Geodynamic hotspots in a periglacial landscape: natural hazards and impacts on productive activities in fjordlands, Chilean Northern Patagonia.

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Summary

In this paper we study natural hazards and their potential impacts on productive activities in the Comau Fjord in Chilean Northern Patagonia. We carried out a hazard mapping to identify areas with evidence of geomorphological activity on slopes in terms of landslides, fluvial/tsunami flooding and glacial retreat. The assessment of different geomorphic process was carried out by both fieldwork and remote image processing. We performed a geodynamic hotspot identification overlapping different hazard maps to derive spatially distributed multihazard terrain units. This information was overlain with spatial data of economic activities in the area in order to establish the impacts of such natural hazards on the local salmon and mussel farming infrastructure. The results suggest significant exposure levels for these productive activities and potential damages due to the ocurrence of natural hazards. The extension of a major highway (CH-7 Austral Highway) on the east coast of Comau Fjord will be a new incentive for economic development in the area. However, the highway cosntruction sites itself have the highest level of exposure to natural hazards.

Our study highlight that the geohazard potential might have a high negative impact on future productive activity in the fjord as well as on the new highway infrastructure.

Key Words: Geohazards; Comau Fjord; landslides; tsunamis; aquaculture; Austral highway

Introduction

The morphoclimatic dynamics of the Andean Comau Fjord and inland sea were assessed, as well as its exposure to natural hazards and the consequent impacts on the economic activities in the area. These impacts are condsideringthe current and projected population when the Austral Highway has been constructed and is operational. This highway is part of an important international connectivity network.

The concept of hotspots in this study is related to exogenous geodynamics, in terms of forms and processes that trigger natural hazards. These hotspots are analyzed geomorphologically, considering scenarios of land use change and climate change, for a fjord region, in a periglacial environment, with meso tides and active tectonics.

Studies on natural hazards and their associated risks are more and more getting in the focus of present day researchsince they have significant social implications worldwide because they are related to the potential loss of human lives and infrastructure, causing substantial social and economic costs [1]. Such losses and costs increased during the last two decades, especially in Latin America [2].

The risk related to natural hazards are often undesirable side effects of economic growth. Particularly, if the natural hazards are not considered in planning stages and subsequent construction activities of agricultural, industrial, settlement and communication infrastructures [3-4-5]. Current climate variability and future climate change constitute new challenges in the study of natural hazards. Hence, it is neccessary to incorporate new climate dynamics and their geomorfological implications into the predictive models of hazards and risks, adapting them to global change scenarios [6-7-8].

Territorial systems and social structures are continuously changing and interacting within the time/space framework. Thus, risk analysts study such interactions in detail, especially in the context of the global economy. The analysis of impacts on economic activities need to be conducted in the context of the increasing frequences and magnitudes of natural disasters around the world, which intensified due to the dynamics of globalization [1]

Chile promoted neoliberal economic policies in the last decades having a dramatic impact e.g. on biodiversity [9-10]. An example of this is the large-scale development of salmon aquaculture in Northern Patagonia that, stimulated by economic globalization, became an important sector in the national and regional economy while having a big ecological impact. The economy of the Los Lagos Region is mainly depending on aquaculture and Chile is ranked as the second largest producer and exporter of salmon in the world [11]. The development of economic activities oriented to the global market resulted in an increasing utilization of extreme territories due to the advantages gained from the production and exploitation of resources. However, these territories often lack connectivity and considerable space and time distances to the national and international markets. The cluster of salmon farms in Northern Patagonia in Chile is an example of this phenomenon [12-13-14-15].

Chilean Northern Patagonia is fjordland in which terrestrial and marine environments are highly complex systems not only from the climatic, ecological and hydrological points of view, but also from a social perspective, especially within the context of climate change and human interventions that are typical for the Anthropocene [16]. Glacial and periglacial environments are morphological systems sensitive to climatic changes [17], particularly in cases where the marine influence is striking.

Within this context, we analyze the potential effects of natural hazards and the fragility of the existing productive activities in the Comau Fjord, characterized by the presence of small fishing coves, aquaculture farms and emerging tourism activities. The construction of a new segment of the national highway, the CH-7 Austral Highway, will foster and reinforce these economic activities in the area (Figure 1). In this regard, ourstudy assesses the geohazards in the Comau Fjord area, as well as the general physiographic conditions around the existing economic activities and of those activities that potentially will be located in the fjord once the CH-7 Austral Highway extension will be completed.

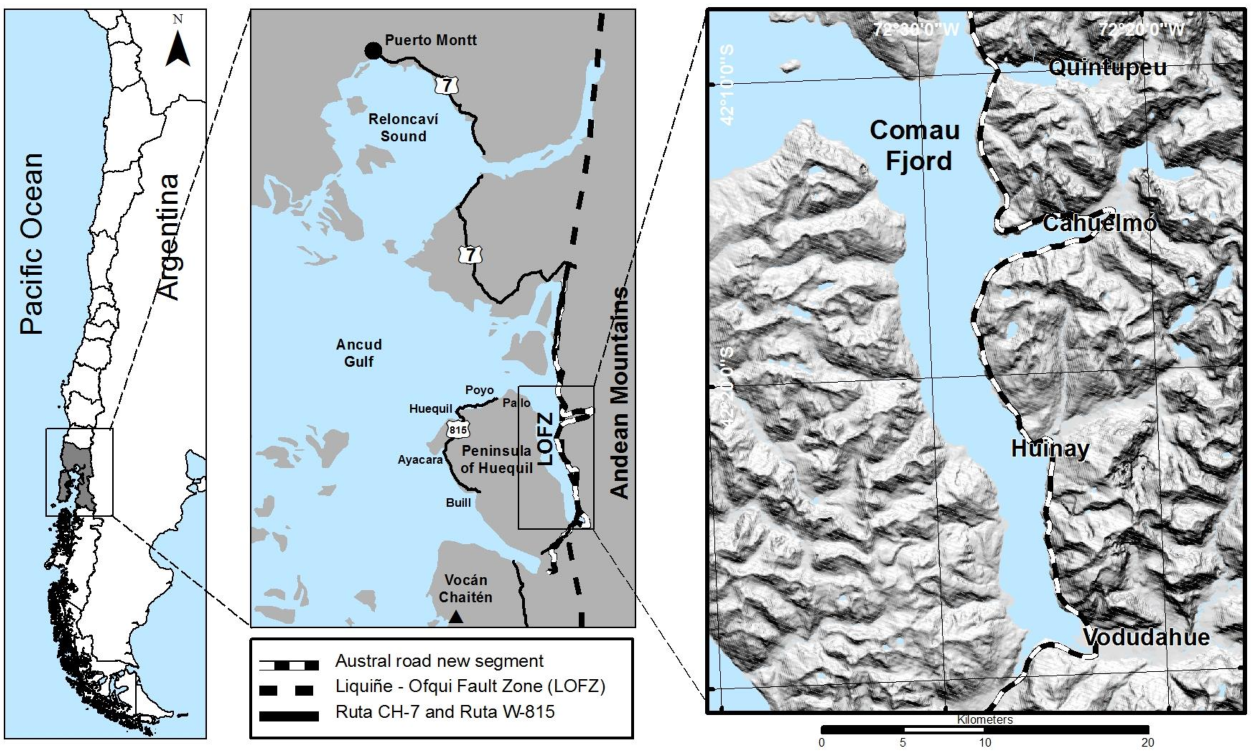

Figure 1. Study Area

The expansion and improvement of transport networks is essential for local development, enhancing the connection of local production with the global economy. The Austral Highway extension in the study area will contribute to increase the connectivity with the regional capital (Puerto Montt) and improve cargo transport of aquacultural products. In Northern Patagonia, the geographical isolation of the fjordlands and the lack of transport infrastructure directly affect productivity due to the difficult acessability of potential markets, high transportation costs and the absence of agglomeration economies. The construction of new roads (i.e. the CH-7 extension near

Comau Fjord) is therefore necessary for future economic growth and the social development of local communities. The development dynamics related to globalization and the expansion of transport networks will result in a reconfiguration of the study area and will come along with new hazard and risk scenarios.

Study area

The Comau Fjord area is located between the districts ('*comunas*') of Hualaihué (east coast) and Chaitén (west coast), in the Los Lagos Region (Figure 1). Along the fjord coastline there are only a few human settlements (Cahuelmó, Huinay, Vodudahue, Leptepu, Porcelana), consisting of scattered fishers' houses, showing no consolidated village structure [18-19]. Both districts are sparsley populated: Hualaihué has 8,944 residents, and Chaitén 5,071 residents (2007), representing only 2% of the total residents in Los Lagos region. Hualaihé and Chaitén also contain an extensive marine area characterized by fishing and aquaculture activities that currently generate most of the local employment for residents.

The Chilean fjorlands of Northern Patagonia also have a distinctive feature related to the impacts of tectonic activity. The area is one of the most seismicically active areas of the world, located in the southern segment of the subduction zone beetween the South American and the Nazca plates. In this area the presence of a significant geological feature known as the Liquiñe-Ofqui Fault Zone, LOFZ [20]. (Figure 1), contributes to the configuration of geohazards. This condition is related not only to recurrent earthquakes but also to volcanic activity, landslides and tsunamis [21]. Recent examples of such active tectonics are the eruptions of the Hudson Volcano in 1991 and the Chaitén Volcano in 2008; the Mw 6.2 earthquake and the subsequent landslides and tsunami in the Aysén Fjord in 2007.

Climate scenarios

The climatic characteristics of the study area correlate to a temperate humid or maritime climate [22]. It has abundant rainfall throughout the year (without a dry season), the annual amount of rainfall exceeds 6000mm. The average annual temperature is 10.5°C, with annual relative humidity between 83% (December) and 93% (June and July) [23].

[24] Indentified some dramatic trends in the region caused by climate change, projecting that the climate will tend towards drier conditions and have a new seasonality of precipitation, with higher temperatures and less precipitation, as well as an increase in their concentration [22]. [25] Estimated a trend of rising temperatures, from 10.32ºC between 1985-1998 to 10.46ºC for the period 2010-2017; the decrease in rainfall is projected from 5548mm to 5295mm, according to data from the local station in San Ignacio del Huinay. The impact of rising temperatures and reduced precipitation, both recent and modelled for the present 21st century, may lead to greater hydro-meteorological hazards.

Methodology

This analysis has considered two main aspects. Firstly, we focus on the geohazards present in the fjord that are linked to the natural conditions of geomorphological processes, including the projected impact of climate change. Secondly, we assess the risks related to natural hazards for the existing economic activities and those that potentially be located in the fjord during the next few years.

Geohazard analyses were based on geomorphological- and hydromorphological processes mapping, such as landslides and floods, identified from an inventory that was generated by GIS tools adjusted and corroborated by fieldwork surveys conducted from 2015 to 2017. The landslide inventory was compiled with photointerpretation of aerial photographs (1982, 1997, 1: 20.000, 1: 70.000) and Google Earth images. The landslides inventory was made by utilizing morphological evidence, according to [26] and the adaptation of [27], [24-28-29], for Andean fjordland environments. Recent landslides were identified using a vegetation as dynamic thresholds, following indications from local settlers who identified different types of vegetation, for instance, fern growing on areas of landslides which ocurred 27 years ago.

Dynamics of Periglacial Hotspots

The periglacial hotspots were defined as groups of geoforms that are activated against climatic, ocenographic and seismotectonic agents in a meso-tidal regime fjord environment. The main agents that trigger the geodynamics of Andean slopes and basins are concentrated rainfall and seismic activity [29-30-31].

The analysis of landslide susceptibility was carried out using the bivariate statistical analysis of [32], applied [33]. The variables used were the gradient, orientation and height of the hillslopes, curvature and profile, distance to the drainage networks and to faults, density of drainage and faults/lineations, and the lithological units as evidence of geomorphological, hydrologic, and geological characteristics of the fjord [24]. This method required a landslide inventory. The weights were assigned as a function of landslide density found in each pixel factor according [34]. [27] reclassified these ranges for the fjordland: high susceptibility, 35% of the highest weighted values; moderate susceptibility, 35-62% and low susceptibility, between 62-100% of the weight [33].

Fluvial flood areas were identified during fieldwork, mapping the different levels of river terraces, channels and banks, thus validating the previous photointerpretations. This information was complemented with a detailed GIS based terrain analysis that that provides information on the terrain morphology and related processes such as areas characterized by accumulation of water and soil saturation, processes of surface runoff, soil erosion and sediment transport or areas susceptible to flooding [35-36-37]. For the terrain analysis we utilized a 12m TanDEM-X DEM provided by DLR.

The flood areas caused by oceanographic tsunamis were established at 30 m.a.s.l. This height constitutes the tsunami safety area in Chile, declared by the National Emergency Office (ONEMI).

The tsuanmi flood areas generated by lansdlides were demarcated at the 50 m.a.s.l. elevation, which corresponds to the flood height measured in the Aysen Fjord tsunami by the Naval Service [38]. This event is the only known case of a landslide tsunami in Chile [28-39].

Hotspot recognition was carried out through a double-input matrix, of qualitative nature, considering only the presence and absence of geohazards. The hotspot or multi hazard overlap areas are defined by overlapping the most frequent events and their susceptibility conditions.

Land/water use and impacts on geohazards

The identification of economic activities and road infrastructure was carried out through the analysis of secondary information from official sources, as well as utilising primary information about the territory collected during fieldwork conducted in January 2016. This research uses the land use classification established by the Chilean Ministry of Economy, Development and Tourism. Fieldwork surveys identified the specific locations of productive facilities along the fjord coastline. Secondary data, obtained from the Chilean Ministry of the Environment from the official records of several Environmental Assessment Declarations (DIA), complemented fieldwork information. We overlapped the spatialized information about geohazards-scenarios with the existing and projected land use and economic activities, in order to derive and identify the risk levels in the area.

RESULTS

Landslide hazards

The landslide hazard conditions of Comau Fjord are associated with the occurrence of hydro-meteorological processes due to abundant annual precipitation of around 6,000mm. The geological and geomorphological features reflect a typical fjord landscape; i.e. steep slopes with 50% of the surface above 30°, with thin or nonexistent soil cover and dense tree vegetation. All these conditions may lead to slope instabilities, triggered by rainfall characteritics and earthquakes.

The landslide inventory (Figure 2) shows the distribution of different landslide types such as rockfalls, rockslides, earthslides, mixed rock and earthslides, and debris flows, with a higher landslide density on the east side of the fjord, due to the genral higher slope gradient (see profiles in Figure 2), and granitic (66%) and metamorphic (26%) lithologies. The occurence of debris flows and earthslides on the western side, characterized by volcanic rocks show a lithologic control on landslide types.

The applied model was validated in the field through the geomorphological evidence of different mapped landslide types; a helicopter flight allowed to map also areas that otherwise are inaccessible due to the dense Patagonian forest.

Debris flows are very common, especially in smaller catchments, draining to main fluvial valleys and/or the fjord developing alluvial fans. The valley alluvial fans are very dynamic and are activated by extreme rainfall events. It is possible to recognize these alluvial fans as Holocene geoforms, overlaying Pleistocene terraces, dated relatively using existing archeological evidences in Patagonia [40]. Larger fans draining into the fjord coincide with fluvial terraces levels and are linked to the Pleistocene time.

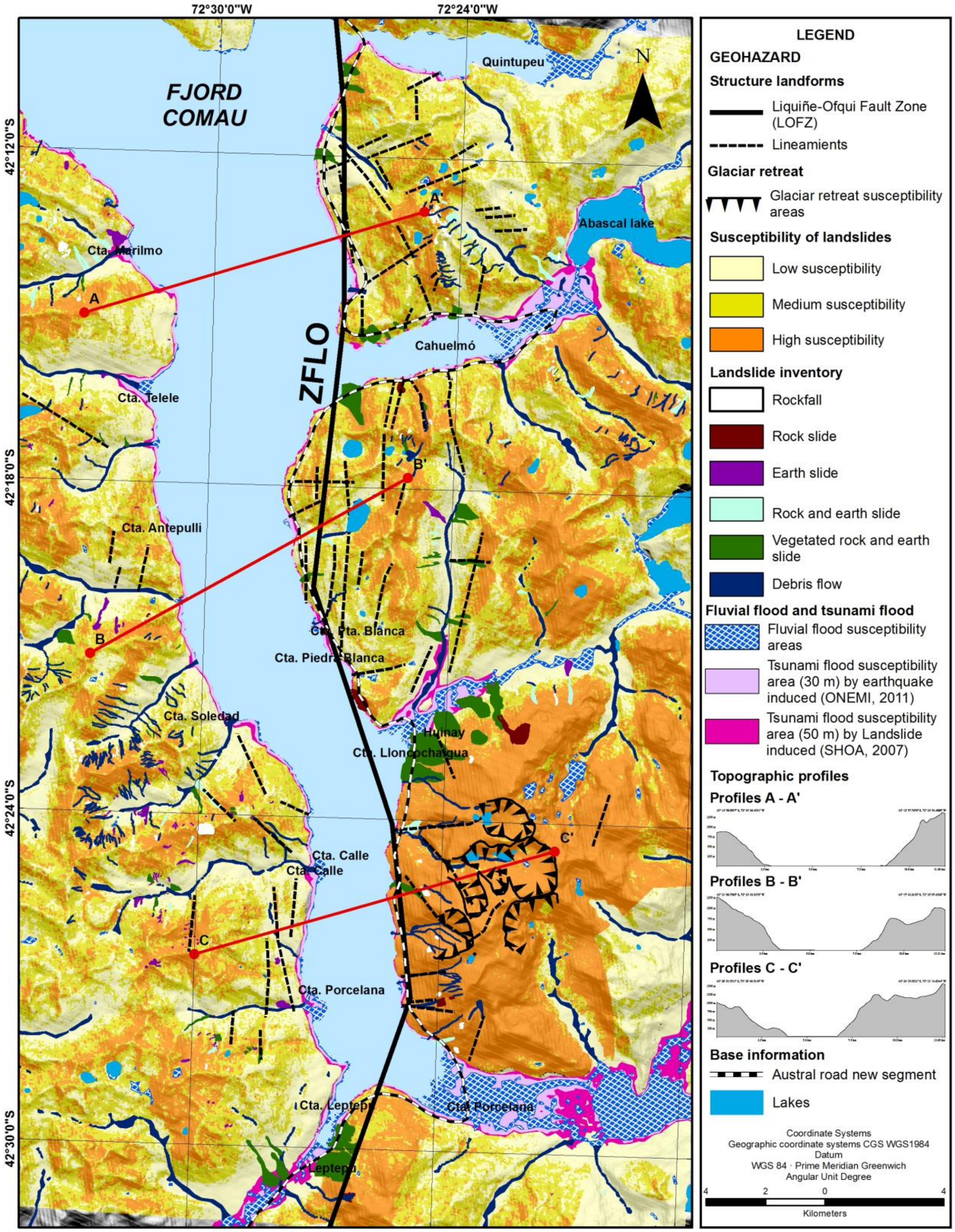

Figure 2. Map of natural hazards.

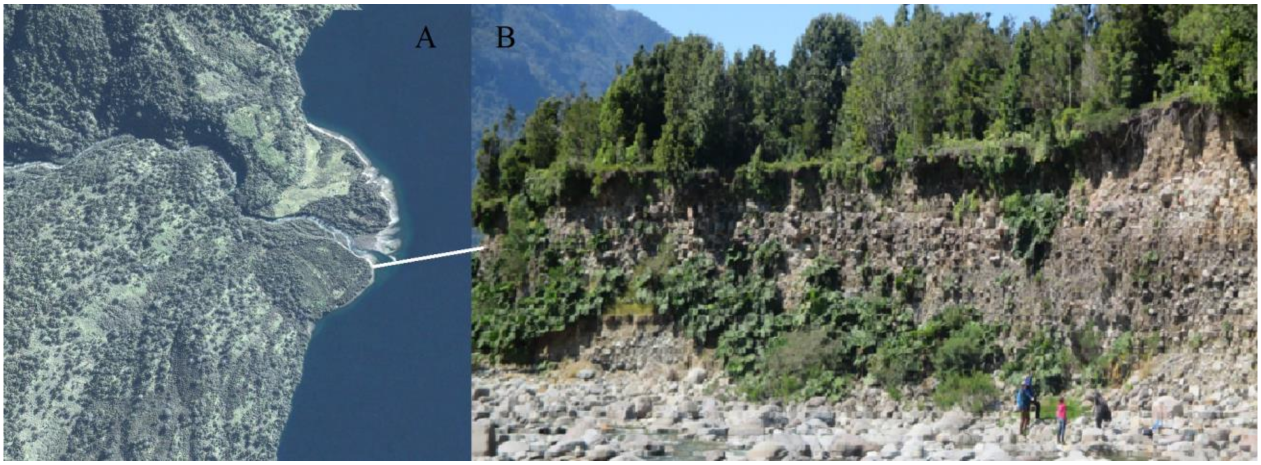

Figure 3. A) Porcelana aluvial fan. B) Debris flow deposit in Porcelana Aluvial fan.

Historic landslide evidence found during fieldwork led to the indentificaion of some extreme rainfall events and recognition of vegetation growth patterns in slopes after landslides. There is historical evidence of landslides, such as the events of July 1957 and February 1980, both associated with extreme rainfall events (Figure 4).

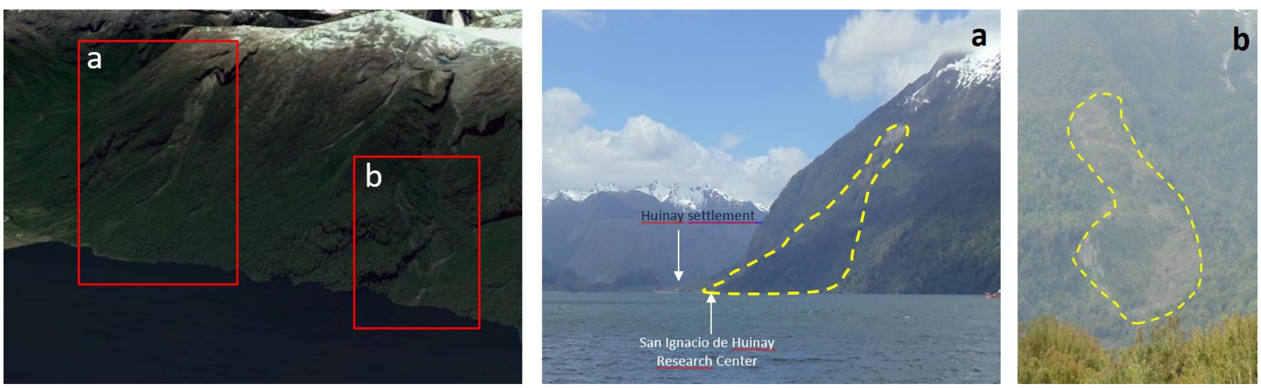

Figure 4. Evidence of landslides of 1957 (a) and 1980 (b), both on the east side of the fjord.

In addition, the regional presence of the active Liquiñe-Ofqui Fault Zone (LOFZ) makes the area prone to recurrent seismic activity, which in turn trigger exogenous processes such as landslides. Earthquake-induced landslides on resistant rock slopes, which occurred in Aysen Fjord in 2007 [29] show the capacity of shallow crustal earthquakes along the LOFZ to trigger large landslides in the fjordland region.

Flood and tsunami hazards

The areas affected by river floods were identified from the river geomorphology of the distal areas of the Andean basins of the Vodudahue and Huinay rivers, through the observation of the river terraces, beds and banks, with evidence of current river action. This information was complemented with a flood susceptibility model [24].

At the mouths of these Andean basins, fan deltas were identified, as described for the northern hemisphere by Blikra [30]. They consist in fluvial gravel deposits, shaped like alluvial fans but with base levels reaching the sea, being subject to current fluvial and tidal operations [41]. These kinds of feature have been considered as fluvial-tidal fan-delta of Holocene age (Figure 2 and 5). They become completely flooded at every high tide.

The study area is affected by another significant latent hazard namely the local tsunamis generated by large landslides. A documented example was registered in 2007 due to a LOFZ earthquake swarm in Aysén Fjord. The mainshock triggered large rockslides that in turn triggered a local tsunami, causing human and economic loss in the salmon industry. [28] described the Aysén Fjord tsunami as associated with a 6.2 Mw shallow crustal earthquake, indicating that fjord environments in the area are favorable to the occurrence of earthquake-landslide-tsunami sequences.

Based on seismic-tectonic susceptibility [24] and recent seismic events linked to LOFZ activity, the areas of flooding of oceanic tsunamis due to interplate earthquakes and landslide tsunami were estimated, according to the data available from the Aysen Fjord tsunami in 2007 indicating a height of 30 masl. This is the height of the safety area specified for Chile by the ONEMI (National Emergency Office). The modeled flood area for Aysén was also used, that is related to an elevation of 50 m.a.s.l. Figure 2 shows that the areas of susceptibility to tsunami flooding are the river mouths and the alluvial fans. Both areas are also susceptible to river flooding

Geohazard hotspots and their impacts

The hotspots identified were obtained through overlapping geohazards, without considering the order of magnitude of events or frequency, but just using ther presence. Table 3 shows the hotspots of dynamic processes and related geohazards that were taken into consideration. The hotspots identified are directly related to the inveterate and modeled events. They represent the largest overlap of processes that might occur simultaneously and interdependently. The superposition of these processes shows the spatial distribution of the geohazards. The area with the highest susceptibility most intensively prone to multihazards isthe so-called Vodudahue Fluvial Plain (number 7, Figure 5). Figure 5 shows the hotspots identified and subdivided into different zones: fjord side and alluvial plains.

Geodynamic processes considered as components of the identified hotspots have been documented in Europe by [24-29-30-31-39], and in Chile, by [28]. Valley hotspots are clearly distributed on the eastern slopes of the fjord (Figure 5), due to the evolution of the Andean valleys and fjords, also affected by the LOZF fault.

The lowest level of hazard means that there is low to medium susceptibility to tsunami and landslides. In the study area, no areas without susceptibility to natural hazards were identified.

Table 2. Dymamic hotspot assessments for multihazards overlap

GEOHAZARDS / HOTSPOTS							
LANDFORMS ZONE (*See Figure 6*)	**SUSCEPTIBILITY TO LANDSLIDES**	**FLUVIAL FLOOD SUSCEPTBILITY AREAS**	**OCEANIC TSUNAMI FLOOD SUSCEPTBILITY AREAS**	**LANDSLIDE TSUNAMI FLOOD SUSCEPTBILITY AREAS**	**GLACIAL RETREAT**	**TOTAL GEOHAZARDS**	***MULTIHAZARDS OVERLAP* HOTSPOT**
1) Quintupeu - Cahuelmó east side of fjord	X	-	-	X	-	2	-
2) Cahuelmó - Huinay east side of fjord	X	-	-	X	-	2	-
3) Huinay - Vodudahue east side fjord	X	-	-	X	-	2	-
4) Leptepu - south side of fjord	X	-	-	X	-	2	-
5) Cahuelmó fluvial plain		X	X	X	-	3	X
6) Huinay fluvial plain	X	X	X	X	-	4	X
7) Vodudahue fluvial plain	X	X	X	X	X	5	X
8) Leptepu fluvial plain		X	X	X	-	3	X
9) West side of fjord	X	-	-	X	-	2	-

The planned Austral Highway is constructed on the Eastern side of the fjord (Figure 2). Following our analysis, it might be highly affected by geomorphological activity and related geohazards, during the contruction phase and when the highway is operational. In addition, current and future facilities linked to this national and international connectivity route are also at risk/vulnerable or will be at risk/vulnerable.

The identification of these hotspots is related to the current land/water uses and future territorial planning of uninhabited areas with enormous potential for economic development due to the construction of the highway extension (Figure 5). Consequently, it is expected that the multihazard hotspots on the one hand endanger, and/or negatively impact the areas that would be otherwise favorable to economic activity and, on the other hand, contribute to the formation of risk areas.

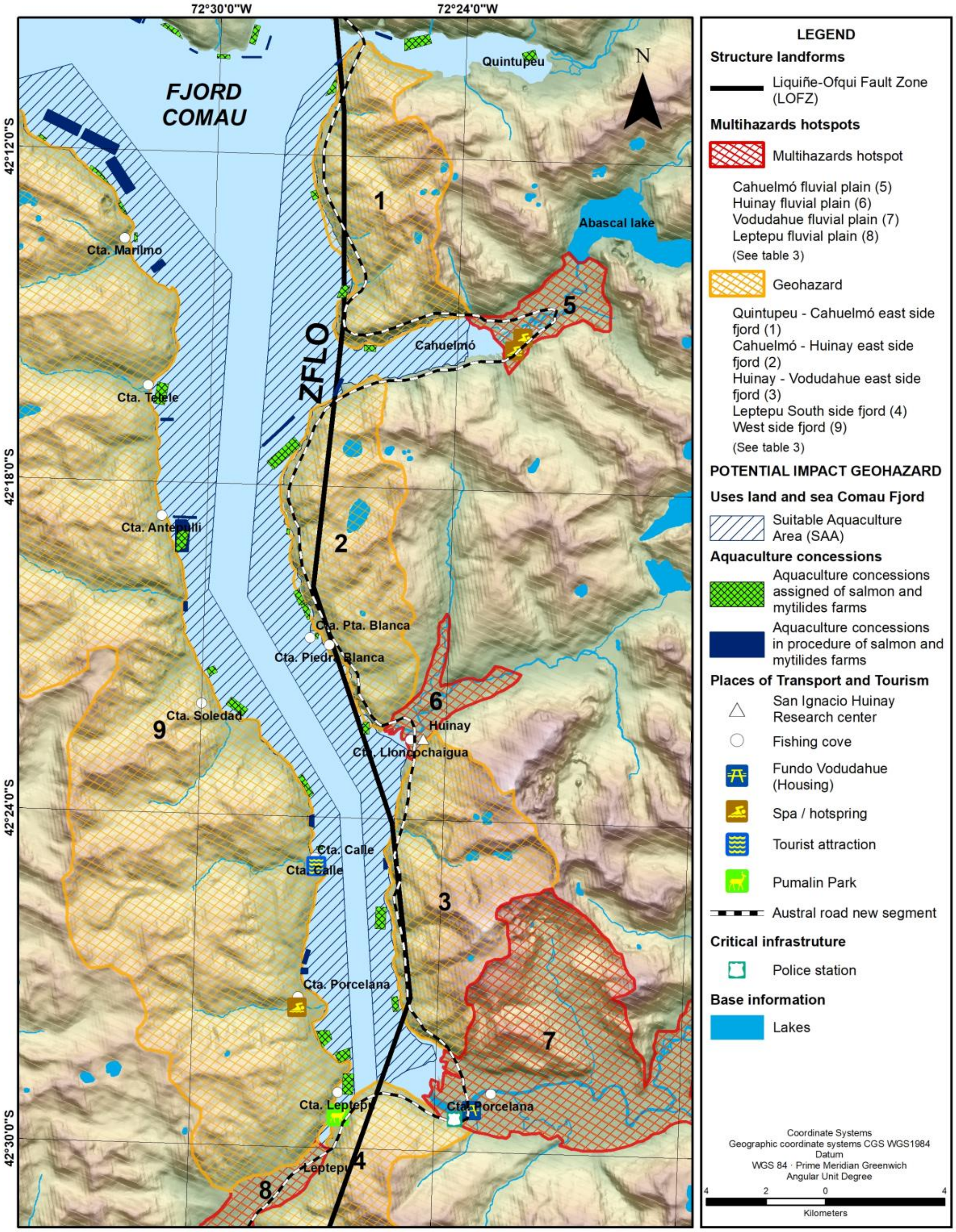

Figure 5. Map of multihazards/hotspots and their relationships with land and water use in Comau Fjord.

Land and sea use in the Comau Fjord

According to the collected fieldwork information, and complementary archival data from public entities, there are several fishers' coves along the fjord, such as Huinay, Piedra Blanca, Leptepu, Porcelana, Soledad, and Calle, among others, located mainly at river mouths (Figure 2 and 5). In each cove, up to three fishers work regularly and they have built temporary shelters. Two coves contain a small number of family houses: Vododahue and Leptepu. All these settlements lack road connectivity, they are only accessible by maritime transport (the *Serenade* boat) (Figure 6). The small number of permanent residents living along the coastline have their income from fishing activity that is oriented to family consumption and small-scale commercialization.

The area sustains tourism activities, which have emerged in recent years and are centred around the presence of unique landscapes and natural attractions, such as hot springs and geysers connected to local volcanism. Tourism facilities are poorly developed and there is a lack of direct road connectivity with the rest of the country. Therefore, currently just a few people visit these sites by taking one-day boat trips, or by camping in the area without access to electricity or any kind of sanitary system (these campers also arrive by boat). However, during fieldwork (2016-2017) we noticed private investments linked to tourist accommodations. In addition, the construction of the Austral Highway could foster further investment in tourism and hospitality in the next few decades.

A diverse infrastructure centred around aquaculture has been built throughout the fjord for seafood production (salmon, mussels and trout), including fattening centers for salmon, mussel long lines and harvest/collection floating centers. It is important to point out that production of mussels requires far less space, infrastructure, and investment than is necessary for salmon production. Most of the salmon farms, which are owned by large national and transnational companies, direct their production to external markets, whereas mussel production is primarily for the national market. Chilean law allows for delimiting the surface of the fjord and its waters, defining permitted and planned marine usage. Figure 5 shows the distribution of Suitable Aquaculture Areas (SAA) granted in the study area by the National Fishery Service (Ist acronim is SUBPESCA).

These marine activities have drawn permanent workers from different parts of the Region to the area. Salmon farm workers live in floating facilities and have work shift patterns of 15 consecutive days. Additionally, in Huinay, companies provide temporary housing and dining rooms for workers. Aquaculture also produces a constant flux of boat trips on the fjord, in order to bring in productive inputs and send out the marine production from the Aquaculture Apt Areas (SAA). The existing flow of workers and boats is economically important at the local level, since it promotes the emergence of small informal comerce in Huinay, in which fishers sell their production to independent salmon workers and acquaculture companies.

According to [42], aquaculture in the fjord will increase, due to the saturation of aquaculture concessions in other areas of Southern Chile (e.g. the western zone of the Chiloé Sea). Article 5 of the Chilean Fishing Law states that: *"fish farms which exist in the Los Lagos and Aysén Regions, may relocate within the same Region if the following requirements are met: a) the same group of species and authorized capacity are kept, b) a waiver of the concession is submitted, c) relocation occurs within the appropriate region and meets the requirements established by law. The holder of two or more aquaculture concessions may merge them, subject to the above-mentioned conditions, or divide a concession to add one or more of its fractions to other concessions which they already own*." Thus, one of the expected scenarios once the construction of the Austral Highway close to Comau fjord has been completed would be the eventual relocation of some of the aquaculture concessions in the areaof the fjord.

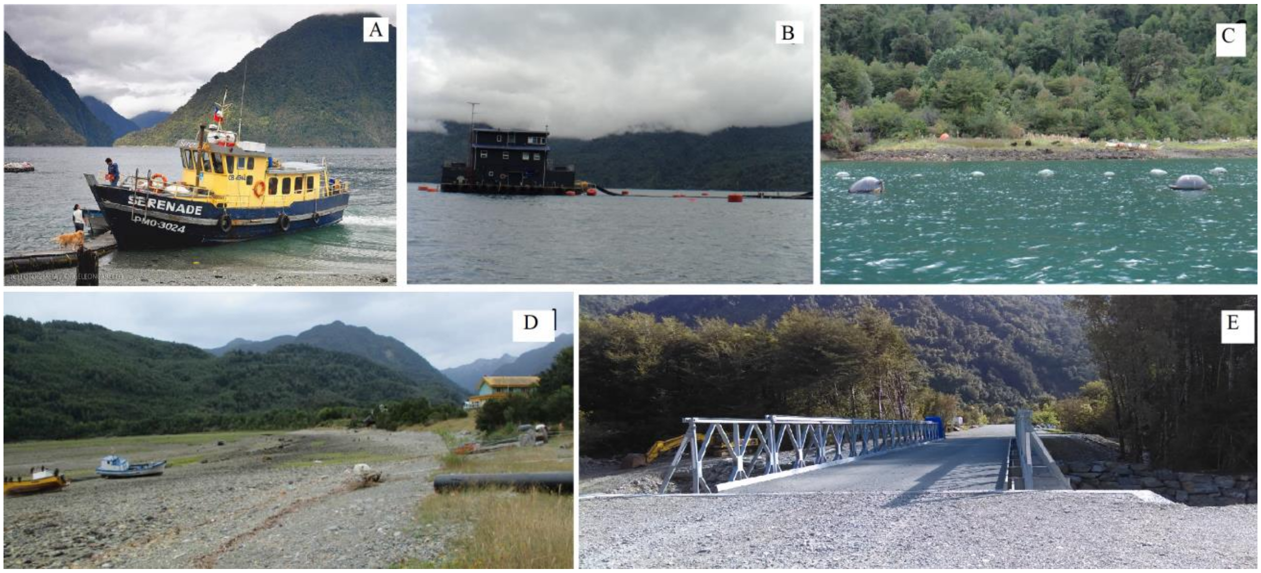

Figure 6. Aquaculture activity and settlements: A) the *Serenade boat*, public maritime transport that connects Hornopitén and Leptetu and all the houses and villages in the sector between these two settlements B) Floating building used to house workers and store salmon crop supplies. C) Cultivation of mussels. D) Jetty, houses and school in Huinay. E) Bridge and road in Vodudahue.

Impact of tsunami and landslide hazards

Regarding the impact on activities due to tsunami hazards, the level of impact of the existing land and sea to oceanic tsunami hazards (Table 3, Figure 5), indicates that 88% of the tourism activities are impacted. The level of tsunami flood hazard is high for transport, fishing, maritime infrastructure and critical infrastructure sectors (e.g. police station). The tsunami hazard situation represents an elevated risk scenario since almost all activities in the fjord would be affected, even in the case of a 30m tsunami wave. In the case of the projected activities, the situation does not seem to be better. However, there is a lower risk level in terms of the planned Austral Highway that will be built at higher elevations than the tsunami exposure level. Nevertheless, the general risk level will remain very high in the entire area.

In relation to landslide hazards, our research have identified two kinds of impact: I) primary impacts that refer to the areas which would be directly affected by landslides (Figure 2), while ii) secondary impacts refer to the areas which would be affected by a tsunami generated by a landslide. Table 4 shows that, in general the levels of potential impact due to landslides are less significant than those produced by tsunamis. In general, landslide impact levels are between medium and low levels. Thus, the fisher's coves located on the river mouths would have low levels of risk, while the police station, a critical service, is located in a place with a medium level of exposure. The general situation of landslide hazards will get worse when taking into account the projected future use. In this scenario, the projected Austral Highway will be built in areas with medium (23.8%) and high (30.8%) susceptibility to landslide hazards, increasing the general risk to the road infrastrutrure and transport in the area.

Table 3. Potential impacts on elements at risk of flooding due to oceanic tsunami

Activity/land use	Area potentially affected by floods due to oceanic tsunamis hazard at 30 m.a.s.l. (%)	Area potentially affected by floods due to oceanic tsunami hazard at 50 m.a.s.l. (%)
Existing Use		
Tourism	88%	88%
Transport	100%	100%
Fishing	100%	100%
Maritime occupation	100%	100%
Police Station	100%	100%
Projected Use		
Transport	19%	27%
Maritime occupation	100%	100%

Table 4. Potential impacts on elements at risk of flooding due to landslides

Activity/land use	Direct			Indirect		
	Area potentially affected by landslides			Area potentially affected by landslide-induced tsunamis		
	High	Medium	Low	High	Medium	Low
Existing Use						
Tourism	0%	12.5%	75%	0%	0%	12.5%
Transport	0%	100%	0%	0%	0%	0%
Fishing	0%	0%	100%	0%	0%	0%
Maritime occupation	0%	0%	0%	35%	65%	0%
Police Station	0%	100%	0%	0%	0%	0%
Projected Use						
Transport	30.8%	23.8%	44%	0%	0%	0%
Maritime occupation	0%	0%	0%	29%	71%	0%

The construction of the Austral Highway will increase the connectivity of the fjord areas with the city of Puerto Montt and therefore, to the global markets. Thus, the fjord could drastically change, becoming a centre of economic attraction due to the enhanced connectivity. Considering the general trend in Chiloé, the territorial pattern in terms of an increase of aquaculture plots in the area can be predicted. However, it is a highly questionable densification with deep impacts on the territory and on the local economic development. However, the fact that there are already pending fish farm concession permit requests awaiting approval can serve as an indicator of a potential future increase in the number of concessions in the study area, particularly considering the economic benefits of fish farming during the last 3 decades and the environmental conditions of the area, which are favourable for this economic activity.

Considering all these dynamics, it is highly probable that the level of hazard and risk will increase significantly, especially in the case of tsunami, since aquaculture activities and their infrastructues cannot be located outside the marine territory and the coastline. In addition, the tourism development related to the future route and better connectivity, may also lead to increased level of risk from both, tsunamis and landslides. Anyway, promoting the location of activities on sites with low levels of landslide hazard, as well as strong, effective evacuation plans to deal with tsunamis, are a prerequisite for future development in the area.

Due to the potential/ increased levels of hazard and risk the need to review territorial planning practices is essential in the medium and long term, to ensure the sustainability of investments and the protection of both residents and visitors. It is vital to highlight the role of the state as well as of the national and regional authorities to establish a national policy for public risk management [43-44].

It is therefore suggested that governance criteria and risk management should be taken into account for land-use planning practice. Moreover, integrated approaches should be promoted sustaining political solutions.

Conclusions

The Comau Fjord shows clear evidence of exposure to natural hazards, with significant levels of susceptibility to landslides and flooding due to oceanic tsunamis and to tsunamis produced by landslides.

The land and sea use of the Comau Fjord is mainly associated with aquaculture activity, along the entire coastline. Aquaculture is specifically dedicated to the cultivation of salmon and to a lesser extent of mussels. Nontheless the high potential for aquacultural farming there is a lack of infrastructure and hence, not many artisanal fishermen live and work there.

The flood hazards level is due to oceanic tsunamis and to tsunamis produced by landslides almost affecting 100% of the land being used for economic activities. Regarding the construction of the Austral Highway, it will be located in areas exposed to fluvial flood hazards. In the case of landslides, all uses are impacted to some extend by geohazard, as well as the cosntruction of the Austral Highway.

The identification of land uses demonstrates that the fjord is characterised by an important economic activity. Moreover, there is a large presence of aquaculture concessions belonging to large companies that exclusively farm salmon and mussels with high economic impact outside the study area, compared to the small number of micro and small companies that work in tourism and fishing.

The assessment reveals considerable levels of exposure for the economic activities located in the study area and that the impact levels are relatively high and homogeneous in the fjord. Thus, future risk studies in the area should consider that the level of risk will be differentiated and determined by the vulnerability level of the proposed economic activities.

In future when the Austral Highway is operational, it is expected that the risk levels due to direct and indirect hazards will increase. In the fjord, through comparative cartography, a scenario of densification of aquaculture crops was modeled, associated with what is permitted by the Fisheries Law and the result is an increase similar to that of insular Chiloé at present.

Likewise, the availability of territorial resources that will facilitate changes in land use, already in incipient development, were identified with private ventures with potentially high economic impact.

Finally, it is important to stress the need to review land-use planning practices and to incorporate an assessment of the geohazards and related potential risks to infrastructure and population in order to guarantee a sustainable land- and sea use. It is essential to establish public policy mechanisms that, with a comprehensive approach and a time horizon appropriate to the magnitude of the hazards and risks identified, systematically considering socio-territorial, environmental, political, administrative and economic criteria, in a proactive and integrated way.

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