo y mi viejo y una chica no más, la otra salió en anca de otro que venía de a caballo por el río (*como a qué hora fue esto*?) fue como a las 2, 3 de la tarde más tarde tiene que haber sido… (*tenían terreno acá*?) no aquí vivía ahí al lado un matrimonio que tenían restaurant, así que ahí nos quedamos nosotros con mi viejo y una chica que vandeo de acaballo al anca, y el resto no sabíamos nada de los más chicos, después a las 11 de la noche, nos vinieron a avisar que estaban allá en el cerro de la virgen con la demás gente, mi viejo lloraba porque no sabía si se habían juzgado los chicos o no y ellos también por otro lado, con ellos…(*cuanto duró la crecida*?) duró toda la noche, porque un caballero que se escapó a la orilla del cerco, aculatado con su caballo, el dentro a ver a su familia si estaban encerrados adentro de su casa, y después cuando salió ya no pudo salir po, se quedó aculatado en el cerco, con su caballo, y el amaneció ahí de a caballo, hasta que bajo el río como a las 11 de la noche, ya empezó a bajar de a poquito recién, al otro día cuando ya fuimos nosotros, como a las 11 del día, era un pantano así po, pura ceniza, como ceniza era la cuestión, igual que ceniza era, así que de ahí ya no vivimos más allá.. en esa época ya tuvimos que cambiarnos, todos no más las camas eran, todas llenas de agua barro encima, no había nada que ver allá, así que empezamos a sacar todo para lavar, las camas todo, nos trajeron camas nuevas todo, el gobierno, todo nos tuvieron que dar todo ayuda, porque toda llena de agua barro… no las casas quedaron allá, una sola casa que vandearon pa este lado, una que vivían por allá, los vecinos, las otras que la íbamos a traer, si era un tremendo trabajo pa trasladarlas con bueyes hasta el muelle allá, y después sacarlas pa ca, una sola casa que sacaron, con bueyes y todo, no las otras que las íbamos a traer, difícil pa traerlas, y tener hartos bueyes pa arrastralas, con rodillo, después se trajo todo lo movible no más, las casas quedaron ahí, la escuela igual todo hecho pedazos, si la escuela quedó llena de palos, la iglesia también, pero después le sacaron toda la palizada a la iglesia, pero la escuela no, quedó así no más, los chicos ya no fueron porque ya venían a este lado a la escuela los niños, los traían en vote…las llenó de barro adentro, si la estufa todo lleno de barro de agua, la maquina aquella igual, le entró el barro el agua, eso fue lo único que sacamos de la casa, y la loza, las camas nada, las camas quedaron puro barro y agua, mojas toda (*había gente viviendo en el pueblo nuevo*?) pa este lado? La escuela no mas, los niños los traíamos del otro lado a la escuela, estaban internados, (donde había más gente), no ya había más gente a este lado, poblándose igual, de a poco, una que por los niños la escuela a este lado, y a veces el lago estaba malo pa venir en vote con ellos traerlos, y llevarlos para allá también, así que muchos se estaban trasladando para este lado igual, ahí ya tuvimos que arrancar todos no más pa acá, yo con una comadre decíamos siempre que nunca nos íbamos a venir al pueblo nuevo, pero no falto la desgracia, arrancamos, ella rajo por el lado del lago en un bote paca cuando se vino la inundación y yo arranqué por el otro lado, ni supimos como arrancamos, que cosa terrible.. si pue venia un poblador de allá, y nadie le creía primero, y él les dijo que venía una tremenda inundación, porque allá cuando llegó un caballero, de a caballo al lado de mi casa al frente, con el agua hasta la montura, casi pasándole por el anca del caballo, ahí yo le creí igual po, que venía la creciente, y pa esto yo me fui a mirar para allá, y venían pasando así como el alto de la casa, palizadas pal lago, témpanos de nieve, de todo que traía el río la revancha, y en eso se hizo tranque a la entrada del lago, y empezó a rebalsar para atrás, para el pueblo, el agua, allá a la entra del engaño, y de ahí empezó a rebalsar para atrás para el pueblo, empezamos a arrancar todos para acá, era porque se hacía tanque la palizada, que venía de arriba, un derrumbe, fue una laguna que reventó ahí, en el nacimiento del engaño, y esa fue la que salió… no estaba boniito, bonito el día, yo había llegado ese día, dos días antes de donde estaba haciendo queso donde una comadre, tenían un cajón, como la mitad de ese cajón con quesos y una saranda y todo, todo eso lo llevó el río, la creciente, se abrieron las puertas con la misma agua, y sacaron queso allá por el lado del lago, encajaos en los cercos por ahí, después la gente peleando con los perros por los quesos, claro todo sacó, el agua abrió las puertas y sacaba todo lo que pillaba, una saranda que deje colgada arriba la única que no la saco, después el resto todo las camas llenas de agua barro, la cocina, así tan alto el barro, si uno se enterraba hasta acá en la greda, como una greda de ceniza así, no era como arena de río, era como que había sido reviente del un volcán, porque la cosa que después se fue secando, era como ceniza, como una explosión de un volcán, unos decían que una laguna que había, había explotado, pero no podía explotar la laguna sin que haiga una explosión de algo, que rompa todo para abajo, tendría que haber habido un reventón de un volcán, por lo que quedó después como ceniza…claro tocaron la campana pero la gente no hacía caso, fuimos todos a mirar a la orilla del río, y en eso ya venía rebalsando para acá, si alcanzamos a llegar no más acá, y ya venía entrando el río acá el agua también, algunos no alcanzaron ni a sacar ropa pa ponernos nada, yo había tendido ropa la entré pa dentro de la casa, quedó al otro día todo enterrado, en la arena y barro, como o a las 11 ya había bajado, pero igual el barro era sí po, los caballos quedaban hasta la panza en partes, con el barro, así que estaba todo inundado, con greda, barro. Habían cercos de palos rodados, caballos, adentro, de esos no había ni uno, claro algunos quedaron estropeados, se salvaron pero quedaron estropeados de los riñones, un caballo que teníamos nosotros, cuando se subían las chicas se echaba, porque llegó a votar sangre en la orina, estropeado, en un potrero de esos con palos como estos, de la estufa así de palos rodados, y ahí seguro que la creciente los saco envuelto con los palos, no sé cómo se escapó el pobre caballo ahí, todo golpeado, un viejito que pasó a ver su gente, cuando ya estaba un poco bajando, con el agua hasta la montura, dice que el pasó a ver su gente, adentro de su casa a ver si estaban ahí, no había ninguno, y ya no pudo salir porque se empezó a llenar de agua el, así que se aculató en un cerco así que había, en una lomita, y ahí se paso la noche con su caballo, hasta el otro día a las 11 salió de ahí… ya empezó a bajar ya, como a las 11 de la noche,(*a que distancia estaban las casas de la iglesia?)* unas más cerca otras más lejos, nosotros la quedábamos más lejos, después las otras estaban al laito así, cerca ahí, pero toda la gente igual tuvo que arrancar, no quedaron nadie... tremendo terrible… no ha habido otras crecidas más grandes que esa, después nunca más, antes tampoco había habido. Revanchas de nieve, témpanos de nieve, todo venia bajando, y nadie creía que era verdad que venía, porque un caballero vino a avisar, porque el venia de arriba, y él había vandeado el río, casi a nado, por el río del engaño, y ya venía a nado el río, y nadie le creía y yo cuando fui a mirar a lo que habían llegado primero, al lado de mi casa, hasta la montura llevaba mojada, hasta el anca arriba todo tapado de agua, los caballos mojados, ahí recién les creí, fui a mirar para allá venia la sonajera de palos y se estancó, en el lago y empezó a salir pal pueblo, y ahí arrancamos para la casa, para sacar, que cuando las cosas que traíamos, las pasaron a botar la gente arrancando, unos de a caballo, otros de a pie, yo deje ropa afuera tendida, tirada en los cercos, que ni una cosa había el otro día, todo perdido, la paliza quedó pa tiempo, toda esa resaca…terrible todo.

Interview 6

Tenía como catorce años, trece, y ahí fue que, cuando se inundó pueblo viejo, pero antes, nosotros vivíamos acá, pero solo en la temporada de ir al colegio, mi mamá nos llevaba a pueblo viejo, en bote, en bote o en caballo había que cruzar el río, había que cruzar lavado a caballo, o en bote, y ahí estábamos toda la temporada de colegio, llegaban las vacaciones y nos devolvíamos nosotros, y a este lado solo estaba la familia de los Puebla Pérez, que es de don Agustín Puebla, que es el único que gracias a dios que está vivo, y ellos eran dueños de todo todo, o sea ocupaban toda esta parte, y la otra gente para allá, mi papá, mi abuela, al otro lado del río, y una tía, y esa era toda la gente que había aquí, estaba la familia de mi abuela, Hada que vivía al otro lado del río Engaño, a este lado vivía mi papá, y hacia allá, hacia la isla don José Benavides, y acá vivían los Puebla, todos los Puebla, toda la familia Puebla, todos los hermanos, don Agustín, don Andrés, don Julio y don Sergio Puebla, y don Gonzalo Miranda, ellos todos con sus familias, y la señora Filomena Puebla, que era la que vivía por ahí por la vuelta, y esa era toda la cantidad, esa era todo la gente porque todo era campo, entonces vivía cada uno en sus campos, después como el año 70, 71, ya la otra escuela era muy chica y vieja, entonces después venían del pueblo viejo los niños para acá, porque esta fue una escuela hogar, entonces ellos estaba de domingos a viernes, en el colegio y ahí se regresaba para sus casas, el 71 yo creo que se empezaron más o menos las clases acá, 71, 72, no me acuerdo muy bien, y antes toda la escuela era al otro lado…la escuela (*en Pueblo Viejo*) ya no estaba funcionando cuando se inundó prácticamente, estaban todos trasladados para acá, estaba acá ya la escuela, allá solamente estaban todas la familias porque no se movían porque era el pueblo, si acá (*Pueblo Nuevo*) solamente estaba la escuela porque no podían construir porque no había espacio, el pueblo era grande allá porque cuando se construyó la escuela, acá habían como, aparte de las 6 familias, de la familia Puebla, la escuela, mi abuela Hada, mi papá y la tía Gema, estaba la gente que vino a construir la escuela no más po, nadie más, entonces no había gente prácticamente, el pueblo en si estaba al otro lado (*Pueblo Viejo*), el día de la inundación estaba acá (*Pueblo nuevo*) de este lado, nosotros supimos después en la tarde, que andaban un profesor, que falleció, que era el director de la escuela, que iban siempre los fines de semana a pueblo viejo, porque allá había de todo, había negocio, entonces ellos fueron para allá, y en eso sintieron el ruido, y se volvieron en bote, el río se desbordó todo, creo que fue un fin d semana, no sé si fue un viernes o un sábado, la gente se tuvo que trasladar para acá, porque quedó, todo inundado, algunas casas las movio el río las giro, y las llenó todas de arena, ha y un caballero que era enfermito, le decíamos manuelito, y él se subió arriba de las vigas, donde sostienen el techo, y ahí se salvó del agua, hasta cuando lo encontraron al otro día… las casas las trajeron como una minga como las que hacen en Chiloé, las trajeron sobre tambores por el lago, los que saben la historia porque fue el papa de ellos, es Mariana y Rodrigo, ellos trajeron su casa, el papá de ellos, don Nicolas Berrios, hicieron tambores montaron, sobre tambores y ahí la tiraron en bote, cruzaron el lago, fue muy lindo eso, parece que se quemó la casa, ellos deben de saber si está todavía la casa, que trasladaron y la historia bien porque ellos la vivieron, era la casa de ellos, el pueblo viejo era pueblo, tenía mucha historia, era más amplio, era un pueblito muy bonito, era tan hermoso el pueblo viejo que era, todo bonito, tenía más extensión, había posta, si habían, si era un pueblito formado, se restauró el santuario de santa rosa, quedó ahí mismo si el río no la, no llegó ahí la inundación, la virgencita poderosa que la protegió, para que no se la llevara para que quedara para la historia…

Interview 7

Si, salió el engaño y mató cualquier cantidad de animales, salieron animales entre los montes, el río Murta…cuando salió el Engaño estaba yo en Sánchez, estábamos carneando…salió el río Engaño, dije yo, nos llevó toda la casa, pero no pasó más que arriba, este, el murta, el Engaño, saco toda la casa, ahí estábamos en la casa nueva…yo viví con un español, Evaristo, cuando hizo la casa nueva de 12 metros, con media agua y todo estaba lleno de negocio arriba y abajo, un tremendo almacén, dos pisos, y tenía puertas pa fuera, tenía una lancha tenia de todo, y de repente salió el río Engaño y llevó, el galpón de los Carmona lo llevo todo, tres galpones que eran de 14 metros de largo, ahí dejaban madera había muelle, y tenían una aserradero arriba en un campo, y de ahí sacaban la madera y la transportaban para chile chico, pa argentina. Y ahí el español al lado de los galpones hizo el negocio, su casa, yo le decía pa que la hiciste puede salir una creciente, dicho y hecho, cuando salió la creciente lo llevó donde los Pérez por allá abajo, en la isla fue a quedar la casa, todo llevo los galpones, barrió, quedo todo todo en pampa…cuando llegamos era puramente playa…no había una sola cosa, la llevaron la gente…estaba contando cuando nos llevó la casa nueva, el almacén ese, y los Carmona todo se llevó…después salió el rio Murta…después de la crecida estuvimos arriba en el campo…un campito allá arriba, teníamos animalitos…nosotros tuvimos mucha perdida aquí 3 veces nos castigó el río… en el pueblo viejo si, en esa isla grande…

La gente del pueblo viejo trabajaba en el aserradero de los Carmona, y ese hombre fue el primero que trajo en aserradero, pa allá pal otro lado, Murta, el Engaño arriba, en el campo de los Barrientos, arrendó el campo de la montaña, y ahí sacaba la madera, ahí lo aserreaban lo hacían tabla, y lo llevaba para Chile Chico, tenían barco ellos, había un muelle con todo, con carretillas de fierro, con este donde corrían los rieles, todo, bien hecho el embarcadero ahí, donde entraban los barcos, ahí hacían de todo, tenían madera un montón, el muelle se lo llevó el río po, lo desarmó todo, no dejo ni una casa, las casas eran de 12, 14 metros, con galpones, esos muelles estaban llenos de madera, de toda clase de madera, pa que los manden pa Chile Chico, pa Argentina, así le hicieron contrato(*que madera*?) de la lenga, laurel y mañio parece. Los Carmona hicieron muelle, ellos hicieron pa que embarquen la madera, si eso estaba bien arreglado, y de repente vino el río Engaño y lo sacó todito, la barrió, después los Carmona ya no siguieron más, porque entregaron, ya sacaron su aserradero y, entregaron el campo y se fueron para Puerto Montt, las casas todavía tienen al otro lado, a donde vivían ellos, todavía viene el avión ahí hay una canchita, de avión, pero según dijeron habían comprado los españoles, es un bajo grande, y ahí donde tengo yo la casa igual.. yo cuándo fue esa creciente sacaron todos esos papeles, los robaron… teníamos de todo nosotros, tremendo negocio una casa de 12 metros, nuevita, la llevó allá abajo en esa isla allá abajo, lo fue a dejar, se llevó los galpones de los Carmona, eran 3 grandes, 4 casas, más la de nosotros 5, como 7 8 casas se llevó ahí, el Murta el pedazo del Engaño, porque lo sacó limpito, las otras casas quedaron del otro lado del río, de la iglesia pa este lado, ahí quedaron, paca, la casas que afectó estaba más al centro, en el mismo sitio de tierra donde estaban los galpones de Carmona, ahí estaba, porque había una parte que estaba, esos eran unos campos, Genaro Berrios, y ese Genaro Berrios arrendó todo ese pedazo debajo ahí, y después fue vendiendo por sitio, todo el resto de la tierra, hasta venir acá al río Murta, la iglesia la hicimos a última hora, cuando yo vine, hicimos la iglesia, la escuela, hicimos de todo porque no había nada, vine con ese español, hicimos la escuela primero, juntamos los padres de familia, los hicimos reunir, pa hacer la escuela, los chicos porque no tenían, había un gringo que daba clases a las casas, y después empezaron, cuando hicimos la escuela, ahí empezaron a venir los profesores, después hicimos la iglesia, con el finao Miguel Ávalos, esos murieron todos, los primeros promotores, y ahí hicimos la iglesia, después hicimos un centro de madres porque no había ropa no había nada para traer, porque era muy difícil traer de Chile chico, mucho viento mucho hielo, y no habían embarcaciones, claro estaban los puros barcos de la empresa, entonces yo les dije vamos a hacer un centro de madres, como yo vivía en Chile Chico y en Murta, yo dije me voy a encargar de traer todas esa cosas que faltan acá, trajimos lana, trajimos mezclilla, trajimos ropa trajimos para hacer sábanas…(*y que año seria eso 60 ,70?)* no recuerdo, antes, yo lo tenía todo escrito pero cuando se salió el río se llevó los papeles también, total que ese tiempo barcos no habían, la gente pilchereaba, una semana demoraban de ir pa Chile Chico, rodeaban todo el lago, y usted sabe como la rodea del lago como es de lejos, tienen que dar la vuelta allá en Bertrán…(*después trasladaron la escuela?)* pero eso ya fue este lado, cuando vino, empezaron a arreglar acá, pa poder venir, cuando empezaron hacer ese camino, cuando hicieron ese camino de Coyhaique acá, ahí hicieron esta escuela, primera era la escuela allá al otro lado, después a los años se hizo esta escuela acá… la última creciente del Engaño, esa pusieron acá toda la gente, esa ya estaba la escuela acá (en *Pueblo Nuevo*).

Interviews 8-9 (two family members)

Cayó al otro lado al río Murta, fue una cosa de una hora más o menos, todo fue super rápido, entre que empezó a bajar el agua y nosotros arrancamos a pie por la orilla del río Murta pa arriba, nosotros alcanzamos a pasar para arriba, y el agua del engaño calló al Murta, mi papá que andaba a caballo, el ya pasó con el agua en la montura, por la orilla del río pa rriba, entró por sanjón de doña Carolina, donde vive Roberto todo eso se llenó de agua, claro entró ahí al zanjón, ahí donde se va a pescar ahora, donde sacan truchas, ahí cayó el agua del río y salió pa ca pal Murta, toda esa pampa si se inundó todo, ha de a ver traído harta altura, un metro un metro y medio, (*donde está la iglesia vieja también se inundó?*) todo eso… no casas no se las llevó, las movió, una casa, la de don Alejandro Martínez, donde estaba la dejó vuelta pal otro lado, pero las otras no movió ninguna, se llenaron de agua arena y barro, justo ahí había una caída de agua, así que hizo más fuerza, lo levantó…(*usted me decía que cruzó en bote?)* en bote, habían como dos botes, un bote municipal me acuerdo que había, de don Alejandro Martínez parece que había otro, así que ahí los tomamos no más, a remo, a buscar gente volver a buscar más, (*cuantos viajes hicieron*?), como dos viajes, porque harta gente arrancó pa arriba, pal lado del cementerio, (*cuanta gente cabía en el vote?)* asustaos cabían más, 10, 15. Eran botecitos grandes como de 7 metros, ahí fuiste a ver a mi abuelita? de ahí fui yo, porque nosotros como habíamos bajado todos de allá, habían quedado mi mamá y mi hermana chica, entonces lo que nos preocupaba a nosotros es que hubiera estado abajo, y ella dice que cuando vio la cosa que venían palos y arrancó pa una mesetita, que en la noche nosotros pusimos evitar de este lado el Río Engaño, al altito arriba se veía la luz del fuego, de la gente que había arrancado pa llá)? claro mi mamá y mi hermana chica, y allá amaneció ella?),claro ahí se quedaron, nosotros no nos atrevimos tampoco a vandear porque no sabíamos, que profundidad tendría todavía en la noche, en la mañana fuimos para allá, ella vio harto más de lo que vimos nosotros, que vio la parte cuando venían los animales, los animales entre los palos, que se veían de repente las cabecitas, las vacas que se hundían, y de ahí dice que como a la media hora, fue ya pasó un poco, y los animales , varios animales que habían ahí, dice que empezaron a volver, algunos se ahogarían tal vez, pero, de vuelta pa arriba dice mojaos enteros, un buey se le cortó la cola, todos los palos, toda esa parte, después del susto dice que se veía muy bonito, la cabecita de las vacas no más, todo lo que estaba en el plan arriba lo arrastró el agua, de don Mario tienen que haber mirado pa dentro pa los valles? claro es que lo que pasó fue, que después, sacando conclusiones, y viendo recorriendo para arriba, no sé si de las termas para abajo hay un salto, que pasa que es pura barda, y hay un salto, y ahí se tapó con palos, entonces empezó a subir a subir el agua, y ahí empezó a volver, si por eso se inundaron tanto los valles para atrás, subió mucho el agua, y cuando ya hizo demasiada presión el agua, salió toda esa palería esa resaca, quedó la pura barda, ahora, está bueno, han salido un par de montes, pero en ese tiempo estuvo pelao, donde con la presión del agua, porque por ahí pa rriba enanltó en partes sus 5 , 6 metros, estaban arriba, los coigues, las marcas del agua, (*como a qué hora vieron la crecida?*) como a las 6 de la tarde nosotros vimos eso, entre que nosotros llegamos arriba y todo se notó que empezó a bajar el agua como a las 8:30, 9 por ahí, oscureciéndose ya porque eso fue en Marzo, el 11 de Marzo…un día sábado, del 77, yo me acuerdo porque nosotros inventamos una canción, no se las canté la otra vez ahí…ahí decía todo pue, que el sábado, un día once de marzo, a las 6 de la tarde, que el pueblo se inundó, que la gente arrancaba y todo, esa canción hizo llorar a la gente…(*cuando la cantaron?)* en la semana Murtina, en la semana hubo un concurso, de las alianzas, me acordé de esa canción, porque es una historia real, (decía, luego de ver mi pueblo tan hermoso, casas llenas de barro, hasta una casa al revés decía po) es un corrido, (*ese día estaba despejado o llovió?*) no estaba hermoso el día, más despejado que ahora, si po un día de sol que había, y el río bajo, bajo, porque en ese tiempo se cruzaba el río a caballo, el Engaño y el Murta…hay pasos, hay vados, en partes que hay quebraderos así…las casas eran de tejuela, madera…y después que pasó la creciente, como a los 15 días vino un helicóptero, y mi padrastro fue en el helicóptero, para ver donde había reventado la laguna, y ahí dice que es una laguna, y tienen donde desemboca, donde empieza a salir el agua de la laguna, rodados de los dos lados, cayendo arena, y seguramente se empezó a tapar a tapar, y subió mucho el nivel de la laguna, entonces cuando ya subió demasiado, explotó, reventó, y ahí fue que pasó la creciente…pero después nosotros anduvimos en la otra cordillera del frente allá y mirábamos, claro que se ve así como rodado de los dos lados, (*y se ve el glaciar?*) más arriba sí, pero, está como en hoyo la laguna, una hoyada, se ven las piedras el faldeo todo donde bajó, donde se nota pero subió una cantidad de metros, pero una tremenda hondura tiene que haber tenido, donde se empezó a tapar a tapar con el rodado, empezó a hacer una pared, y eso fue lo que reventó y quedaron, quizás a lo mejor hasta un tempano se trancó…ahí en el pueblo viejo quedó una persona, que empezó a sacar sus chanchos sus gallinas, quedo una persona a caballo, amaneció a caballo, en una yegua…dice que lo más que tuvo es el agua hasta la guata de la yegua, pero un filito se ganó, en una partecita que era más alto que el resto, y ahí amaneció caminando para que no se le…sabíamos nosotros que había durado poco también porque él dice que como a la hora empezó a bajar, empezó a sacar los animales y no alcanzó a salir, cuando quiso salir ya estaba rodeado de agua, como no era planito po, habían zanjones que cruzar así, unos bajos, tuvo que esperar así no más…(*en que trabajaba la gente en ese tiempo?)*si, había un aserradero, pero en esos tiempos, ya no, el finao Norberto Sanz, un turco, pero no lo estaba trabajando, si po si estaban sacando madera, quedaron carros con madera, haa o sea estaba sacando la madera ya, o sea no estaba aserrando, no no, estaban sacando la madera que tenían acopiada, y Murta principalmente ganadería, animales…(*había un muelle?*) sí, el mismo turco hizo un muelle cuando empezó a trabajar, ahí sacaba en el Chile en ese barquito que está en la foto, en la Unión, y el General Carrera era el otro…(*esos usaron para arrancar?)* no esos eran barcos, grandes, viajaban a Chile Chico a Ibañez… en esos sacaba los productos el árabe…(*el pueblo nuevo ya estaba?*) quedaba poca gente en el otro pueblo, ya se estaba trasladando la gente pa este lado, (*y después de la crecida*?) ahí se vinieron todos, ya toda la gente se empezó a venir, el mismo año se empezaron a trasladar, quedaron como 2 o tres familias no más allá, don Alejandro, don Raúl, y el Navarro, el viejito yo creo, Berríos, nosotros nos quedamos en ese lugar como cuatro años más, y doña Carolina que todavía vive allá, como 6 familias quedaron allá todavía, se vino doña Joaquina, se vino la mamá de doña Ana, la Tola, quedó allá la tati con el lara…(*se trasladaron unas cosas en bote, cuantas serían?*) unas dos no más, pasaron por el lago, la de don Nicolas Berrios el viento se llevó los botes pa bajo…claro si ahí se ayudaban los pobladores, porque para llegar al lago lo tenían que traer con bueyes, la pasaban en vote ahí, y acá la recibían con bueyes…(*en el momento que pensaron que era la crecida?*) salimos corriendo a mirar que era ese ruido, había un cerco pero de palo así, (grande) y nos subimos arriba de ese cerco a mirar, y vimos el agua que venía, y él me dijo hermaniiita el mar viene saliendo, así que ahí conocí el mar, ahí yo todavía no lo conocía, claro y nos largamos abajo y nos arrancamos, y le gritábamos a mi mamá que arranque, y arrancaba, y la señora de don Norberto, el turco, que tenía el aserradero, arrancó con nosotros, tenía un niñito chiquitito, como de un año y tanto tenía el niño, dos añitos, con su chico en brazos, y poco pa arriba se hincaban en los palos a rezar, y yo les gritaba corran corran, que rezan huevas, corran corran, que rezan huevas les decía yo, y después llegó otro, un hombre que andaba de a pie porque quiso, agarró unos caballos que andaban sueltos, con el cinturón, se sacó el cinturón, amarro un caballo, y los saltó así para arrancar a caballo, y el caballo lo votó po, corcoveó y lo votó, y se le fue con el cinturón, y él iba con los pantalones en la mano, tiraba un poco los pantalones y corría, y le ayudaba a su hermana a llevar el niño, Ramiro Romero, y ese de repente llegamos había una lomita así, con hartas raíces de estos palos, secos, quemados, secos, y empezó súbanse aquí, súbanse aquí, yo iba más atrás, y llego y habían como 4, 5 personas arriba de esa raíz, que, bájense de ahí corran, corran, y ahí llegó mi papá a caballo, y les hizo que se bajen y sigan corriendo. Sí alcanzó esa raíz, no quedó ni noticia, no claro se la llevó, así que ahí seguimos corriendo, alcanzamos a pasar, y la corría tenía que ser antes que el engaño entre al Murta, claro y de ahí mi papá volvió para la casa, porque se acordó que había cerrado las puertas, y volvió para la casa a caballo, y nos decía a nosotros que corran, que corran hasta el cerro, ordenó que corramos hasta el cerro, y después cuando el ya volvió, pescó una paleta de carne, y se la echó por delante, de ternera, que habíamos carneado, y se la llevó po, y cuando volvió, ya pasó con el agua casi a la montura, ya había caído el agua del Engaño al Murta, si porque le Murta está casi más bajo que el Engaño, si ahora porque hay barranca no más, porque como corrió con tanta facilidad pa acá…ese es el galpón de Roberto, y por aquí paso el agua, pasó por la costa, por esos galpones y calló acá, por la orilla del cerro se podría decir, dice la hija por la costa, por donde está el cementerio en el plan por ahí calló, no se inundó todo…donde venia el caudal del río yo creo que esa parte venia mucho más alta, porque se empezó a desparramar para acá ya venía más bajo, las casas le quedo como un metro, más metro y medio…todo eso, si un hermano del estaba copeteao, lo votó un caballo y lo aturdió, y en el plan abajo, y el papá de él lo arrastró, arrastró hasta que lo sacó de ahí, a un cerrito una lomita, chiquita que hay donde Roberto, hasta ahí lo saco si no arrastra se lo lleva, si po estaba aturdido, el finao Mauro, lo votó andaba en caballo mañoso, un potro…(*donde tomaron el bote?)*, en la montañita que se ve al otro lado, en la puntilla esa con montañita, el muelle no tenía nada que ver, la gente cruzaba donde era más angosto no más, el muelle estaba donde desembocaba el Engaño en el lago, de ese muelle ya no queda nada, antes había un muelle antiguo, este es otro muelle. Había una cancha linda, una pampa parejita…(*en esa fecha había arboles?)* sí si había hartos árboles, hartos álamos, los sitios eran así como estos de árboles frutales, había harto árbol frutal, en las quintas, ahora no hay árboles…la crecía los inundó no más…

Interview 10

Estábamos en el pueblo viejo, si estábamos allá nosotros, cuando creció, cuando se vino la laguna al pueblo, una laguna fue si, si se llenó todo el pueblo de agua, disparamos nosotros, disparamos nos vinimos para el cementerio, allá en esos cerritos nos salvamos, varias personas hartos, vivíamos ahí nosotros, se lleno el pueblo de agua, las casas todo, pero ninguna se llevó el, se llenaron de agua no más, de barro de todo, pal cementerio, estábamos nosotros con mi viejo unas hijas que teníamos, todo, éramos 6 que vivían ahí, estaban los chicos en la escuela…(*usted que estaba haciendo ese día*?)yo estaba lavando, había tendido harta ropa, la había tendido en cerco que teníamos, en un cordel, cuando vino la creciente la llevo toda, vino mi hijo a avisarnos a nosotros, nos dijo que estaba en el campo no sé donde que andaba, llegó y dijo disparen que viene crecido el Engaño, viene crecido el Engaño así que disparen, otro notaba dijo, no, no era cierto, nosotros venimos de allá y el río está casi seco, no es na cierto dijo el muchacho, está mintiendo dijo, y al ratito empezó la gente, se viene el Engaño al pueblo, y claro el andaba avisando el hijo de nosotros, como va a ser mentira, es grande, es hombre ya, como va a estar mintiendo, nosotros somos los padres y el nos pasó a avisar, así que nosotros disparamos enseguida no más, hartos, éramos varias familias como 20 (*en el cementerio)*si el pueblo tenia harta gente, vivía harta gente en el pueblo, así que ahí todos disparamos… *tocaron la campana para visar*?) si claro para avisar, en ese momento que se vino el rio al pueblo, de repente llegó a avisar el hijo de nosotros, y salió avisando por las casa por todos lados que disparen que el engaño venia muy crecido, por el nos salvamos si no nosotros nos ahogamos, no íbamos a saber nada, iba a llegar el golpe de agua no más, no íbamos a hallar pa donde disparar, si toda la gente dispararon…si amanecimos, así que la gente del pueblo nuevo nos llevaba de comer, carne, pan todo, porque el Murta no estaba na crecido, no el Murta estaba bajo, nos fueron a ver llevarnos pilchas también, así nos salvamos (*cuanto duró la crecida*?) como dos días duró, nosotros como un día estuvimos allá, toda la noche, al otro día, al otro día, como al medio día nos vinimos para la casa, pero el barro estaba así tan alto…si tronco de todo, palos grandes, todo, tremendos trozos, la casa de nosotros la saco no más, y un poquito más abajo la dejó, si la movió, la sacó, pero no le pasó nada no (*cuanto tiempo siguió viviendo en el pueblo viejo*?) harto tiempo, más de un año, como dos años más, y después ya empezamos a cambiarnos para este lado…porque decían que iba a volver a salir el Engaño al pueblo…una laguna parece que hay, y ahí salió…(*y sus vecinos*?) no casi todos nos cambiamos para acá, que ahora ya no hay gente en el pueblo viejo, ahora se ven como dos familias , tres habrán…(*en que trabajaba la gente allá en esos tiempos*?) era chacra, en sus campos, la mayoría de la gente era campesina, tenían casa en el pueblo, eran como nosotros, nosotros éramos campesinos…estábamos en el campo teníamos los chicos en la escuela, por eso estábamos en el pueblo…(*la escuela estaba allá, en el pueblo viejo, o acá*?), no estaba al otro lado, si allá era pueblo acá no era pueblo, acá habían pobladores pero, que tenían campo, chacras…(*y había un aserradero*?) aserradero? Ahh, si don Norberto Sanz tenía aserradero, no había aserradero… si había, ahí la gente sacaba madera, (la hija, si mamá si había aserradero) si el muelle quedó ahí no más, no se lo llevó el río…si don asir, tenia gente trabajando, sacaban madera, un motor tenia, un aserradero…(*como cruzaban de un pueblo al otro?)* de a caballo no más si el Murta estaba bajito en ese tiempo…no me acuerdo que fecha fue, sería en enero, Diciembre, Enero, el río estaba bajito el Murta…habían bote, un bote municipal, así que cuando estaba el río crecido, bandeábamos en bote pa este lado…había un bote que tenía que bandear los chicos de la escuela, y era de la municipalidad, tenía que llevar los chicos y traerlos (*se cambiaron algunas casas para acá?*) de a poco empezó a cambiarse la gente, de a poco no más se fue cambiando, sacando las casas de a poco, hasta que se cambiaron de este lado…(*y allá quedó solo la iglesia?*) si quedó todo abandonado ahí, pero hay gente si como dos o tres pobladores, nosotros disparamos, porque a lo mejor iba a volver a crecer más, pero no ha venido mas ya, decían que había sido un rodado, que había venido, y se había caído a la laguna, la laguna hizo explosión, salió toda porque, quizá que profundidad de barro tenía el rodado, de piedras, de todo, nieve…(*a qué hora fue la crecida*?) tienen que haber sido como a las 2, 3 de la tarde, por ahí más o menos, no me acuerdo bien porque hace tantos años, por ahí era, si después de doce, capas que no sea ni parecido, no me acuerdo muy bien tampoco, hacen años… *y que pensaron que era*?) disparamos no mas, unos de a pie, otros de acaballo, la cuestión era que teníamos que salvarnos, disparamos pa los cerros…disparamos de allá y el camino salió…ni vehículo venían tampoco…(y el Engaño lo cruzaba de a caballo?) si de a caballo no más cuando estaba bajo, cuando estaba hondo en bote, así se ahogaba gente también, se ahogó mucha gente en el río ahí…cuando estaba crecido…perdone que no tengo más que decirle…todo eso es verdad no más. Si le digo más es mentira, así que para que le voy a estar diciendo más.

Interview 11

Yo vivía en el pueblo nuevo, fue una persona en bote a buscar más botes, para poder sacar la gente, y dio el aviso, y yo en ese momento estaba donde mi suegro, en la costa del lago allá, y ellos tenían bote, así que ellos prestaron el bote, así que yo con mi niña menor, que era la única que yo tenía, fui arriba, al faldeo arriba, donde está Agustín Puebla ahí, y de ahí pudimos ver como venia, pero venia, el agua así como por un cañón redondo de agua venia arrasando con todo, eso es lo que yo pude ver, desde lo alto se veía, se veía ese sector del cementerio bajo, por donde venia inundándose de agua, claro y con una altura de unos 5 metros de agua, o más quizás porque los arboles quedaron los palos encajados arriba, bueno después en la tarde la gente se trasladó para este lado, o sea pal pueblo nuevo, y decían que había durado más o menos unas dos horas el agua, y después ya se había empezado a retirar, claro porque bajó de una (*y como a qué hora fue*?) como a las 3 y media cuatro de la tarde, pero había un día de sol, un hermoso día, no si era que se tapó la laguna, el motivo por el cual salió la crecida. La mayor parte de la gente estaba en el pueblo nuevo, si el pueblo nuevo se empezó a trasladar para allá en el 65 y en adelante, se empezó la escuela y todo, y el aluvión fue el 78, así que ya había hartos años, había más de 10 años, de gente que vivía en el otro pueblo, en el pueblo viejo quedaba la gente que vivía más enraizado y que no veía tanto peligro po, en un primer momento se decía que podría haber sido algo de volcán, que había recalentado los hielos milenarios, que habría sido la consecuencia, pero después lo sobrevolaron, tampoco quedó muy claro, pero en el pueblo mismo la gente que vive ahí, dice que fue que se ganó un tempano de nieve en la salida, y después desbordó po, y que tal vez nunca más va a ser nos decían ahorita, mi sobrino porque decía que hizo un tremendo boquerón…yo no sé a qué altura llegaría en las casas porque yo trabajaba en la escuela así que no, y tampoco soy muy amiga de andar curioseando. Los primeros días se quedaron en la escuela, ahí los atendíamos en albergue, después se fueron cada uno distribuyendo, entre las mismas familias, y otros volvieron a sus casa no más, y ya varios empezaron a hacer movimiento para trasladar sus casas para el otro lado, porque las trasladaban con bueyes hasta una parte, y ahí las lanzaban al lago y en bote al otro lado, para no tener que desarmarlas, (*cuantas casas habrán transportado por el agua?*) unas 10, no tengo muy claro, no no si fueron varias, y desde antes también ya se estaba haciendo eso, ya se habían trasladado…(*cuantos botes habían para cruzar gente?)* no después se juntaron todos los botes que habían, 4 serían, porque allá al otro lado habían botes, en todos lados habían botes por las orillas porque se movilizaban en bote, no había puente (*así que otra gente se fue al cerro?)* claro pero esa gente después tuvo que venirse para el cerro para este lado, claro se fueron por la orilla pa rriba y salieron, por allá por la altura del cementerio, para que no les corte la pasada, había un cerrito ahí, (*alguien alertó que el rio venía?*) no, lo que alertaron es que el río se había secado, que algo pasaba que más tarde iba a venir la creciente, eso fue lo que alertaron, una gente que trabajaba en el aserradero por ahí, en ese tiempo, y ese vino a alertar que el río se venía secando, que algo pasaba porque, no podía ser, (*usaban como alarma la campana?*) claro, siempre se usó y se usa hasta la fecha ante cualquier emergencia la campana porque no hay otro, no hay bombero, para alarmar a la gente y escuchando sonar la campana en la noche o algo todo el mundo se levanta rápido porque saben que es una emergencia…para saber generalmente donde está el incendio…(*en el pueblo viejo había un aserradero?)* no, no era en el pueblo viejo, era en el Engaño para arriba, en los campos…acá había un muelle donde embarcaba don Norberto Sanz, que era un hombre que tenía unos barquitos y tenía un aserradero, él era el que trabajaba , hacia convenio con los dueños de los campos ahí sacaba la madera…La persona que empezó todo el trabajo para trasladar el pueblo, de acuerdo por supuesto con el resto de personas, fue Lucho González, un poblador humilde y sencillo del lugar… Toda la gente sugería pero él cuándo venían autoridades se dedicaba 100% a mover la comunidad y la mayor parte de las cosas que hay, se hicieron con el apoyo, o la iniciativa de él, y todo el resto de gente apoyaba por su puesto, pero él fue un hombre muy cooperador…(*y cuál era el motivo para cambiarse?*) bueno, porque el Río Murta atacaba hacia allá, y el rio engaño atacaba de allá hacia acá, entonces el pueblo estaba quedando en un lugar muy angosto, con un riesgo inmenso, y no había el sistema de hacer gaviones ni como tampoco hacerlo, no había para poner defensas, porque ahora se colocan estos empedrados de defensa, y el rio tiene que partir para otro lado, antes no había, no había nada de eso, yo creo, calculo yo que el pueblo ya pensó en pensar en cambiarse como el año 60, 61 porque el 64 ya se logró cambiar, o se logró empezar a cambiar, porque todo lo que contraía hacer la diligencia, tenía que la gente en barco a hacer las diligencias, no es como ahora que pesca el teléfono. Ahí no estoy muy claro cuando se empezaría a cambiar el pueblo, pero por lógica tiene que haber sido por ahí, el 64 ya se cambió, la escuela nueva se fundó el 65,66 por ahí, y se inauguró el 67. Venía un profesor del pueblo nuevo a hacer clases acá, o habían unos que pagaban una pensión y hacían clases a los grupos de los niños, pero después empezó a querer terminar con eso porque la escuela del internado era una excelente escuela, bonita, con todo, aquí (Pueblo Viejo) era una escuela que carecía de hartas cosas, pero igual se mantuvo un buen tiempo así a pelea porque la gente no quería asumir que tenía que irse porque no le gustaba el lugar, acá era mucho más bonito, si po, un lugar plano bonito, allá al otro lado (*Pueblo Nuevo*) hasta parecía que podían caerse rodados de arriba, no ve que si usted ve el cerro lo ve bien empinado, no la gente no le gustaba nada, nosotros no po, yo con mi marido por ejemplo, nosotros vivíamos en una isla (antes) y cuando nos vinimos de allá porque nos dieron un sitio en Pueblo nuevo… (*esos sitios como los conseguían*?) los daba bienes nacionales, a nosotros nos dieron sitios, a otros les dieron quintas, chacras, nosotros nos vinimos ahí y siempre fuimos ahí, nos vinimos el 68 y ligerito empecé a trabajar en la escuela…(*cuantas casas habrían en el pueblo viejo para la fecha de la inundación*?) yo creo que quedarían unas 12 familias, una cosa así más no, si no quedaba tanta gente, pero muchas casitas desocupadas si porque estaba la gente esperando para trasladarse, gente que estaba en el proceso de trasladarse, y adaptarse porque a la gente no le gustaba allá el *Pueblo Nuevo*, ya el 71 se hizo la cancha de aviación, el 73 se empezó con el muelle, la rampa, ahí donde está el Agustín Puebla, al ladito del faro…*se usa el muelle*?) no nada ya po, nada de embarcaciones… se dice que los primeros pobladores llegaron en la década del 38, 40 por ahí, porque hay gente que tienen hijos que nacieron acá y nacieron en 1941, o sea uno lo deduce y el pueblo se formó como el 52, 53 yo creo, el pueblito, ya se declaró pueblo porque antes, había un pueblito que era de la naviera pero como un campamento maderero, el que era el patrón de la madera era don José Carmona, pero después cuando ya se fundó, para que se entreguen sitios y todo, fue entre el 52, 53, otras personas dicen que todo se hizo muy rápido, pero eso o no lo creo mucho porque la gente para hacer un trámite tenía que viajar a Puerto Aysén, y los barcos venían una vez al mes, así que ahí es donde hay que arreglar la historia…si cuando los pobladores hicieron la escuela, el 54 yo creo que la entregaron, yo vine a la escuela el 55 y ya estaba, y ellos hicieron la escuela, y después la fueron, una persona que fue a hacer el tratado, y a ofrecer que dieran un profesor, para que sea el director, y ellos los pobladores entregaban la escuela, la escuelita era muy chiquita para, no sirvió mucho…y ahí como que unas personas me han conversado de…yo me acuerdo partes, pero no me acuerdo de todo.. nosotros entrabamos en septiembre a la escuela, y salíamos en Mayo porque en invierno era muy rudo porque la escuela no tenia calefacción ni nada…era my lindo lo que hicieron…se hizo la escuela, después la iglesia, y el resto las casas de cada cual (*habían negocios*?) de don Leandro Huerta y don José

Carmona, los que tenían negocios, don José Carmona tenía un almacén que se le llamaba la pulpería que tenía como para surtir a su gente, que trabajaba en la madera, y don Leandro Huerta tenía un almacén, un almacencito así, aparte de eso venían los mercachifle que se le llamaban, que vendían genero, zapatos, todas esas cosas…

Interview 12

Estaba en Pueblo viejo el día de la inundación? En el mismo momento no, pero llegué, estaba en Chile Chico, pero cuando llegué estaba todo barro barro barro, estaba todo cubierto, a la altura de las casas pues, si las casas quedaron enterradas en el barro, sepultadas en el barro, claro, eso ver casitas sepultadas en el barro, lleno de palizadas, raíces, troncos matorrales, de todo lo que el río pudo arrastrar, lo llevó al pueblo, vivía en la casa del lado, en la casa vieja, aquí mismo en este mismo lugar, si po, el agua llego hasta las ventanas en la casa, y se ladeó la casa, y por eso después hice esta casita, ahí quedó después esa casa, si el río bañó bañó cubrió, cubrió el río, esa fue una avalancha que vino de la cordillera, que al parecer hubo un estancamiento, acumulación de agua muy grande, y cuando esa acumulación reventó, y se esparció, y lleno todo esto, del cerro de allá hasta acá, todo esto cubrió pues, si esto es increíble, si aquí donde estoy yo el agua estaba pues, claro si la casa esa grande, que está ahí está abierta, esa le llegó a las ventanas, y mi marido arrancó para el cerro, si en ese momento él estaba, y arrancó para el cerro el cerro del cementerio…de arriba de una distancia, como a 3 kilómetros, la persona que vio que venía la avalancha del río a una distancia de más o menos cuando lo vieron, serían unos 5 kilómetros de distancia…vieron la acumulación de agua que venía, así así como arrollando arrollando, y venia rio abajo, entonces esta persona tomó un caballo y se vino, a todo correr a caballo, al pueblo a avisarle que arranquen que viene el rio, se venía, el mar, decía que se venía, pero el mar de donde se iba a venir, el río se venía así que arranquen, con tal que la gente arrancó, esto eran como a las 5 de la tarde, si había solcito y todo, si fue que un caso muy…fue una acumulación de agua, no fue causado por una lluvia, fue una acumulación de agua que se fue estancando estancando, haciéndose la represa la represa, y después esto reventó, y se vino por el rio, bañando todos los campos que están alrededor de los ríos, hasta llegar al pueblo, y ahí el pueblo quedó inundado todo, y la gente alcanzó a salvarse porque, arrancaron gracias a ese hombre que vino a caballo a decirle que arranquen arranquen, grito por aquí por allá, que el río se viene se viene el río, y la gente alcanzó a arrancar, no murió nadie, pa lo cerros habían hartos cerritos, por allí se ven ve, llegó como hasta la mitad de los cerritos, entonces ellos arriba de los cerritos ahí, y otros que arrancaron en bote hacia el lago, para irse pal otro, pal Pueblo Nuevo, entonces fue muy complicado mucho susto pasaron la gente, (*cuanta gente había en el pueblo en esos tiempos*?) tienen que haber habido más de 200 habitantes, claro si era un pueblo, si el mismo pueblo que ahora está al otro lado, es el que estaba aquí, pero gracias a dios que fue de día, si es de noche esa gente no se salva nadie, porque nadie iba a ver el río que venía para abajo, a cubrir todo, no se salva nadie, gracias que fue de día, (*y esta casa la movió*? La ladeo, le hizo un forado debajo, entonces la casa se ladeo, ahí estaba ladeada y no la pude arreglar, entonces después por un subsidio salí beneficiada con esta casita, y entonces ya tengo esta casita (*de que vivía la gente en ese tiempo*?) buscando trabajitos con los pobladores de los campos, ya sea de esquila, o cercos, limpia, sembrados, de eso trabajaba la gente, y hay mucha gente que se vino de la empresa minera Aysén, cuando trabajaban en Puerto Cristal, muchos obreros que acumularon platita, ellos tienen sus ahorros y vivían de eso, cuando estaban dando, entregando sitios, en el pueblo esta gente se vino, a tomar los sitios y hacer sus casitas, sin costo, en esos tiempos regalaban los sitios no más, el gobierno de la época daba los sitios no más, no, no los vendía, se formó un pueblo, lo trazaron, y repartieron los sitios gratuitamente, de esa manera se formó ese pueblo, entonces la gente pudo con mucha facilidad tener su casita, pero fuentes de trabajo no habían, ellos se las ingeniaban, ya sea a ser maestros, zapateros o trabajándoles a los mismos pobladores del alrededor y ganaban su platita, de esa manera, esa escuela se hizo con beneficio de la población, toda la población cooperó, por medio de una directiva, de un centro de padres, encabezó la directiva esa para poder adquirir fondos, plata y se hizo esa escuela ahí, esos fueron los primeros estudios que recibieron los niños de este sector, de Murta, porque aquí no habían profesores, andaban claro algunas personas educando a domicilio sus conocimientos, habrían hecho buenos estudios por ahí, y sabían algo, y por las casas andaban enseñándoles a los chiquititos, y después ya salió la escuelita y empezaron a ir para allá, (*cuando se habrá fundado la escuela*?) no la escuela fue en 1954, en el mismo tiempo que se hizo la iglesia, 54, 55 estaba en construcción todo eso, porque el pueblo fue inaugurado en 1952, trazado, y entregado para que la gente reciba su sitio, y hagan sus casitas, (*antes igual había gente viviendo*?) los pobladores, los que colonizaron, los colones eso es otra cosa aparte, la colonización en la región fue extensamente en toda la región, y aquí sucedió todo el sector de Murta igual se colonizó por medio de esta gente que venía de Chiloé, de Temuco, de Arauco de por ahí, venía la gente y ahí se colonizaba, pero la mayor parte de la gente vino de Chiloé, a colonizar, (*aparte de la escuela y la iglesia que otro edificio había*?) las casas hechas por los mismos que vivían, los que llegaron a vivir ahí, como gente que recibió su sitio, hizo su casita y empezó a vivir ahí, (*había un muelle también*?) sí había un muelle, ese muelle se lo llevó el río también, claro, cada creciente el río fue deteriorando, deteriorando, y con esa avalancha ahí culminó, eso fue los más terrible, y bueno, de ahí, el pueblo definitivamente al otro lado, ya habían hecho estudios las autoridades, que este pueblo no era pueblo de futuro, pero nunca le dijeron a la gente que es lo que podía pasar, si por eso ya habían trazado al otro lado el pueblo, y le estaban pidiendo a la gente que se retire, que se vayan, allá había una escuela mucho, muy bonita, moderna, con internado, y la gente no se iba, porque añoraba lo que recibieron primero, su sitio, su pueblo, donde ellos llegaron a vivir, añoraban eso y no querían irse a otro lado, ya estaba trazado el otro pueblo allá, para que la gente se traslade, por eso nunca la gente no se le advirtió, que peligro corría, para que la gente se pudiera haber ido antes, sino que ya cuando se inundó el pueblo recién se dieron cuenta de que no era inútil lo que se estaba pidiendo, había un estudio, pero lo sabían las autoridades, la gente no lo sabía, de ahí entonces pucha las casas ya enterradas enteras, en el barro, era todo palizada, una altura de 20 metros diría yo, 20 metros hacia abajo lleno de palizada que toda la rivera del rio la limpió y vino acumulando para acá, entonces quedó todo ahí arrinconado en el pueblo, fue una pena porque ese pueblo era muy bonito, porque es un lugar bonito, es plano, (*la gente no se quería ir*?) no po añoraban su pueblo, que se iban a ir si tenían su casa todo, pero nunca supieron, nadie supo, de que acechaba un peligro, y eso cuando ya aconteció, ya tuvieron que irse no más, (*y la gente se fue el mismo año de a poco*?) de a poco, se fue, con ayuda, se ayudaban unos a otros, a acarrear restos de casas, pedazos de casa, para ir haciendo su casita en el pueblo, de a poco pues, los recursos, no había recursos, la gente con sus propios medios, con su propio esfuerzo, (*como llevaban los materiales*?) por el lago en bote, porque tampoco había camino, el camino vino a salir como en 1987, hasta aquí, pero de Aysén para acá ya había camino, pero aquí a nosotros llegó ya en 1987, 86, 87 en ese lapso de tiempo, estaba terminado el gobierno militar cuando estaba llegando el camino acá, antes cruzar el río a caballo, todo a caballo, o en bote por el lago, y de ahí ya hacia el pueblo, todo se trasladó en bote en pedazos, de paneles en pedazos, se fue trasladando lo que quedó, de la inundación, *(y usted se fue quedando sin vecinos*?) no es que nosotros somos colonos, el campo sigue pa arriba pa allá, nosotros no teníamos gran, aparte que la casa se inundó, no había más peligro, que bajó el agua y ya quedamos bien otra vez, la casa un poco ladea no más..(*y su marido*?) él estaba solo y arrancó para el cerro, y de ahí veía como la avalancha iba llenando llenando, el campo para abajo, hasta llegar al pueblo, el lo vio todo, la inundación en si duró como tres horas más o menos me decía el, como tres horas en bajar, se vació todo eso, pero quedó cubierto, eso no se limpió así no más, quedó cubierto, ese barro, esa mansa capa de barro, arbustos, arboles, (*hubo crecidas anteriores*?) si hubo crecidas pero no en grande, crecidas grandes que bañaban, bañaban no más pero no hicieron daño, inundaron el plano, no está vino de arriba no fue la crecida del rio no más, hay que, entre la crecida del río, a la inundación hay diferencia, porque eso fue una acumulación de agua de barro de todo, y eso una vez que hizo esa acumulación de agua como una represa, pero inmensa de grande arriba en los campos para arriba, yo conozco gracias a dios donde se hicieron las represas, y son los campos de Ríos y Jeria, ahí se hicieron las represas grandes, y entonces esa acumulación se abrió con la misma fuerza y se vino toda esa acumulación, (*quedó muy afectado para arriba*?) todo, murieron vacas, animales, todos quedaron afectados, con mucho barro, mucha palizada, lo que era pasto quedó todo tapado por el barro, entonces fue una ruina, para la gente porque los animales quedaron sin comer…los bosques verdes quedaron, lo que limpió fue, no sé si usted sabe, de que hubo años anteriores, allá por a fines de, a principios de los años 50, a fines de los años 40, un grande incendio que se incendio toda la región, ardieron todo los campos, ardieron, ardieron y esa palizada muerta, árboles muertos de esos incendios, estaban botados en el suelo, eso fue lo que arrastró el río, esa palizada muerta que había, todo lo que abarcó el río limpió, (*aquí cuando hizo erupción el Hudson llegó la ceniza*?) aquí quedamos cubierto de cenizas y tuvimos una oscuridad de casi 3 días, una oscuridad que oscureció como de noche, fue una columna, columna de cenizas, que cubrió el cielo y quedamos a oscuras, el 71, 20 centímetros de ceniza, donde acumuló más fue en las partes altas, de aquí como 70, 80 kilómetros de donde reventó el volcán, para el lado ahí, Erasmo…(*la gente tubo ayuda del gobierno para trasladarse*?) la gente se ayudó sola, no tuvo ayuda del gobierno de la época, la única ayuda fue que le entregaban los sitios gratis, para que se vuelvan a trasladar allá…pero la gente fue muy solidaria y se ayudaban, unos a otros, (*y cuanto se demoraron en restaurar y volver a las casas*?) no si después que se inundó no volvieron nunca más, desarmaron todo lo que había, para llevarlo al otro lado, el pueblo se terminó para siempre, se salvó una sola casa, dos casas, que todavía están allí, nada más y la iglesia, que quedó por caer, esa la restauré yo gracias a dios, el 30 de agosto de cada año se celebra un año más de restauración, para darle gracias a dios que nunca murió nadie ahí, por esta inclemencia, se hace una misa en acción de gracias, no solamente porque no murió nadie, si no po toda la gente que vive, celebración de santa rosa…*antes habían protecciones fluviales*? Nunca, antes vivíamos a la suerte de dios, ahora que se están haciendo defensas por los ríos, antes nunca, vivíamos a la buena de dios…