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Cascading processes in a changing environment: Disturbances on fluvial ecosystems in Chile and implications for hazard and risk management

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HIGHLIGHTSHIGHLIGHTS

- Several Chilean rivers are disturbed by the compound effects of multiple hazard processes
- Process cascades in a changing environment may result in extreme floods and complex geomorphic adjustments
- Chilean river basins are classified according to the number of different disturbances they are subjected to
- Paradigmatic examples of occurred process cascades are presented, described and discussed
- Adaptations of hazard and risk assessment procedures are necessary to account for such process interactions

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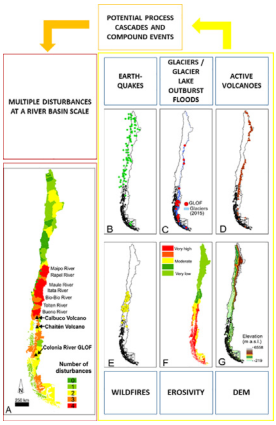
GRAPHICAL ABSTRACT



ABSTRACT

The compound hazard effects of multiple process cascades severely affect Chilean river systems and result in a large variety of disturbances on their ecosystems and alterations of their hydromorphologic regimes leading to extreme impacts on society, environment and infrastructure. The acute, neo-tectonically pre-determined susceptibility to seismic hazards, the widespread volcanic activity, the increasing glacier retreat and the continuous exposure to forest fires clearly disturb entire riverine systems and concur to trigger severe floods hazards. With the objective to refine the understanding of such cascading processes and to prospect feasible flood risk management strategies in such a rapidly changing environment we first classify the large river basins according to a set of disturbances (i.e. volcanic eruptions, earthquakes, glacier lake outburst floods, wild fires and mass movements).

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Then, we describe emblematic cases of process cascades which affected specific Chilean drainage basins and resulted in high losses as tangible examples of how the cascading processes may unfold in other river basins with similar characteristics. As an attempt to enrich the debate among management authorities and academia in Chile, and elsewhere, on how to sustainably manage river systems, we: a) highlight the pivotal need to determine the possible process cascades that may profoundly alter the system and b) we suggest to refine hazard and risk assessments accordingly, accounting for the current and future exposure. We advocate, finally, for the adoption of holistic approaches promoting anticipatory adaptation which may result in resilient system responses.

1. Introduction

Aiming at promoting a sustainable development, the Chilean Ministry of Public Works has recently launched a comprehensive and participatory planning process, called "Plan Chile 30/30", which explicitly considers the paramount importance of water in the context of urban and rural planning and establishes the assessment of the associated natural and anthropogenic risks as an essential requirement. This plan constitutes a long-term vision for the definition of the requirements in terms of public infrastructure and water to be fulfilled until the year 2030. This public-private participative plan was conceived as an attempt for decentralization, considering the local needs, as an integral part of a strategic plan (Ministerio de Obras Públicas, 2014). The assessment of compound hazard effects of multiple process cascades that severely affect Chilean river systems is a prerequisite to achieve the above mentioned, ambitious, developmental goals. Hazard assessment is, however, particularly challenging when different processes interact, and their coupled effects not simply superpose in space and time but rather compound in complex and not yet understood ways (Zscheischler et al., 2018).

Despite a relatively long tradition in applying the risk concept in different mountain and lowland regions of the world (Kienholz et al., 2004; de Vries, 2007; Fuchs, 2009a, 2009b, de Vries, 2011; Fuchs et al., 2015, Mazzorana et al., 2014), losses due to flood hazard processes are growing (Barredo, 2009) even if there is uncertainty regarding the overall increasing or decreasing trends in their frequency or magnitude (Fuchs, 2009a; Gall et al., 2009; Hirsch and Archfield, 2015; Berghuijs et al., 2017). Recently, Chile has experienced large and extreme events resulting in important hazards and causing significant environmental disturbances, damages and economical losses. More than 70 earthquakes with magnitude larger than 7 have been reported, including the strongest recorded by modern seismology, the Valdivia 1960 earthquake (Mw 9.5), and recently the 2010 Maule (Mw 8.8) event. At least 15 ice-dammed lakes have failed since the eighteenth century triggering extraordinary outburst floods (Iribarren Anacona et al., 2015). Some of the >90 active volcanos located in the country erupted in the last years, such as the Villarica and Calbuco volcanos with major eruptions in 2015. Wildfires have extensively affected forested areas. More than 8000 fires were responsible for burning approximately 130,000 ha in 2014 (Úbeda and Sarricolea, 2016) and 587,000 ha during the summer season 2016–2017 (Conaf, 2017; Onemi, 2017). Catastrophic flooding and mass movements were triggered by heavy precipitation, such as the 2015 flash floods in Northern Chile, the Salado River flood in 2017, and the mass movement that destroyed Villa Santa Lucia in 2017 in Southern Chile. In Section 2 we provide a comprehensive account of these processes, focusing on their cascading signatures and the associated disturbances at the river basin and corridor scales.

Section 3 is deserved to the detailed description of emblematic process cascades. Thereby, we characterize their disturbances and effects in fluvial systems and highlight their destructive potential when inhabitants and infrastructure are exposed.

We contend that, in river basins prone to complex process chains, the direct adoption and application of flood hazard and risk assessment procedures developed without considering these processes ensemble is particularly challenging. For this reason, in Section 4 we discuss a clear set of priorities for natural hazard and risk assessment as basic requirements for an enhanced preparedness throughout the different management phases of the "risk cycle" (compare www.nahris.ch; Carter, 1991; Alexander, 2000; Kienholz et al., 2004; Fuchs, 2009b). Acknowledging that still considerable knowledge gaps need to be filled to comprehensively understand from a holistic perspective the multiple impacts generated by such process cascades we also outline specific requirements that should be contained in future research agendas.

2. Processes and associated disturbances in Chilean drainage basins

2.1. Processes

2.1.1. Earthquakes

The Chilean territory has been regularly affected by earthquakes (Barrientos, 2007), which are associated with the subduction zone where the Nazca Plate converges below the South American Continental Plate at a rate of about 70 mm/year (Angermann et al., 1999). This boundary condition extends from northern Chile to Taitao (19-47S). In addition to the subduction zone megathrust fault, which constitutes the primary source of great (Moment Magnitude - Mw > 8) and giant (Mw > 9) earthquakes in Chile, a few secondary seismic sources may pose a high but local hazard to drainage systems (e.g., crustal and intraplate activity). Megathrust earthquakes commonly affect large areas (>10^4 km^2). Such giant events reoccur more periodically than expected according to recent paleoseismic studies in southern Chile (Moernaut et al., 2018). In relation to their potential to trigger complex process cascades their spatial distribution becomes, in addition to their magnitude, a key issue to be considered. With respect to the generated disturbances, the impact of such giant seismic events remains clearly detectable in the geomorphology of river systems (Yanites et al., 2010). Changes range from abrupt alterations of the drainage system through an intensified landslide activity, vertical shifts macroscopically changing the rivers long profile (i.e. knickform initiation and distribution) and planform, stream offsets (i.e. displacements of the river basin outlets form the previously connected fan apexes) (Bierman and Montgomery, 2014). These alterations have to potential to dramatically and long lastingly change the structural and functional connectivity of entire river basins (Cavalli et al., 2013). Further, great and giant megathrust earthquakes are commonly associated with tsunamis that pose an additional hazard to coastal areas with the potential to disrupt estuarine environments, as occurred during the 2010 Maule earthquake at the mouth of the Maule River.

2.1.2. Glacier lake outburst floods (GLOFs)

Circa of 3% of the national territory is covered by glaciers (Barcaza et al., 2017), and glacial lakes are now developing in Chile in response to glacier retreat (Davies and Glasser, 2012; Schaefer et al., 2017). Some of the ice-dams of these lakes have failed in the recent past (Iribarren Anacona et al., 2015) causing high-magnitude floodwaters, the so-called glacier lake outburst floods – GLOFs which can pose a high risk to downstream populations and infrastructure (Westoby et al., 2014). In the extratropical Andes (i.e. Andes of Chile and

Table 1
Main effects of volcanic eruptions on riverine environments and relevant bibliographic references.

Main effects	References
Impact on the entire riverine system	Wisner et al., 2003; Manville et al., 2005
Alteration of hydrology	Major, 2003; Pierson and Major, 2014
Alteration of sediment fluxes	Pierson et al., 2011; Major et al., 2016
Impact on forest cover	Swanson et al., 2010; Úbeda et al., 2011; Ghermandi and González, 2012; Swanson et al., 2013
Increase in recruitment of woody material	Lisle, 1995; Ulloa et al., 2015a; Mohr et al., 2017
Widening and aggradation	Pierson et al., 2013

Argentina) GLOFs-from ice-dammed lakes have been frequent (Iribarren Anacona et al., 2018a), especially in Patagonia where dynamic glaciers impound large water bodies resulting in quasi-cyclic GLOFs (Stuefer et al., 2007; Dussaillant et al., 2009; Dussaillant et al., 2012). Also, in the central Chilean and Argentinean Andes, major GLOFs have resulted from episodic glacier advances and the temporary blockages of mountain streams (Peña and Klohn, 1989; Fernández et al., 1991). Iribarren Anacona et al. (2015) also document one GLOF from an ice-dammed lake in Arid Andes, one of the few known GLOFs that originated from a high-altitude cold-based glacier worldwide. The GLOF originated from the Río Seco de los Tronquitos Glacier (5200 m.a.s.l) and occurred in May 14th of 1985 (Peña and Escobar, 1987; Iribarren Anacona et al., 2018b) causing severe damages in the Manflas valley. Due to the extraordinary stream power of these processes the geomorphology of the affected rivers is profoundly altered (Jacquet, 2016) and their river style (Brierley and Fryirs, 2005) may be subjected to relevant changes which may persist long after the disturbance has occurred (Dussaillant et al., 2009).

2.1.3. Volcanic eruptions

Chile is affected by an active offshore subduction zone and characterized by a volcanic arc built onshore by the eruptions of many stratovolcanoes and volcanic complexes. Currently the subduction zone is dotted with ca. 90 active volcanoes (i.e., with geological evidence of eruptive activity in the last 10 ky) and ranks 5th worldwide (Siebert and Simkin, 2002). Among the eruptions occurred in the last 20 years, it's worth mentioning the following events: Nevados de Chillán (2003), Llaima (2009), Planchón-Peteroa (2010), Puyehue-Cordón Caulle (2011), Chaitén (2011), Copahue (2012), Lascar (2013), Villarrica (2015), Calbuco (2015).

In this context, studying the short, medium and long-term impacts of recent eruptions is crucial to underpin an accurate volcanic hazard assessment and a sustainable risk management (compare Table 1 for an overview of the main effects of volcanic eruptions on riverine environments).

In fact, volcanic eruptions are catastrophic extreme events that can strongly affect the entire riverine system, from the hillslopes to the channel networks (Wisner et al., 2003; Manville et al., 2005). These episodic events typically produce fluxes of tephra, ashes, and flow processes like lahars, pyroclastic density currents (PDCs) and debris avalanches that are able to directly alter the hydrology (Major, 2003; Pierson and Major, 2014), and the sediment fluxes at a river basin scale (Pierson et al., 2011; Major et al., 2016). Moreover, forest and riparian vegetation is affected, or even destroyed, during the volcanic eruption (Swanson et al., 2010, 2013). The tangible consequences are changes in vegetation structure and composition and, frequently, a reduction of the biodiversity (Úbeda et al., 2011; Ghermandi and González, 2012). These impacts can extend over and beyond the adjacent riparian areas and favour the input of huge amounts of large wood (LW) into the system (Lisle, 1995), producing consistent fluxes of biomass and carbon through the river downstream to the mouth and the fjords (Ulloa et al., 2015a; Mohr et al., 2017). As a result, all these direct and indirect impacts strongly affect the morphological settings of a riverine system, favouring its aggradation and subsequent widening phase (Pierson et al., 2013). In case of extreme flood events the easily entrained and transported LW is a frequent cause of bridge clogging and subsequent inundation phenomena (compare Mazzorana et al., 2018a for an overview).

2.1.4. Wildfires

More than one fifth (i.e. 23%) of the Chilean territory is covered by forest (CONAF, 2015), but thousands of hectares are lost every year due to wildfires. An increase in fire events has been recently registered, due to driest seasons, rural depopulation, and abandonment of traditional land use practices (Piñol et al., 1998; Mazzoleni et al., 2004) raising awareness to risk related aspects also in Chile (Úbeda and Sarricolea, 2016; Bronfman et al., 2016).

Wildfires can be defined as one of the most important natural disturbances affecting the forested landscape (Agee, 1993), and they are frequently caused by human activities (Martin and Moody, 2001). The extent and severity of burning and position within the catchment also might influence the observed channel response. Headwater tributaries having a greater percentage of burned drainage area might exhibit greater modifications than higher-order streams in which less of the watershed has been affected (Minshall et al., 1998). Combustion of forest, partial or complete, has considerable impacts on sediment fluxes, wood load, and hydrological responses even at basin scale, influencing fluvial dynamics and landscape evolution (Tiedemann et al., 1979; Swanson, 1981; Morris and Moses, 1987; Meyer et al., 1992, 1995). As reported by Shakesby (2011), many authors demonstrated there is a clear change in sediment yield subsequently to a wildfire (Rodríguez Avellanas et al., 2000; Benavides-Solorio and Mac Donald, 2005). Moreover, fires can greatly increase the available amount of LW into the active channel or in the riparian area that is easily eroded thanks to the lack of resistance in the roots. Loss of bank strength due to riparian tree mortality is an important cause of post-fire channel instability (Eaton and Giles, 2009). Related to this, LW load can rise to 50% more of the total wood recruited (Benda and Sias, 2003). Finally, fires can reduce soil infiltration capacity, increasing the potential erosion and mass wasting during rainstorms (Swanson, 1981); the triggering of mass movements can be easier, where the conditions are apt (Benda and Dunne, 1997). Although numerous studies have examined fire's short-term localized impacts the integration of these effects across entire basins and over time periods of a decade or more remains poorly understood. Linking fire-related disturbances (compare Table 2 for an overview of the main effects of wildfires on river basins) to observed channel morphology from a synoptic, watershed-scale perspective might help address this void (Legleiter et al., 2003). In the USA (Connaughton, 1935) the effects of wildfires found an early consideration on both a scientific and practical level, while in South America the focus of attention was only recently placed on this type of disturbance (Litton and Santelices, 2003; González and Veblen, 2007).

Table 2
Main effects of wildfires on river basins and relevant bibliographic references.

Main effect	Reference
Alteration of infiltration	Swanson, 1981
Alteration of sediment yield	Rodríguez Avellanas et al., 2000; Benavides-Solorio and Mac Donald, 2005; Shakesby, 2011
Increase in mass movement	Benda and Dunne, 1997
Impact on forest cover	Agee, 1993
Increase in recruitment of woody material	Benda and Sias, 2003
Channel instability (bank failure)	Eaton and Giles, 2009

2.1.5. Mass movements

From a morphometric viewpoint, Chile is also characterized by a particularly high relief energy, which naturally disposes the territory to frequent mass movements. In fact, the extratropical Andes can be defined as a young mountain range, characterized by a very rough and abrupt topography with steep slopes (Sepúlveda et al., 2015). This geomorphic setting combined with features as the high elevations, vegetation patterns, glaciers dynamics and regional climatic conditions, make that mass movements are widely spread over the entire Andean Cordillera and the connected valleys. In the last decades, several authors documented the occurrence of landslides, debris flows, rockfalls and debris avalanches in Chile (Veblen and Ashton, 1978; Petrakov et al., 2008; Sepúlveda et al., 2015). As expected, mass movements were frequently triggered by heavy rainfalls, as well by volcanic and seismic activity. However, mass movements frequently do not represent a terminal stage in the process cascade but can trigger, in turn, further processes like tsunamis, GLOFs and massive floods or wood transport along the river network (Harrison et al., 2006; Andreoli et al., 2007; Naranjo et al., 2009; Mazzorana et al., 2018a).

In this sense, one of the well documented cascading process related with this issue was the mass movement occurred near the San Pedro River drain, close to Riñihue lake, in southern Chile, and as a direct consequence of the giant ($M = 9.5$) 1960 Valdivia earthquake (Castedo, 2000), as explained in detail later.

2.2. Relevant disturbances for fluvial systems in Chile

The brief introductory account provided in the previous subsection highlights that in Chile a broad process set has the potential to affect riverine systems and catchment response, resulting in multiple disturbances on river systems that may ultimately concur to trigger severe floods or exacerbate their effects posing human live, land and property at risk, especially when more than one of these disturbances synergize. We define disturbance here as any event, such as earthquakes, GLOFs, volcanic eruptions, wild fires and mass movements, that disrupts the physical environment and thus the fluvial ecosystem (according to White and Pickett, 1985). The combined influences of these disturbances, together with climate, geology and topography determine the suite of landscape-forming processes that govern fluvial characteristics and processes (Montgomery, 1999). In this respect, Chile offers a unique opportunity to understand the interaction among different processes and its influence on catchment and river response. Therefore, the identification of drainage basins where compound events might take place is a relevant initial step and may help to better define priorities in terms of research and management. To do so, we compiled relevant information regarding the above-mentioned processes and mapped combined disturbances at the river basin scale (Fig. 1).

Fig. 1 shows river basins where simultaneous disturbances occur and therefore the combination of multiple processes might render an

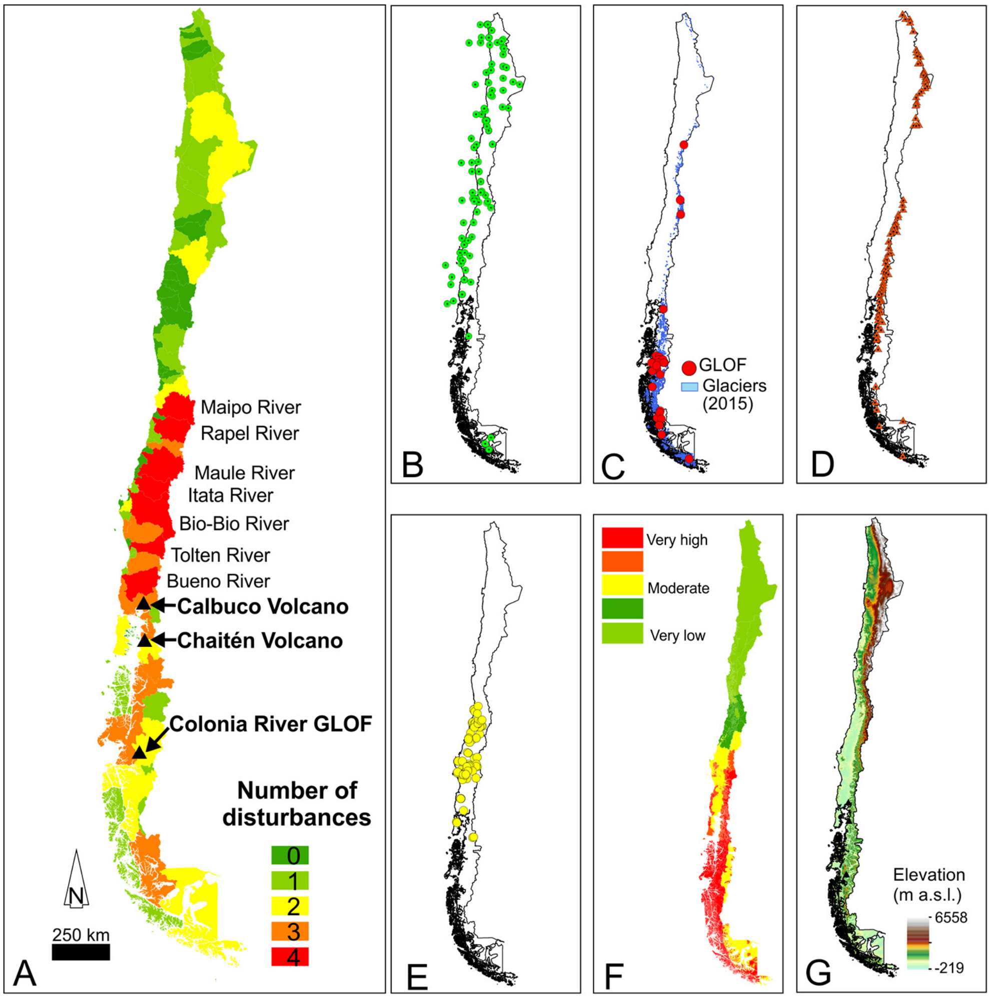

Fig. 1. Overview of multiple disturbances at the river basin scale in Chile. (A) Major river basins classified according to the number of disturbances (sites mentioned in the text are shown): (A) earthquakes location magnitude >7, catalogue (considered time period: 1570–2014) (http://www.sismologia.cl); (B) GLOFs location and glacier extent (Dirección General del Aguas, 2018; www.dga.cl); (C) active volcanoes (http://www.rulamahue.cl); (D) 2015 wild fires locations (CONAF and published by Catálogo Nacional de Información Geoespacial, 2016; http://www.geoportal; (E) erosivity defined as the soil susceptibility to be mobilized and eroded, used here as an indicator for potential mass movements (Ministerio del Medio Ambiente de Chile, 2016; http://www.geoportal.cl); (F) elevation (45 m pixel size, obtained from DIVA GIS: http://www.diva-gis.org).

exceptional event. This clearly highlights the need to characterize in detail the possible process cascades by describing exemplary cases and by highlighting their disturbances and effects in fluvial systems and pointing out specific challenges for hazard and risk assessment. Section 3 of the present paper is devoted to the description of such emblematic cases. Albeit their importance and adverse impacts, coastal hazards affecting fluvial systems have not been included in our current selection. We refer the interested reader to Wahl et al. (2015) for a detailed overview.

3. Case studies for different disturbances

3.1. The “Riñihuazo” flash flood associated to the 1960 Valdivia giant earthquake

In autumn 1960, southern Chile was the scene of a process cascade whose legacy is still anchored in the local culture (Rojas, 2010). The mass movements triggered by this giant megathrust earthquake constitute a unique case study in the global seismological context because of its magnitude (Mw = 9.5) that constitutes the largest instrumentally recorded value at global scale (Smith, 2010).

The associated impacts were particularly devastating for the region and resulted from a unique concatenation of natural processes unleashed, as previously mentioned, by a giant earthquake that occurred on May 22nd, which was accompanied by a severe tsunami, a volcanic eruption in the Andean mountain range, numerous mass movements obstructing the drainage of the Valdivia River basin, and a triggered flash flood. Triggering of the flash flood was controlled by excavations conducted at the mass movement site during the weeks that followed the earthquake, and propagated along the entire river corridor and eventually debouched into the sea at the river mouth in the bay of Corral. This extreme flash flood is known as “Riñihuazo” (Castedo, 2000; Rojas, 2010).

Among the numerous mass movements triggered in a rapid sequence by the earthquake both in the Coastal and Main Cordilleras, those occurred in the drainage gorge of the Lake Riñihue (Davis and Karzulovic, 1961; Keeper, 1984) played a pivotal role in determining the extreme hydrologic loading conditions (i.e. stored water volumes) for the downstream river segments. In fact, the Lake Riñihue is the last in a series of seven lakes which are topographically arranged in a staircase like fashion and interconnected by short river reaches and prevailingly discharging into the San Pedro River at 117 m a.s.l. and 85 km from Valdivia (see Fig. 2; Panel A).

Three massive multirotational landslides on the northern flank of the river valley (overall volume of 38×10^6 m^3) caused its occlusion forming natural dams in three sectors between 3 and 4 km downstream of the outlet (see Fig. 2, Panel B and Fig. 3, Panel A), causing an increase of Lake Riñihue water level elevation of ~20 m.

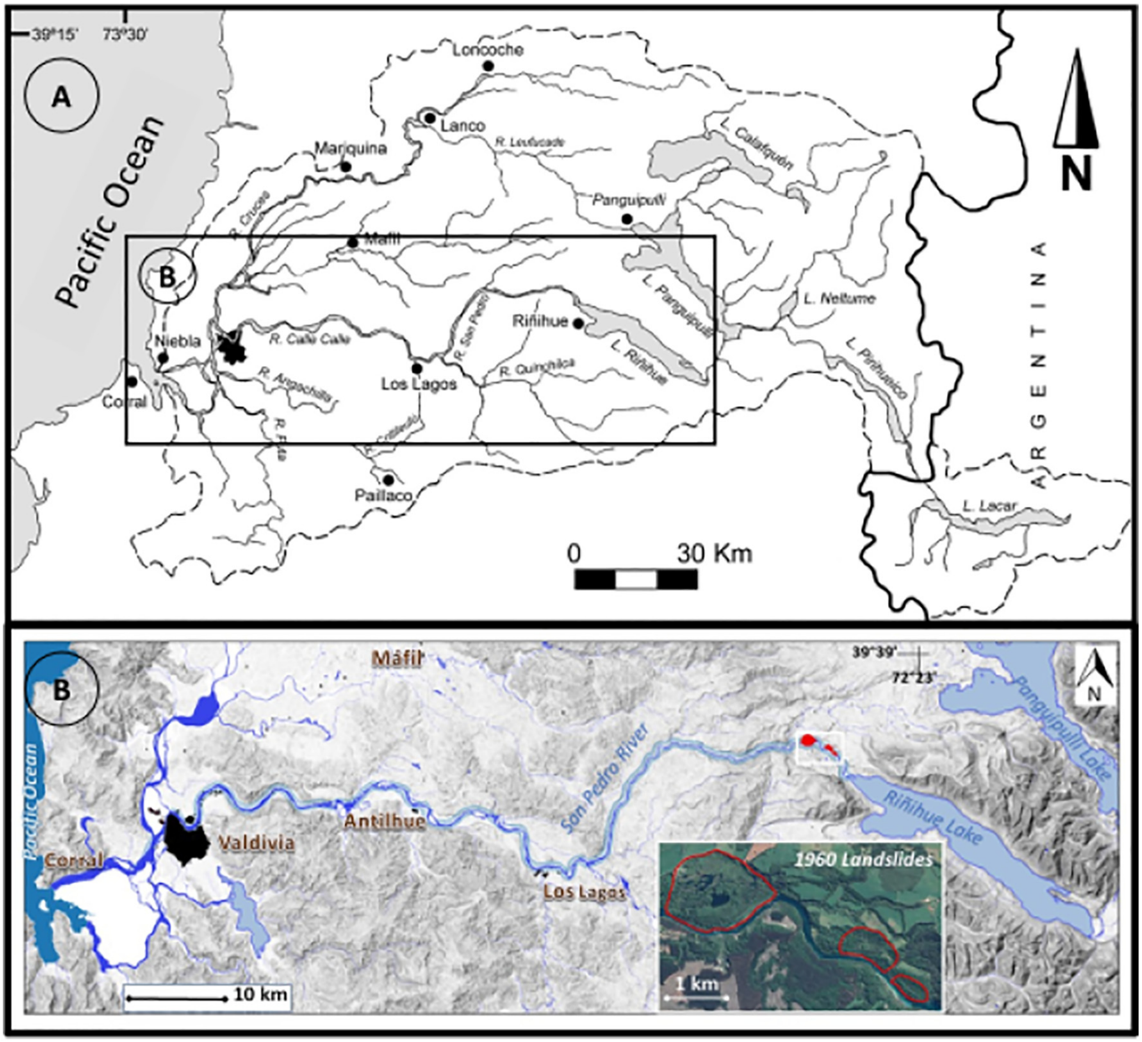

Fig. 2. The “Riñihuazo” and 1960 Valdivia earthquake. Panel A: The Valdivia River basin and, embedded, its interconnected lake system; Panel B: Excerpt showing the floodplain of the San Pedro/Valdivia river which was affected by the Ruñihuazo and the locations where the damming occurred as a product of three massive multirotational landslides in close vicinity to the outlet of Riñihue Lake.

Fig. 3. The "Riñihuazo" - Triggers and effects. Panel A: Detailed view of the multirotational landslide damming the Riñihue lake (image on courtesy: ex Instituto de Geociencias, Universidad Austral de Chile); Panel B: Flooded urban sectors of the city of Valdivia because of the Riñihuazo (image on C. Rojas' courtesy).

The landslide masses were predominantly constituted by sub-horizontally oriented sequences of Pleistocene lacustrine clays (aprox. 80 m thick) which overlay Palaeozoic metamorphic rocks (Hauser, 1993). A topographic survey revealed that the lowest parts of "Taco 1" (i.e. damming toe of the first landslide body) were at 16 m, those of "Taco 2" at 19 m and those of "Taco 3" at 27 m above the normal level of Lake Riñihue. Moreover, there are clear geomorphic evidences of older landslides in the same area. A particularly large one on the orographic left side of the river (100×10^6 m^3 of non-consolidated sediments) can be associated to the previous large-magnitude earthquake occurred on December 16th, 1575 (Davis and Karzulovic, 1961). Employing a combination of methods (i.e. historic data sources, dating techniques and geo-morphometric surveys) Araya et al. (2013) contend, however, that this landslide must have had a smaller event size and its niche should rather be relocated on the northern flank of the river. The extreme hydrologic loading corresponding to a contributing area of 4135 km^2 (37% of the total basin area) together with the low shear strength of the damming landslide masses constituted a ticking time-bomb awaiting to release an uncontrollable dambreak surge. As outlined by Castedo (2000), by raising its water level at a rate of 0.4 m/day, the Lake Riñihue increased its water level by a total amount of 26.5 m in a 63 day's timespan and concurrently its water volume by 20% (approx. 2.5×10^9 m^3). As a consequence, the free surface of the Lake Riñihue and the one of the Lake Panguipulli (140 m asl) could merge and reach an extension of 200 km^2. In an attempt of mitigating the risk of an incumbent disaster, artificial dams were built at the outlet sections of the Lakes Calafquén, Panguipulli and Pirehueico, respectively, to partly disconnect the continuous water supply to the Lake Riñihue. The mitigation effect of these measures was lower than expected, since the induced extreme water level rise in the Lakes Panguipulli and Calafquén, respectively, caused the inundation of the most flood prone areas of the city of Panguipulli and the village of Lican Ray (Rojas, 2010). The primary mitigation efforts had, however, to be devoted to avoiding mayor damages, loss of life and long-lasting economic consequences all along the river system downstream of the lake Riñihue. Cutting through the damming landslide masses at a lower elevation through the construction of an artificial channel, the release of an increasing discharge should be achieved in a controlled way. During a month and a half, in a unique and unprecedented effort in Chile, the complicated and costly emergency works described in detail by Castedo (2000) were carried out. When, ultimately, 63 days after the earthquake, the water level of the lake had increased by 26.5 m, the huge water volume started being released. Although this effort partially achieved its purpose leaving sufficient time for evacuation, it did not prevent all the towns and cities located downstream from being severely affected by one of the greatest floods experienced in almost 4 centuries in Chile (Rojas and Mardones, 2003). The flow peak at the outlet of the Lake Riñihue was estimated in 7500 m^3/s and occurred on July 26th and exceeded by a factor of 3.75 the value of the maximum discharge recorded in the previous 100 years (Canisius, 1961). Flood marks in the first mayor urban area located downstream of the damming landslides, the city of Los Lagos, indicated that the local water depths could have reached 7.5 m. Between 70% and 80% of the urban area was inundated (Sáez, 2016). Further downstream, in the villages of Antilhue y Huellelhue a water depth of 6 m could be measured, whereas in the eastern and western sectors of the city of Valdivia water depths of 3.5 m and 2.15 m could be retraced. Approximately 40% of the urban area was flooded (see Fig. 3).

The water severely damaged the road and the embankment of the railroad between Los Lagos and Valdivia. Moreover, the flood could sweep away several residential buildings and warehouses and transport considerable volumes of large wood and sediment to the sea. Deposition layers (thickness > 1 m in the sector of Purey and approx. 0,5 m in some sectors of Valdivia, compare Rojas, 2010) characterized by downstream grainsize sorting clearly reflect the remarkable intensity of the underlying flood process. To conclude this section, it's worth reiterating that this flood represented the final element of a complex process cascade, which apart from the absence of noticeable climate change effects, featured the whole disturbance spectrum and a remarkable event size.

3.2. Recurrent GLOFs and their effects in the Colonia River in Patagonia

Patagonia hosts >3800 glacial lakes of which at least 50 had produced outburst floods (Wilson et al., 2018). Ice-dammed lakes in Patagonia are particularly unstable since temperate glaciers are subject to seasonal changes in glacier-bed adhesion and ice-conduit dynamics that can open pathways to catastrophic lake drainages (Iribarren Anacona et al., 2015). Moraine-dammed lakes can also fail, and common failure mechanisms are overtopping and breaching of the dam by waves generated by avalanches, mass movements or glacier calving (Clague and Evans, 2000).

Patagonian glaciers are currently exhibiting high retreat and thinning rates, which favours the occurrence of GLOFs (Iribarren Anacona et al., 2015; see Fig. 1C). In the Northern Patagonian Icefield, the increasing frequency of such events is well documented in literature (Harrison et al., 2006). The most emblematic case in Chilean Patagonia is the Lake Cachet Dos, located in a side valley dammed by the Colonia Glacier that feeds the homonymous river, a tributary of the Baker River in the Aysén Region (Dussaillant et al., 2009). At the end of the Little Ice Age (1850–1880) the Colonia glacier probably exceeded the current area of about 1250 m in downstream direction (Harrison and Winchester, 2000). Rivera et al. (2007) reported, based on repeated measurements from 1944 onward, a particularly high average retreat rate (63 m/year). By systematically mapping the retroceding front of the glacier a total retreat of approximately 4 km could be measured in the same time (compare CECs, 2012). Numerous dam failures of both the

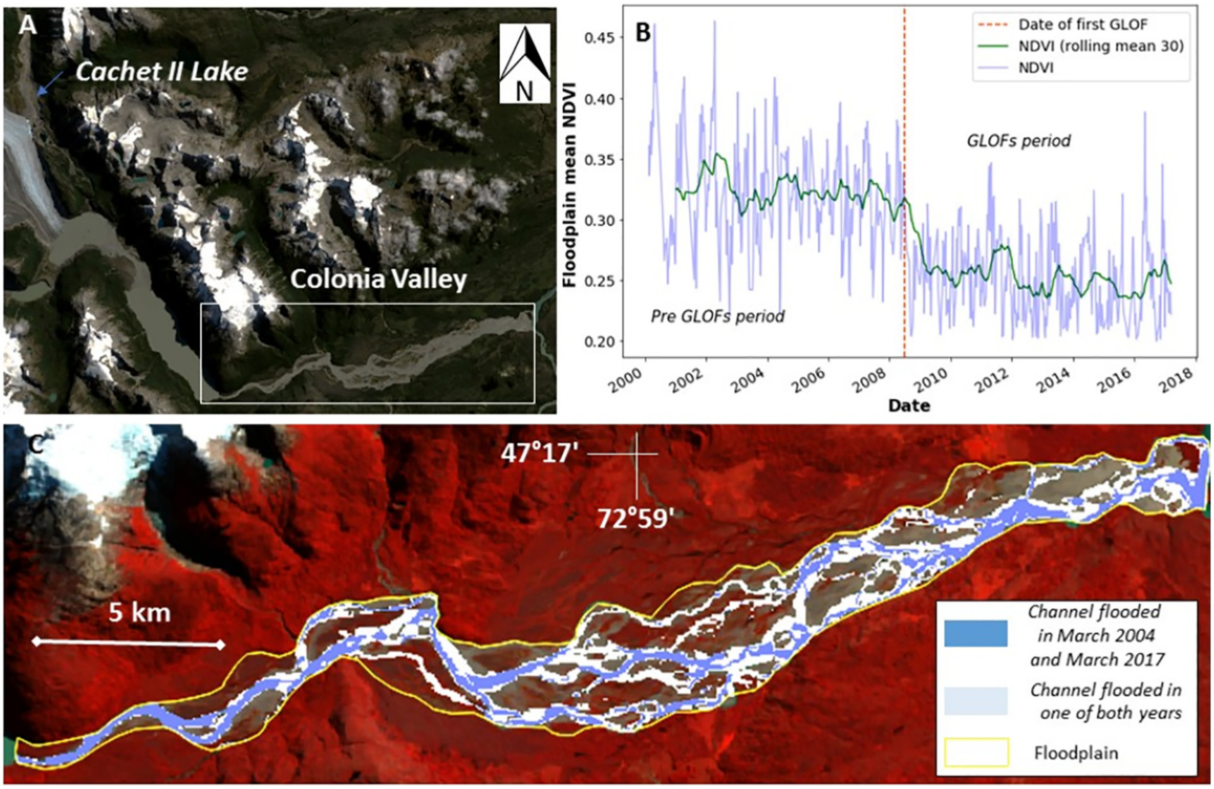

Fig. 4. Glacier lake outburst flood in the Colonia river. A) Location of the morphologically altered river planform of the Colonia river. B) Normalized Difference Vegetation Index (NDVI) of Colonia river floodplain showing a decrease in vegetated areas after the onset of the Cachet II GLOFs. NDVI calculated from MODIS MCD43A4 images (temporal granularity 8 days; pixel size 500 m). C) Flooded channels in Colonia River floodplain in March 2004 and March 2017 indicating river planform adjustments to GLOFs. Channels mapped with the Normalized Difference Water Index applied to Landsat images (pixel size 30 m).

Arco and the Cachet Dos Lake, resulted in voluminous outburst floods. Since 2008, a total number of 20 GLOFs has occurred. Each event drained on average a water volume of about 230 million m^3 with peak flows that could exceed 3500 m^3/s (Dussaillant et al., 2009, 2012). It should be remarked that, prior to this more recent succession of events, the last documented GLOF of Cachet Dos Lake in the Colonia River occurred in 1967, whereas in 1960 a GLOF affected the Colonia river, but it was originated from the Arco Lake. By synoptically analysing discharge data recorded from 2004 onward at different measurement stations along the receiving Baker river, Jacquet (2016) could reconstruct an estimated flow hydrograph for the Colonia river. This analysis showed that GLOFs in the Colonia river, which occurred from 2008 onward, featured maximum discharge values which generated an up to twentyfold increase of the average discharge of the Colonia river itself and a three to fourfold increase of the average discharge of the Baker river. Furthermore, they report that, due to the enormous available stream power, an estimated amount of 25×10^6 m^3 could be eroded and transported downstream (see Fig. 4; Panel A). This has resulted in changes in the Colonia River floodplain such as a reduction in vegetation coverage and channel migration.

This repeated sudden release of remarkable water volumes from the Lake Cachet Dos and the consequent mobilization of huge amounts of sediment has rapidly and profoundly altered the morphology of the Colonia river in a short time span. A very dynamic braided setting occupying almost the entire river corridor has developed because of the extreme boundary conditions (i.e. liquid and solid discharges as guiding variables as per Thorne et al., 1997) imposed on Colonia river (compare Fig. 4; Panels B and C). Further reaching geomorphic effects in the receiving Baker river are discussed in Ulloa et al. (2018).

Although in southern Chile economic assets exposed to extreme GLOFs are still low compared river floods in urbanized areas, risk concerns arise if projections of infrastructural development (i.e. transport routes to increase the connectivity, hydropower plants etc.) are to be considered. Even without such a long-term perspective on potential developmental trends, GLOFs in the Colonia river and the associated reverberations in terms of hazard pose settlers at risk and their economic subsistence in jeopardy. Continuously confronted with the threat of such natural hazard events the settlers proactively and in close cooperation with the water management authority developed an observational warning system. The water level in the Lake Cachet Dos is constantly monitored and mayor outbursts can instantly be detected. The alarm warning is transmitted via radio communication technology among settlers in a cascading fashion in downstream direction (Iribarren Anacona et al., 2015). Despite the persistence of not negligible margins of residual risk, this adaptation strategy proved so far to be effective in reducing damages. Thinking anticipatorily, especially considering the aforementioned prospects of infrastructural development and land occupation, it is of paramount importance not only to continue the monitoring program and refine the operational early warning system, but also to determine and map potential hazard zones. In this regard, it is worth highlighting the importance of a geomorphological assessment of river dynamics which allows a delimitation of potentially affected areas. A hazard mapping approach based on both a spatially explicit representation of process intensities and the associated return periods is, despite its desirability, almost unfeasible, because such hydrosystems (i.e. recently affected by glacier retreat, glacier lake formation and, hence, highly susceptible to GLOF phenomena) underwent a system change, practically invalidating the return periods for discharge which have been determined based on time series that largely mirror the old system behaviour. In addition to the increasing GLOF frequency in Chilean Patagonia and, hence, especially where dynamic temperate glaciers exist, it is worth pointing out that, although less common, GLOFs from lakes dammed by high altitude cold-based glaciers located at lower latitudes have already been reported and analysed (Iribarren

Anacona et al., 2018a, 2018b). The associated risks may become an issue also in other areas where people may be more vulnerable to such hazards.

3.3. The dynamics of the Blanco River (Chaitén) altered by a volcanic eruption

The Blanco River, a fourth order water course, is located in the Los Lagos Region (Northern Patagonia, Chile) and drains a basin of about 70 km^2, flowing from the southern face of the Chaitén Volcano for about 18 km until the Pacific Ocean. Native forest and shrubs, mainly composed by *Nothofagus dombeyi*, *Nothofagus nitida*, and *Nothofagus betuloides* (Donoso, 1981), originally covered its basin for about 84%. The Blanco River basin was severely affected by the Chaitén Volcano eruption in 2008–2009. After a short ash emission phase, a first plinian explosive phase of about 15 days set on, followed by a longer effusive event of about 20 months. Later, the collapse of the volcano dome generated a high magnitude mass movement running out directly into the active channel. The effects of these concatenated events were detected over a wide area of the Blanco River basin, affecting the morphology, the riparian vegetation, the hydrology and the ecological settings of the riverine environment (Hajdukiewicz et al., 2018). More details on the eruption can be found in Lara (2009), Pallister et al. (2013), Major and Lara (2013), Major et al. (2013), Pierson et al. (2013), and Swanson et al. (2013).

Before the volcanic eruption, the water courses were characterized by a narrow mean active channel corridor of about 36 m wide (Ulloa et al., 2015b), an almost complete forest cover all over the river basin and a very low presence of logs and wood-jams within the active corridor, 16 and zero, respectively (Ulloa et al., 2015b). Moreover, hillslopes instabilities or erosional processes did not affect the basin significantly.

Once the volcanic eruption occurred, the entire riverine system underwent a profound modification. Direct impacts were observed in the forested basin, the channel width, sediment and fluvial wood availability. Following the different volcanic eruption phases, a total amount of about 3–5$\cdot$10^6 m^3 of lahars were delivered directly into the fluvial corridor through the Caldera Creek (Major and Lara, 2013), that connects the Chaitén Volcano crater to the Blanco River. A mean deposition of 4–6 m of ashes affected almost the entire river basin (Major et al., 2013). As already reported by Meyer and Martinson (1989) and Lisle (1995), the riparian area is strongly affected by the impact of volcanic eruption. This fact greatly increases the input of wood into the active channel. Ulloa et al. (2015b) reported that in 2009, after the volcanic eruption a total amount of 756 logs and 302 log jams were rapidly recruited and built into the active channel. Moreover, in the near future a considerable amount of wood will be recruited during lateral shifts of the main channel. In fact, many dead standing trees are still present along the riverine corridor and a considerable number of logs is buried in the volcanic sediments. In this sense, it is important to underline that the dead trees are not able to exert their natural and fundamental function of stabilization of river banks and vegetated patches. The lack of resistance provided by the roots greatly increases the potential lateral shift, producing consistent bank erosion processes also during low flow conditions. This fact may greatly increase the recruitment of both, sediment and wood. The almost vertical and instable banks, mainly composed by very fine volcanic material (i.e., ashes and lahars), are very easy to be eroded by flood events. Considering the riverine corridor affected by ashes deposition and lahars fluxes, Oss Cazzador et al. (2016) detected a total area of about 1.32 km^2 not yet eroded. Assuming a mean deposition of 5 m (following Major et al., 2013), a total amount of about 6.5 × 10^6 m^3 of sediment is still available along the Blanco River corridor. On the other hand, taking in count a mean forest density of about 700–1000 trees/ha (Swanson et al., 2013), the authors defined a potential total amount of 7.3 × 10^4 m^3 of wood material that will be recruited in the near future and will be transported downstream. Looking beyond the river corridor and considering the hillslopes, it is important to identify another effect of the volcanic eruption: mass movements and hillslope instability. In fact, due to the combined effect of ash deposition and vegetation death, surficial erosions and mass movements from

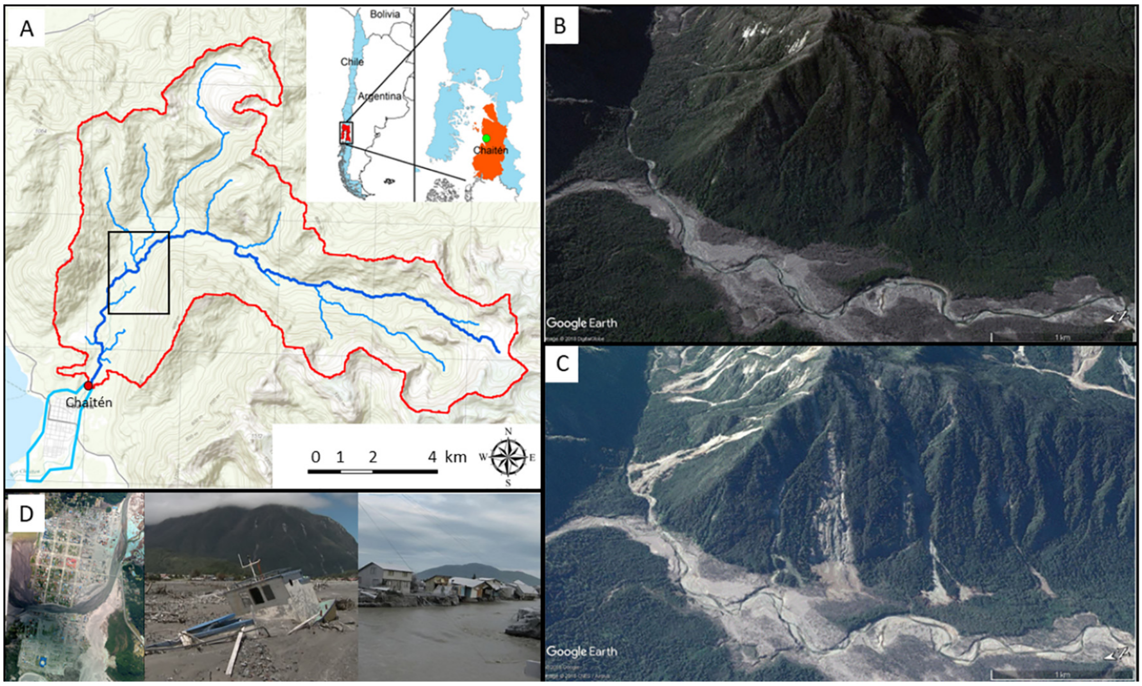

Fig. 5. Process cascade in the Rio Blanco basin after the volcanic eruption. Panel A: Overview of the Rio Blanco basin (i.e. divide represented by a red polygon), its drainage network (i.e. blue and light blue coloured streams), and the urban area of Chaitén (i.e. cyan polygon); Panels B and C corresponding to the areal extent of the black rectangle nested in Panel A: changes along the mountain slopes and the river corridor after the volcanic eruption from 2012 (Panel B) to 2016 (Panel C), along the Blanco River. It is possible to see different erosional processes and landslides that produced new source areas of sediment and wood. These new source areas are also more connected to the active channel due to the continuous lateral shifts of the active channel due to the weak resistance to erosion of dead standing trees affected by the volcanic eruption (images taken by Google Earth); Panel D: from left to right: View of the distributary dynamics which affected the whole village of Chaitén, and details about the damages due to morphodynamics (images by courtesy of H. Ulloa and S. Basso). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the hillslopes to the river corridor raised in number and extent, further increasing the availability of sediment and wood in areas prone to lateral shifts. It is important noticing that, possibly due to the increasing weight acting on the hillslopes and the augmented instability due to the lack of resistance of roots, there was an increase in landslides along the forested slopes (Fig. 5).

It's worth reiterating the need to carefully assess the legacy left by mass movements in the river basin considering potential changes in the connectivity between source areas and the active channel. These changes can be assessed, for example, by calculating the connectivity index proposed by Cavalli et al. (2013). As it can be appreciated in Fig. 5 (Panels B and C, respectively), the combined effect of the volcanic eruption, the changes in bank stability, sediment and wood availability, and frequent mass movements can rapidly change also the connectivity of an entire basin. In this sense, previously not directly connected areas because of their distance from the active channel became rapidly connected. This change in structural connectivity altered the budget of sediment and wood available for recruitment, entrainment and subsequent transport. In Fig. 5 (Panel C) an insight into the damages induced by fluvial morphodynamics is provided. Hence, it is pivotal to increase the knowledge of these of the process cascades and the induced disturbances in particular with respect to the connection of previously unconnected sediment and LW source areas. However, in the specific case of the Blanco River, the wide floodplains on both sides of the active channel, may attenuate the direct supply of solid material and LW. In fact, even if hillslope processes are becoming more frequent, the source areas may still be disconnected from the active channel due to the presence of such a wide buffering zone. On the contrary the current dynamicity along the active channel banks (i.e. intense lateral erosion, river widening) is remarkable and, therefore, a rapid connectivity increase at a basin scale must be expected and carefully considered in river corridor management and, particularly, in risk assessment and mitigation.

3.4. Multiple effects of wildfires on the riverine environments of the Tres Arroyos and the El Toro basins (Araucania District)

Chile is also exposed to severe and recurring wildfires (see Fig. 1E) which may result into considerable damages to the natural ecosystems

Fig. 6. The El Toro and the Tres Arroyos river basins. Localization of the El Toro Basin (red rectangle, and box A), and the Tres Arroyos basin (yellow rectangle, and box B) in Chile. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
(Images taken by Google Earth).

and to the anthropogenic environments. However, it must be underlined that wildfires are also a fundamental element in the natural living cycle for many native forest species, shaping the forested landscape (Gonzalez et al., 2005). In fact, as reported by many authors (Burns, 1993; Gonzalez et al., 2005; Comiti et al., 2008), the most common Chilean native species take advantage from wildfires to reproduce themselves. These species are mainly the *Nothofagus* spp. (i.e., *Nothofagus dombey*, *Nothofagus nervosa*) and the Araucaria (i.e. *Araucaria araucana*). Moreover, 2.7 million ha are covered with exotic fast-growing species established for wood production purposes; also these species, notably *Pinus radiata* and *Eucalyptus* spp., are susceptible to wildfires. Considering these aspects, it appears of fundamental importance to consider the potential effect that wildfire events can exert on river catchments. Here we present the main effects of two different fire events that severely affected two river basins of the Araucania District in central Chile (see Fig. 6).

The Tres Arroyos (907 ha, compare Fig. 6, Panel A) is located within the Malalcahuello Nalcas National Reserve and is characterized by a forest cover of about 71%, 64% of which is composed by old-growth native species and around 7% by conifer plantations. The remaining areas are covered by sandy volcanic ashes and by grasslands (Iroumé et al., 2015). The basin was affected by a widespread wildfire occurred more than one century ago. Hillslope stability decreased significantly due to the absence of plant roots anchoring. Landslides, debris flows, and surficial erosion became more frequent and diffuse. Consequently, a considerable amount of wood has been deposited into the channel network (Andreoli et al., 2008; Comiti et al., 2008; Mao et al., 2013; Iroumé et al., 2015).

The Toro basin (1750 ha) is located within the Malleco Forest National Reserve (see Fig. 6; Panel B). It was, until 2002, almost entirely covered by old-growth native forest mainly composed by *Nothofagus* spp., when an impressive wildfire burned around 88% of the native forest, while the other 12% was severely affected. Contrarily to the Tres Arroyos basin, the El Toro basin do not present yet hillslope instabilities (Iroumé et al., 2015). The same area was hit, again, by a large wildfire in 2015 which destroyed natural regeneration.

Wildfires affected the two riverine systems that responded in different manners. It's worth highlighting that the timespan between the disturbance and the observation of the effects is completely different in the two study cases (Andreoli et al., 2008; Comiti et al., 2008; Mao et al., 2013; Iroumé et al., 2015). In fact, the Tres Arroyos study case is the result of about 90 years of dynamics, processes, and morphological changes, while the El Toro was affected only 3–11 years before the field surveys. As reported in literature (Benda et al., 2003; Zelt and Wohl, 2004), after a wildfire in mountainous basins, several decades are needed to observe the recruitment of LW into the channel network. Hence, in developing effective management plans to mitigate flood risk due to LW transport, the time-dependency of the response to the disturbances induced by wildfires must be accurately considered. In fact, the Tres Arroyos was characterized by the presence of an LW volume of about 1057 m^3 per ha of channel bankfull area while in the El Toro basin LW volume was ~200 m^3/ha (Iroumé et al., 2014). Moreover, the Tres Arroyos featured also much more, and bigger, wood accumulations than the Toro (Comiti et al., 2008).

Contrarily to what observed in the Tres Arroyos, these authors also found that along the Rio Toro no log-steps were present. Moreover, another important aspect of the time lag of fire occurrence, is the characteristic of distribution of logs along the main channel. Iroumé et al. (2015) found that the El Toro is characterized by a widespread distribution of logs, whereas in the Tres Arroyos many logs were trapped to form big wood accumulations. The authors found also that the El Toro is characterized by a higher mobility of wood which could be related to three main reasons. First the presence of wood jams is a hindrance to the continuous displacement of LW from the upper part of the basin. Second, the relative dimension of logs compared to the bankfull, as in El Toro large wood diameter and length are smaller relative to bankfull dimensions than in Tres Arroyos, and in addition at El Toro basin the bigger trees are still standing, dead, on the hillslopes. Third, the presence of log-steps along the Tres Arroyos contributes to inhibit a continuous movement of wood elements downstream, insteps increasing the stability of the system and decreasing the energy of the flow particularly during low to moderate flow conditions. To conclude, wildfires can strongly affect a catchment, but medium to long term observations are necessary to detect the effects of the wildfire disturbances on the system. Instabilities at basin scale, mass movements and wood recruitment can exert huge impact on the entire riverine system, but they normally do not act shortly after the wildfire occurrence.

3.5. Mass movements and their effects in fluvial systems

By widely impacting human activities, infrastructures and the socio-economic development, mass movements represent a relevant natural hazard all over the Chilean territory. Along the channel network, the material-input locally delivered by mass movements can cause significant alterations, modifying the geomorphic setting and, consequently, the stream functioning (Brummer and Montgomery, 2006; Andreoli et al., 2007). Due to their complex nature and the interplay between different controlling factors, mass movements are hardly predictable phenomena (Petrakov et al., 2008; Gu et al., 2017). It was demonstrated that both in the Patagonian sector (Naranjo et al., 2009) as well in the central Chile (Sepúlveda et al., 2015) the climatic conditions can strongly influence the occurrence of mass movements, with a key role played by the recent climate warming and by the high rainfall intensities.

An example of this behaviour was observed during the summer 2013, when a large number of landslides, debris flows, rockfall and debris avalanches were triggered in various valleys of the central Chile by summer storms, featuring high rainfall intensities (Sepúlveda et al., 2015). The areas mainly affected were the Maipo and Aconcagua valleys. Precisely, on January 21 several debris flows were triggered in the Maipo river basin, with the largest event (deposit ~ 5000 m^3) occurred in the San Alfonso creek, a lateral tributary. Then, a large number of debris flows were newly generated on February 8 and, specifically, in the tributary called Colorado river as well the Aconcagua valley, along the Riecillos creek (Sepúlveda et al., 2015). Such mass movements caused considerable damage to the local communities, by affecting, in particular, the road network and the potable water supply system (Moreiras and Sepúlveda, 2013). In this respect, about one million inhabitants of the city of Santiago suffered a one-day interruption of the drinking water supply because the January events led excessive sediment concentrations (i.e. three times higher than the permitted maximum) in the Maipo river, the main source of potable water for the capital city. This issue reappeared as a consequence of the February events, affecting again Santiago as well the cities of Valparaiso and Vina del Mar. For both the January and the February events detailed precipitation measurements are missing in the source areas, but, analysing the nearest meteorological stations, Sepúlveda et al. (2015) highlighted that the mass movements were probably triggered by high intensity/short duration localized rainfall, induced by convective cells. Another very emblematic case, worth being mentioned, is the tragic Parraguirre event occurred in November 1987 (Petrakov et al., 2008). The climatic conditions and, specifically, the copious snowfalls during the winter 1987 followed a rapid subsequent snowmelt phase seemed to have played a key role as triggering mechanisms. On November 29, in the upper part of the Estero Parraguirre basin (Región Metropolitana) a rock avalanche (~6×10^3 m^3 in volume) has originated by a rock wall collapse (Hauser, 2002). Moving downstream the mass movement progressively incorporated ice, snow and, once reached the channel network, sediment from the streambed of the Estero Parraguirre, thereby increasing its volume and mutating into a debris flow. Due to hyperconcentrated nature and the extreme magnitude (~15×10^3 m^3) the debris flow could travel ~57 km from the source basin to the

Colorado river, and then, propagate along the Maipo river (Hauser, 2002). This mass movement killed 37 persons and severely damaged the hydropower plants of Maitenes and Alfalfal. The 2013-events in central Chile and the Parraguirre debris flow clearly showed that the climatic conditions can act as triggering factors for mass movements. However, also other factors contributed to unleash the Parraguirre process cascade. González-Ferrán (1988) suggested that an initial rock wall collapse, additionally to the abovementioned extreme particular climatic conditions (abundant snowfall – snowmelt), could have been favoured even by instability due to previous seismic activity. A clear example of mass movement triggered by the interplay between climate warming and seismic activity has been documented in the Calafate valley (Northern Patagonian Icefield) by Harrison et al. (2006). The Calafate glacier is located in a small tributary valley of the Northern Patagonian Icefield and, as most of mountain glaciers, experienced a recession due to the climate warming, which led to the formation of a moraine dammed lake. In late 2000, a rockfall has originated by the collapse of a bedrock cliff; by falling into the proglacial lake this mass movement caused the abrupt displacement of water (Harrison et al., 2006). The resulting flow partially eroded the moraine and travelled downstream in the form of a debris flow, where ~2×10^6 m^3 were deposited. The research done by Harrison et al. (2006) seems to suggest that the event was caused by the interplay between two controlling factors, which acted over different time scales. On the one hand, the long-term proglacial response to the glacier recession has to be mentioned, that “predisposed” the basin to the event. On the other hand, the seismic activity it's worth being highlighted, which in the form of a small earthquake rapidly triggered the event. The seismic activity acted as triggering factor also in 2007, in the Aisén fjord (Patagonian fjordland, Aisén County). Since January 2007, the fjordland suffered a long-lasting seismic swarm, consisting of about 7000 events, which peaked on April 21, when the main earthquake ($M = 6.2$) occurred with epicenter at 25 km from the Puerto Aisén village (Naranjo et al., 2009). Due to the seismic activity, several landslides and debris flows were triggered along the steep slopes that characterize the entire area. Particularly, three massive mass movements released about 21×10^6 m^3 of material from the northern coast of fjord (Naranjo et al., 2009). In turn, these multiple collapses triggered a destructive tsunami inside the Aisén fjord, which has rapidly propagated causing the 3 deaths, 7 disappeared and several damages to the local salmon industry.

As extensively documented, in Chile, the presence of steep slopes combined with intense rainfall seem to favour the generation of mass movements (Naranjo et al., 2009; Sepúlveda et al., 2015) and, occasionally, remarkable wood laden flows (Ravazzolo et al., 2017). These triggering conditions can be further exacerbated in case of basins affected by wildfires (Andreoli et al., 2007). This is the case of the Tres Arroyos basin, which in the first half of the last century experienced a large number of wildfires. Several authors (Andreoli et al., 2007; Mao et al., 2008) showed that in the Tres Arroyos basin, the wildfires acted both on the triggering of debris flows, by decreasing the hillslopes stability, and on the magnitude of the wood-laden flows, by supplying large amounts of large wood (LW) easily recruitable. In 1992, the basin was affected by a high magnitude flood, that transported downstream about 5300 m^3 with the mobilization of a massive quantity of LW and heavy damages to the local road network. The steep tributaries affected by wildfires and, thus, by frequent debris flows were identified as the main source areas (Mao et al., 2008). Andreoli et al. (2007) demonstrated that the morphological setting of the Tres Arroyos stream was strongly altered by the 1992-flood, that caused a large LW storage along the riverine system, i.e. ~1000 m^3 per km of channel length. Over the long term, such LW accumulation acted as an additional source of flow resistance (Mao et al., 2008), inducing deposition along the channel network and leading to a high in-channel sediment storage, that was assessed in 2007 as equal to the 119% of the mean annual sediment yield (Andreoli et al., 2007).

4. Discussion

4.1. Process cascades

In the previous section we described a set of emblematic process cascades which occurred in Chile from 1960 onward. Most of the presented events featured as one element of the process concatenation a flow propagation in form of flash floods, debris flows, sediment and wood laden flows through the channel network, which eventually caused major geomorphic changes and generated severe damages as soon as assets were exposed. Three primary triggers (i.e., seismicity, volcanism, wildfires) fuelled the process cascades in the considered drainage basins (1) by releasing significant amounts of energy for the initiation of secondary processes (i.e., mass movements, lahars, pyroclastic density currents) and (2) by progressively lowering stability thresholds and trigger ice or moraine dam failures which led to the sudden release of stored water volumes. River basins affected by the process cascades described in this paper also inherited long-lasting disturbances in form of a not yet remobilized sediment infill, the creation of wetlands, an ongoing glacier retreat and proglacial lake formation, a disrupted vegetation cover, and an augmented landslide susceptibility. These disturbances may continue to exert a significant influence on fluvial dynamics in the decades to come.

Further interesting features that emerge from the analysis of the study cases are (i) a connectivity change between the relevant sediment sources and receiving water courses; (ii) an alteration of the interconnection of the lacustrine systems enabling an additional storage of water volumes for potential floods; (iii) a profound physical modification at the transition between glaciers and downstream fluvial systems attested by the formation of a large number of proglacial lakes dammed by potentially unstable moraines or ice masses susceptible to be rapidly breached.

On the other hand, wildfires and volcanic eruptions can rapidly affect entire basins (Agee, 1993; Manville et al., 2005), changing dramatically the forest cover composition, favouring also forest rejuvenation (Gonzalez et al., 2005). These changes, in contrary, may trigger huge fluxes in terms of sediment and woody material. In this sense, the reduced capacity of plant roots of stabilizing the soil appears as one of the most important aspects to be considered.

Some of the described process cascades highlight the importance of explicitly considering climate change as an integral part of the analysis. In this respect our study confirms that climate change acts as a catalyser of otherwise naturally occurring process cascades making them either more intense or more frequent (Zscheischler et al., 2018). For instance, the reviewed study cases highlighted that mass movements were frequently triggered by intense precipitations or by proglacial degradation (Harrison et al., 2006; Petrakov et al., 2008; Sepúlveda et al., 2015), and amplified in the basins affected by wildfires (Mao et al., 2008). If the scenario expected of an increment in the heavy rainfall and climate warming will be maintained, events as those occurred in the Estero Parraguirre in 1987 and in the central Chile in 2013 (see Section 3.5) may become more frequent. In this sense, mass movements might also occur in areas previously not affected by such process magnitudes. Also, the effects of climate change will have to be combined with the increasing vulnerability of the Chilean territory: the event of 2013 in the central Chile showed that, already under current conditions, severe but localized precipitations can trigger many mass movements, producing severe damages to the social-economical activities (Sepúlveda et al., 2015).

4.2. Hazard, risk and disaster management

Aiming at supporting anticipatory adaptation strategies we classified mayor Chilean river basins according to the number of disturbances acting upon them (Fig. 1). This knowledge base might enable the development of simple but powerful risk indicators (i.e. the number of disturbances affecting a certain river corridor versus number of people living there and, hence, being potentially at risk). One might also think of incorporating future trends in the analysis by considering, for example, scenarios of change both with respect to an intensification of the hazard processes and the projected land occupation. With foresight institutional capacity could be increased by implementing anticipatory adaptation strategies targeted at avoiding unnecessary exposure to hazards which are impossible to mitigate in the first place (i.e. the primary triggers mentioned above) and at significantly reducing the vulnerability of critical infrastructure. Reducing the vulnerability of the built environment is possible via the adoption of enhanced building codes considering impacts from multiple hazards as design loads (Mazzorana et al., 2014). In the light of the paramount role of earthquakes as a primary trigger, it seems reasonable to suggest the development of enhanced probabilistic seismic hazard assessment tools in order to provide for reliable estimates of earthquake recurrence (Zöller, 2018) and of the likelihood of events of a given magnitude within defined time horizons (Stirling et al., 2013). Subsequently, it is pivotal to assess whether the associated energy release is capable of inducing rapid and profound geomorphic changes in critical river segments paving the way for the continuation of the process cascade (i.e. by causing the occurrence of mass movements). The probability of the trigger combined with the possibility of the subsequent process cascade is important, albeit not conclusive, elements of a robust hazard assessment. Formative Scenario Analysis Techniques (FSA) have been widely applied to judge the possibility of multiple hazard processes (Mazzorana et al., 2009, 2012, 2018c). The determination of the exceedance probability (i.e. recurrence interval) of the induced flood hazard, which is a particular process chain element of the entire cascade, is a challenging endeavour. In fact, a system that underwent a significant change also adjusts its liquid and solid discharge regimes accordingly. The application of extreme value statistics based on the recorded time series of the considered flow variables might prove inadequate to predict the recurrence interval of extreme events occurring after the regime shift. In the light of large margins of uncertainty, it is recommendable to start an extended monitoring program to measure at characteristic hydrologic nodes the water, sediment and wood fluxes and to retrace in selected river segments the ongoing geomorphic adjustments.

The five outlined study cases clearly demonstrate the acute predisposition of the Chilean territory to be affected by analogous process concatenations, which may result, in absence of adequate management strategies, into significant direct losses and which may leave behind a complex socio-economic heritage to cope with in the long term. As reiterated throughout this work we do not suggest that the proper analysis of single hazard sources is maintaining a crucial role in hazard assessment and risk mitigation. We rather suggest, from a precautionary standpoint, that hazard assessment should be complemented by a thorough verification of the possibility that more complex process cascades might occur (Bronstert et al., 2018). Overseeing or even neglecting such hazard scenarios is a risky endeavour, especially in a country that is naturally predisposed to extreme events and which pursue a sustainable economic development.

Reflecting about the Chilean developmental context (Ministerio de Obras Publicas, 2014; www.mop.cl), we argue that limiting the hazard exposure due to expanding infrastructural network and settlement areas through an adequate and coherent land-use planning approach on regional and local levels (i.e. Plan Regional de Ordenamiento Territorial – PROT; Planos Reguladores Municipales) is pivotal to sustainably reduce natural hazard related losses in a country which is particularly prone to natural hazards. Moreover, we contend that, spatial planning quality should be based on an enhanced understanding of the underlying hazard processes both with respect to their spatial and temporal dimensions, to increase resilience (Birkmann et al., 2013; Fuchs et al., 2012). Successful prevention through spatial planning would reduce the need for cost-intensive mitigation strategies (Mazzorana et al., 2018a, 2018b).

It must be amended that, in spite of their importance, other well-known natural (i.e. tsunamis, windstorms) and anthropic disturbances (i.e. mine tailings and hydropower dam failures) on river systems were not covered in this paper.

4.3. Outlook

Far from being conclusive, our investigation highlights the importance of studying in detail potential process cascades in Chile and other regions of the world characterized by a similarly broad range of predisposing factors. Fundamental research issues need still to be tackled, for example: What are the right scales both in space and time that must be considered to adequately represent and quantify the cascading processes and their disturbances? With respect to the spatial scales, we contend that in regions located above very active subduction zones, the proper identification of neotectonic segments may provide a useful spatial scale to progressively and hierarchically refine the analysis of process cascades tightly linked to the seismic cycle. In case of the potential cascades triggered by volcanic eruptions, it appears reasonable to delimit first the area of influence of potential eruptions originating from active volcanoes. The area of influence to be taken into account results by merging all river basins either reached by ash and tephra depositions or by any flow process directly from the crater or from collapsing domes.

With respect to process cascades culminating in glacier lake outburst floods continuing the ongoing efforts to map the glaciated areas experiencing rapid retreats appears to be a reasonable starting point to identify the most susceptible river basins. Study areas should be delimited where the effects of the flash floods become negligible.

The definition of criteria to set spatial scales for the study of process cascades where mass movements play a pivotal role is inherently challenging. However, bearing in mind that in the dynamic Chilean territory mass movements can be an intermediate step in a hypothetical multiple cascade system, the inherited mass movements landforms could be a good proxy to identify the most susceptible basins.

In this paper we also addressed issues related to hazard, risk and disaster management by formulating important, albeit general recommendations. The question whether it may be possible or not to define a holistic management approach, once different disturbances act in synergy and progress contemporarily still remains largely unanswered. Knowledge based, participatory river basin management initiatives seem to promote social learning mechanisms which play a relevant role in any attempt of anticipatory adaptation (Mazzorana et al., 2018a; Thaler et al., 2019). In this context it must also be clearly emphasized that institutional adaptation is pivotal in a context of global change to implement necessary preventive management strategies thereby shifting the focus from reactive disaster management to proactive risk management (Pouget et al., 2012).

5. Summary and concluding remarks

By taking the widely acknowledged high disposition of the Chilean territory towards natural hazards into account, in this paper we highlighted the paramount importance of complementing the traditional assessment, centred on the separate analysis of the different process, with an explicit consideration of so called process cascades often culminating into destructive flow processes and accompanied by a specific set of disturbances acting on the river system at variable spatial and temporal scales. Since the pronounced seismicity, the intense volcanism, the high relief energy, and the sensitivity of the bio- and cryosphere to climate change play a relevant role in triggering and driving the process cascades, we provided a synopsis in form of a map showing a classification of large river basins according to the number of potentially acting disturbances (volcanic eruptions, earthquakes, GLOFs, wildfires and mass movements). This map indicates that a considerable number of river basins may host the occurrence of such processes cascades which may cause severe losses. To corroborate this scenario, we described, in a dedicated section, a set of study cases involving the unfolding of such process cascades, all of which occurred in the last 60 years. These examples clearly show the large diversity of how different processes can concatenate, synergize and disturb the river system in multiple ways and over different time periods. In the Discussion section we described their common and distinctive characteristics and formulated recommendations for natural hazard and risk management. Reckoning that significant knowledge gaps related such processes cascades still exist we provided an outlook on particular research issues that need to be addressed to advance in our understanding on how process cascades are triggered, how they may unfold and how their adverse effects can be mitigated.

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