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Water evacuations in remote tourist regions: evaluating case studies from natural hazards in North Patagonian lakes, Argentina

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Abstract: The remote North Patagonian region is a sparsely populated territory and a world famous tourist destination located on the leeward side of the Andes Mountains. Recent disasters triggered by various types of geoenvironmental hazards (including volcanic eruptions, mass-wasting processes and extreme weather events) heavily disrupted ground transport networks in a region with already limited territorial accessibilities. All these catastrophes prompted the need to evacuate or assist a number of secluded visitors, locals and livestock extemporaneously on board of coastguards and tourist passenger-ships from the shores of the many glacial lakes that make up part of the regional attraction. Despite the recurrence of these types of events, water evacuations in the region continue to be spontaneous, improvised and hazardous procedures. This contribution reconstructs and assesses a number of recent local-scale cases of lake evacuations and assistances from a number of Patagonian urban centers, rural areas and tourist sites. For each case study, we systematically elaborated on the prime components of an evacuation process, which enabled us to recognize key achievements, failures and conditioning factors for managing emergencies via water transport, most of them inherent to the studied region. Some of the complexities to emerge from case studies referred to: complex hazard-related scenarios; limited ground-based accessibilities and risk of isolation; various inter- and intra-organizational issues, incidental to natural reserves and tourist regions; a wide range of particular demographic features; and the availability and vulnerability of water transport resources. We suggested fundamental and replicable recommendations for developing water evacuation plans, also identifying forthcoming problems to solve in order to improve the management of emergencies through this alternative means of transport.

Keywords: Water transport; Emergency management; Accessibility problems; Tourism activities; Volcanic crises; Mountain area

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1 Introduction

Evacuations are one of the most common and efficient strategies when hazardous events threaten the safety of those within an area (e.g., Perry et al. 1981; Baker 1991; Lindell and Perry 1992). The term *evacuation* usually depicts withdrawal actions from a specific area because of a real or potential disaster (Leonard 1985). However, evacuations actually encompass a broader range of scopes and procedures (e.g., Lindell and Perry 1992; Vogt and Sorensen 1992; UN General Assembly 2016), and commonly become necessary only when the benefits of leaving significantly outweigh the risks of other options (Tomsen et al. 2014). Hence, evacuations are part of larger disaster management strategies (e.g., Lindell et al. 2006; Hughey 2008; Marrero et al. 2010), that also include planning for other non-evacuation based protective actions, such as sheltering in-place and supporting those at refugee (e.g., Haynes et al. 2009). During an emergency, functional transportation resources are one of the most critical components of a region's infrastructure, as they provide mobility for human populations, livestock, and goods (Amdal and Swigart 2010; Wilson et al. 2012a; Tomsen et al. 2014), while also supporting operations of assistance, and recovery efforts in post-event environments (Lindell and Perry 1992; Perry and Lindell 2007; Phillips 2013). Because evacuations occur in a variety of contexts, those different modes of transport (Wolshon and Donahue 2013) may be logically hampered by a number of different-nature constraints (e.g., Cutter 2003; Marzocchi and Woo 2007; Moriarty et al. 2007).

Although evacuations derived from natural threats are common, little specific information is available in the literature assessing procedures carried out specifically through water transport, and procedures undertaken particularly through lacustrine means of transport are even scarcer. Waterborne evacuations triggered by natural hazards encompass one of the largest mass evacuations by sea in history: the 1906 San Francisco earthquake and resulting fire (California, USA), which led to the evacuation of 60.000 refugees, crossing the bay on ferryboats towards Oakland (Grossi and Muir-Wood 2006). During the 1886 Tarawera volcanic eruption and ashfall (New Zealand), several thousand livestock were evacuated by ship from Whakatane to neighboring islands (Wilson et al. 2009). Most recently, multiple cruises, navy and general cargo ships cooperated with the evacuation of the almost 25.000 residents from the vicinity of La Soufrière volcano, in St Vincent and the Grenadines, to neighboring islands during its April 2021 eruption. The efforts for displacing and sheltering evacuees were particularly hindered by poor visibility resulting from heavy ashfalls and the current COVID-19 outbreak (PAHO 2021). Apart from evacuating people and livestock, water transport may be addressed for pre-disaster and post-disaster emergency management. For example, the Louisiana waterway, a part of the Missouri-Mississippi river system, proved to be a vital recovery component in the post-Katrina environment, providing safe harbor for ships transporting supplies after the storm in 2005 (Amdal and Swigart 2010). Lessons learned were put into action three years later during the Hurricane Rita when, prior to making landfall, ships were stationed at strategic locations along the Gulf of Mexico to provide shelter for emergency equipment and personnel, supporting a rapid post-event response (Amdal and Swigart 2010).

In North Patagonia (Argentina), a number of recent disasters triggered by various types of geoenvironmental events gravely impacted the region, disrupting land-transport networks and urging the need to improvise response actions via alternative water means of transport. These events included the major explosive eruptions (and resultant heavy ashfalls) of Chaitén (Chile 2008), Cordón Caulle (Chile 2011-2012) and Calbuco (Chile 2015) volcanoes; and the complete isolation of an entire city resulting from a massive rock topple event, and a severe snowstorm that blocked the only two connecting roads for an entire month. Attention has been drawn to these four events as they represent, collectively, the first relevant instances of emergency responses in the region, particularly held via lacustrine transportation. Each of these major events entailed a wide range of different responses, ranging from non-authorized evacuations taking place when not entirely necessary (a phenomenom termed *shadow evacuations*; Zeigler et al. 1981; Baker 1991; Gladwin and Peacock 1997), to instances of some residents failing to evacuate (e.g., Dash and Gladwin 2007) and remaining sheltered in-place. Noticeably, there were also numerous instances of extremely risky attempts of evacuations taking place during adverse navigation conditions, putting evacuees and emergency managers at greater risk. All these cases revealed various flaws in disaster management planning in the region, and a significant lack of understanding about the feasibility of using water transport to manage natural hazard-related crises. Moreover, several local circumstances (distinctively characteristic of North Patagonia) repeatedly arose, seemingly constraining each water-based response. Most importantly, prior instances of poorly managed evacuations tend to have a negative impact on decision-making processes and reduce the willingness of threatened communities to evacuate on future occasions (e.g., Tobin and Whiteford 2002; Perry and Lindell 2004; Bourque et al. 2006). Despite the foregoing, water transport is still overlooked as a viable resource when planning emergency management in Patagonia.

Evacuations are becoming increasingly more frequent around the world (Sparks 2003), and Patagonia is expected to follow suit due to an unconscionable increase in urbanization and tourism influx. Given the numerous challenges that must be addressed in order to safely implement water transport in future events, this research intends to: evaluate the capability of North Patagonian natural hazard management institutions to cope with disasters via water transport; examine the actual effectiveness and limitations of such strategies, in the face of a wide range of different environmental hazards; identify key influencing issues that systematically affect this practice; and highlight potentially useful strategies for accurately planning responses, meeting future evacuation demands.

The paper is structured as follows: • Reconstruction of recent local-scale cases of water-based evacuations, response actions, and recovery operations from various Patagonian cities, rural areas and tourist destinations. • Profiling of each case study, based on the key aspects of an evacuation/assistance procedure (See Table 1), in order to better organize these findings. • Identification of the most common issues affecting the efficiency and effectiveness of water-based evacuations, enumerated as critical knowledge gaps. • Suggestions of fundamental and replicable recommendations for creating water evacuation plans in North Patagonia. • Analysis and discussion of the study's implications for future research in the region, as well as its relevance for other areas with similar features.

2 Study Area

The Argentinean North Patagonia, eastwards of the Andes range, is a vast and sparsely populated territory and a world famous tourist destination. This study focuses on a number of different coastal sites within two different areas: *Los Alerces* National Park and Reserve, to the south (Fig. 1) and the *Nahuel Huapi* and *Lanín* National Parks, to the north (Fig. 2).

2.1 Hazard framework & climate setting

North Patagonia is exposed to a wide range of different natural hazards that might directly endanger or isolate populations by disrupting transport networks. The study area is located on the leeward side of the central and southern sections of the Andean Southern Volcanic Zone (Fig. 3), extending from ~33° S to ~46° S (Stern 2004). This volcanic zone fully comprises 43 active volcanoes specifically for the Argentinean and Chilean North Patagonian active volcanic arc, accounting almost 300 historically observed eruptions recorded since 1558 (GVP 2013). Argentinean North Patagonia is recurrently affected by volcanic ashfalls derived from the eastward-drift of pyroclastic material transported by the prevailing mid-latitude westerly winds (e.g., Nakamura and Shimpo 2004; Garreaud 2009; Viale et al. 2019).

In other respects, high mountainous reliefs and several glacial valleys with steep hillsides characterize the Andean Patagonian landscapes (Ehlers and Gibbard 2004). Mass-wasting processes, triggered by the combination of different drivers (such as volcanic activity, intense precipitations, seismic activity, etc) are one of the most common natural risks for critical infrastructure at these latitudes (Naranjo and Stern 2004), frequently causing widespread and long lasting disruptions of surface transport.

North Patagonia features a strongly continental climate, with significant seasonal and daily temperature fluctuations (Fig. 4). The regional distribution of temperatures is determined by the latitudinal position and elevations, the different atmospheric and oceanic circulation features, and the adiabatic heating of air masses descending from the leeward side of the Southern Andes (e.g., Garreaud et al. 2009). The mean precipitation decreases strongly towards the eastern Patagonia, resulting in one of the steepest precipitation gradients on Earth (e.g., Smith and Evans 2007; Garreaud 2009; Viale et al. 2019).

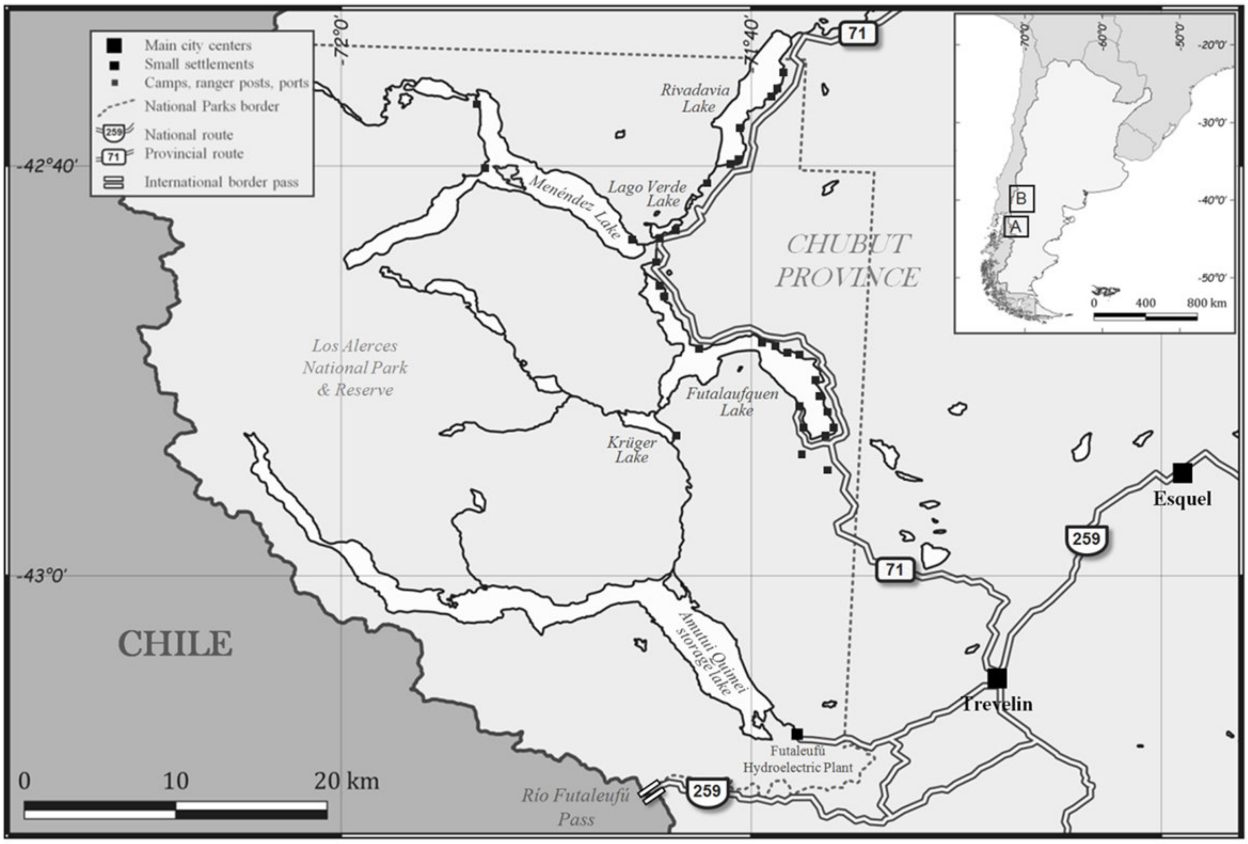

Fig. 1 Study area A, Los Alerces National Park region, Chubut Province, Argentina.

The bulk of annual precipitation occurs in autumn and winter months, with frequent snowfalls (Fig. 4).

2.2 Demographics of coastal communities

North Patagonia comprises a sightseeing north-to-south-trending lane that crosses a cluster of natural reserves and a series of glacial lakes. Most of the cities, villages and tourist destinations settle sparsely on the shores of these massive water bodies.

Towards the south, Los Alerces (Fig. 1) includes a chain of lakes connected by short courses of rivers and a great number of lodgings, campsites and wharfs, all of them sitting on the eastern shores and linked by a single gravel road. There are no major localities permanently inhabited within the area, beyond tourist dwellings and facilities (mostly visited during summer) and very small rural communities in the lake surroundings.

In the Nahuel Huapi and Lanín National Parks region (Fig. 2), the greater Nahuel Huapi Lake gathers a number of larger settlements and cities as Bariloche (Fig. 2), the third most visited location in Argentina throughout the year (e.g., the number of occupied bed-places reached more than 2.8 million during 2017). The city held a stable population of almost 113.000 inhabitants in 2010 within an urban area of 220 km². On the northwest shore of the lake sits Villa La Angostura (Fig. 2), a smaller village that also relies almost entirely on the tourist activity that concentrates mostly on summer (and a shorter winter season). The city held a stable population of almost 10.900 inhabitants in 2010 within an urban area of 80 km². However, great influxes of tourists (and tourism workers) strongly increase the not-accounted population during peak seasons. Northeast Villa La Angostura, the nearest hamlet is Villa Traful (Fig. 2), a very small settlement holding a population of barely over 400 inhabitants, in 2010. Located on the southern shore of the Traful Lake, it is only accessed through the Provincial Route 65. Tourism is an important component of its economy and concentrates almost exclusively in summer.

Northwards sits San Martín de los Andes (Fig. 2), one of the main tourist destinations in the Lanín region during both summer and winter. The city is located on the eastern shore of the Lácar Lake and held a stable population of almost 36.000 inhabitants

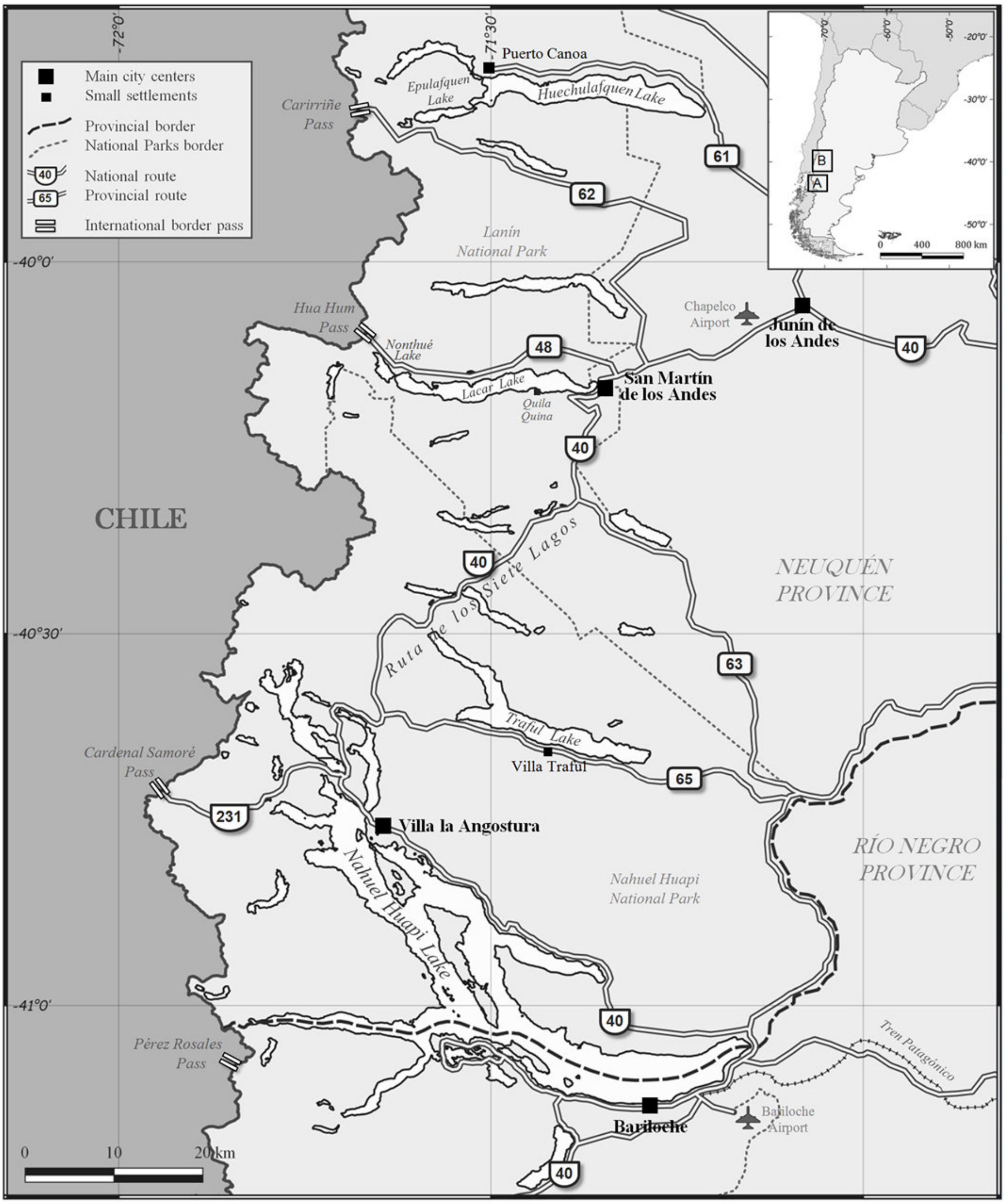

Fig. 2 Study area B, The Nahuel Huapi and Lanín National Parks region, Río Negro and Neuquén Provinces, Argentina.

in 2010 within an urban area of 140 km². As for many other lakes in the region, there are a number of tourist sites with difficult or restricted land-access, sitting on the shores of the Lácar and Nonthué Lakes. Many of these remote places, such as the famous Quila Quina village (Fig. 2), depend on the daily tourist passenger-ships services for commuting into the city.

The at-risk population in Patagonia is not only composed of urban dwellers. There are also a number of rural communities in the surroundings as well, located on the shores of the many lakes in the region. For most of them, subsistence incomes rely mainly on a low-intensity and poorly registered pastoral farming of cattle and sheep. In some cases, economic activities also involve a small-scale community-based tourism, as for rural communities in western Nahuel Huapi

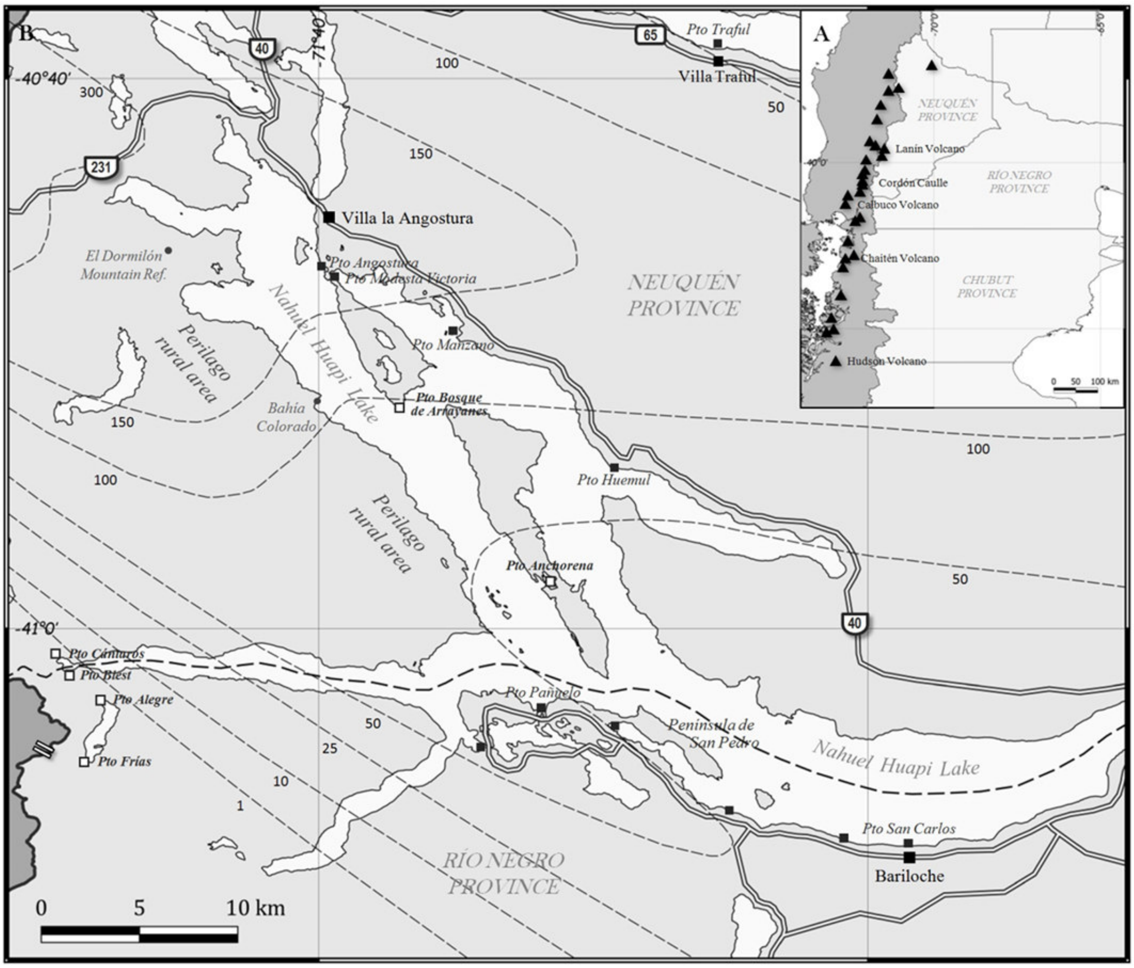

Fig. 3 A) Location of some of the active volcanoes from the Southern Volcanic Zone (Stern 2004) on its central & southern sections. B) Detail into the Nahuel Huapi Lake area, affected by the 2011-2012 Cordón Caulle eruption. Dashed lines indicate the ashfall deposit thicknesses (in millimeters) after the eruption. Some of the main port facilities are indicated (Pto); sites inaccessible by means of ground transport are highlighted with empty squares.

Lake, specially fomented after the 2011-2012 Cordón Caulle crisis (Anselmi et al. 2012; Outes et al. 2015; PNNH 2019), and the Quila Quina settlement in Lácar Lake.

2.3 Territorial accessibility overview

2.3.1 Accessibility

Accessibility considers the ability to reach places, people and economic activities with more or less ease (D'Ercole and Metzger 2009). Owing to its mountainous geography, climate settings and relatively high exposure to natural threats, this sparsely populated region features a fragile land-based accessibility, which is commonly a fundamental component of territorial vulnerability assessments (e.g., D'Ercole and Metzger 2009; Defossez et al. 2017; Leone et al. 2019).

In Los Alerces region, the only access route to the different lodgings, campsites and departure wharfs corresponds to the gravel Provincial Route 71 (Fig. 1). In the Nahuel Huapi and Lanín National Parks, the main access route corresponds to the National Route 40, an arterial paved road that links the major urban centers. Noticeably, there is a heavy traffic flow of residents, tourists and heavy-duty vehicles between Bariloche and Villa La Angostura: annually, traffic averages between 2.200 and 11.000 daily passing vehicles, depending on the season and the section of the route. The route also connects Villa La Angostura with San Martín de los Andes through a famous tourist 100 km-long stretch known as *Ruta de los Siete Lagos*; this road holds an estimated average of 1.300 daily commuters, with great seasonal variations. Specifically, Villa La Angostura poses high terrestrial isolation risks, as all ground transport into and out of

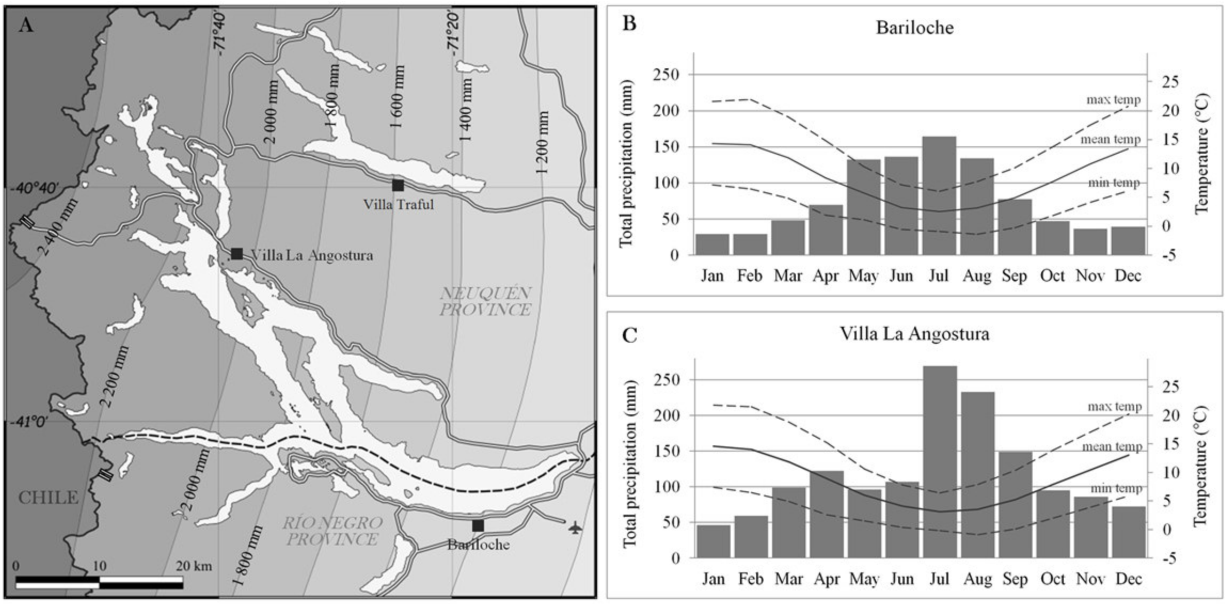

Fig. 4 Detail into the climate settings of the Nahuel Huapi Lake region. A) Isohyets map, adapted from Bianchi et al. (2016); B, C) Climographs representing the monthly distribution of total precipitation (columns, unit: mm) and maximum, minimum and mean temperatures (dashed and continuous lines, unit: °C) for Bariloche and Villa La Angostura.

the city is restricted to the National Route 40. Villa La Angostura is also located eastwards from the international border with Chile and the main Cardenal Samoré pass, a key commercial and tourist passage. Southwards, the Pérez Rosales pass is a far smaller tourist passage that requires the navigation through three different lakes, connected by stretches of land. The main airports within the area correspond to the International Bariloche Airport, the fourth most important airport in Argentina (regarding the number of passengers annually handled), and the smaller Chapelco Airport (Fig. 2).

Particularly, there is also a high degree of territorial accessibility restrictions among the coastal rural communities throughout the study region. For farmers on the western shore of the Nahuel Huapi Lake, an area commonly referred to as the *Perilago* (Fig. 3), there is no ground-based access to any urban population center. The only access to the neighboring Villa La Angostura's urban area, and to any other pathway out of the city, is by means of lacustrine navigation (See section 2.3.3). Most of the families rely on their own small ships, or assistance from local authorities, for stocking with basic supplies, health care and marketing livestock and other products. Similar scenarios also apply to the rural communities in the western part of Los Alerces (Fig. 1), the northern shores of the Traful Lake and the areas around the Lácar & Nonthué and the Huechulafquen & Epulafquen Lakes (Fig. 2).

2.3.2 Water transport networks

Originally, all infrastructure associated with water transport in Patagonia was introduced for sustaining the regional and international trade commerce and transport of people, in absence of a well-developed ground network in a remote and geographically rugged region (e.g., Bandieri 2011). Nowadays, lacustrine outings and water sports are most common activities, entailing only diurnal visitations that range from recreational sailings to organized excursions of hundreds of passengers (Fig. 5). Particularly, some of the tourist ports receiving large yachts and catamarans can only be accessed by means of lacustrine navigation (Fig. 1; Fig. 3). Water transport is also greatly significant for rural communities that rely exclusively on lacustrine transport to satisfy basic needs (See section 2.3).

Prefectura Naval Argentina, the national marine authority and security force, supervises the lake and port activities. Being located almost entirely within natural area reserves, water activities must also comply with safety and environmental regulations for preservation, supervised by National Parks authorities. Lake authorities are mostly based on the main coastal urban centers and patrol waters by means of a number of speedboats and other small ships.

Fig. 5 Example of some of the largest tourist passenger-ships operating in the Nahuel Huapi Lake: the Catamarán Futaleufú, seating 300 passengers and sailing from Puerto Modesta Victoria, in Villa La Angostura. Photo courtesy of Joaquín Claps.

3 Methodology and Data Sources

The paper takes a mixed methods approach for surveying, compiling, and evaluating water evacuation case studies.

Survey methods for reconstructing each case included a large number of consultations, direct field observations, and the collection of supplemental data from various sources. Consultations were carried out through meetings and semi-structured interviews with a number of local officials and first responders (public safety authorities, emergency managers, ship crews and land authorities, decision-makers, private executives and suppliers, etc.) from different organizations and institutions, who were directly involved (formally and unofficially) in the management of the different stages of each procedure studied (Heckathorn 1997, 2002; Salganik and Heckathorn 2004). Semi-structured interviews were role-driven and specifically designed to survey the primary components of the evacuation process, aiming to exhaustively draw on qualitative and quantitative data about water evacuations, allowing the accurate reconstruction of each event. Specific factual information requested from interviewees included: • A general depiction of evacuation strategies undertaken. • Existence of foresee planning. • The quantification of people, livestock and supplies displaced. • The length and rates of transports. • The main reasons for people and authorities to initiate or not the evacuations. • The departure and destination areas, routes, and distances involved. • The available transport resources deployed. • Information about evacuees safe returning processes. • Specific difficulties arisen during and after the evacuation process. • And mitigative and remediative measures undertaken to cope with different events. However, consultations also aimed to encourage spontaneous dialogues and free discussion with interviewees, including creative thinking about lessons learned and possible future scenarios (Strong et al. 2020), while also favouring the ease of identifying gaps in knowledge and lacking resources. In-person meetings were then continued by frequent feedbacks through videoconferences. Our observations on volcanic emergency-management initiated during the 2008 (and subsequent) volcanic crises, through research and participation in emergency committees; however, the bulk of consultations specifically referring to water evacuations was carried out mostly between 2019 and 2020. A total of 52 interviewees from 24 different organizations were consulted. A list of these institutions and their main inputs into this study are summarized in Appendix 1. Fieldwork was completed with regular visits to affected areas. Surveyed data from consultations was supplemented with unpublished technical reports and with local and official media report reconstruction. Population and tourism influx data was sourced from the *Dirección Provincial de Estadística y Censos de Neuquén* webpage and the 2010 Argentinean National Census (https://www.indec.gob.ar/indec/web/Nivel4-Tema-2-41-135). Road data was obtained from the *Vialidad Nacional Argentina* webpage (https://www.argentina.gob.ar/obras-publicas/vialidad-nacional/sig-vial; https://transito.vialidad.gob.ar:8080/SelCE_WEB/variaciones_temporales.html). Meteorological data was sourced from the *Autoridad Interjurisdiccional de Cuencas de los ríos Limay, Neuquén y Negro*.

There are numerous criteria available for summarizing the various details attended during each stage of an emergency response (e.g., Quarantelli 1982; Leonard 1985; Southworth 1991; Vogt and Sorensen 1992; etc.), and to some extent it relies on the research scope and depth of coverage desired or permitted (Perry and Lindell 2004). Using an eight-stage typology to organize our findings, we summarize case studies in Table 1, categorizing water evacuations-data into eight basic emergency response functions.

Table 1 Summary of water evacuation case studies. NP: National Parks; PNA: Prefectura Naval Argentina; CLER: Comité Local de Emergencias Rurales; TC: Tourism company; PTW: Private tourism workers; SIEN: Sistema Integrado de Emergencias de Neuquén; CP: Civil Protection; NRA: National Roads Authority

Event	Case study	Type of procedures	Reasons to initiate response actions	Transport resources	Organization	Timing	Evacuation degree	Evacuation constrains
4.1 The 2008 Chaitén volcanic eruption	Evacuation of Los Alerces	Impromptu and preventive vehicular displacement	Fear and no need to stay	Private vehicles	Individual actions	Immediate and long term responses	All but skeleton managers (no written records)	Lack of foreseen planning
	4.1.2 Assistance of sparse communities	Sporadic assistances of refugees sheltered in-place	No ground accessibility; critical services vulnerabilities	Coastguard ships	NP	Trans to post impact and long term responses	No written records on people and supplies displaced	Lack of foreseen planning; volcanic ash effects on shipping
4.2 The 2011-2012 Cordón Caulle volcanic eruption	Evacuation of Villa La Angostura	Impromptu and preventive vehicular displacement	Shadow evacuations triggered by inadequate communications and fear	Private vehicles	Individual actions	Immediate and short to long term responses	Partial evacuation ~5.500 inhabitants (unofficial) to neighboring areas	Warning issues; volcanic ash effects on vehicles; bottlenecks; high background traffic (peak season)
	Evacuation of *El Dormilón* refugee	Protective displacement	Exposure to proximal to medial volcanic hazards	Two private smaller *RIB*s	Individual actions	Immediate and long term response	Total evacuation of 9 people to Villa La Angostura	Hazardous conditions for shipping (airborne and waterborne ash)
	4.2.1 Evacuation and assistance of the *Perilago*	Impromptu attempt of rescue evacuation	Exposure to volcanic hazards; no ground accessibility; lack of communications; critical services vulnerabilities	Three coastguard ships	PNA; NP	Immediate withdrawal attempt	Non-evacuation	Lack of foreseen planning; inadequate communications; volcanic ash effects on shipping (including ship's total damage)
		Rural and social assistances of people and livestock sheltered in-place	Exposure to ongoing volcanic hazards; no ground accessibility; critical services vulnerabilities; families' reluctance to leave	One tourist ferry barge, and supporting coastguard ships	PNA; NP; CLER; and one TC	Post impact and long term recovery actions	No written records on people, livestock and supplies displaced	Lack of foreseen recovery planning; poorly censored farming activities; hazardous conditions for shipping (airborne and waterborne ash)
	4.2.2 Aid of rural communities in Traful	Impromptu attempts of rescue evacuations; rural and social and assistances of people and livestock sheltered in-place	Idem 4.2.1	Two coastguard ships, and other tourist smaller ships	NP; local emergency committee	Immediate withdrawal attempt; post impact and long term recovery actions	No written records on people, livestock and supplies displaced	Lack of foreseen evacuation and recovery planning; inadequate communications; lack water transport resources on site (low season); volcanic ash effects on shipping; poorly censored farming activities
	4.2.3 Strandings in *Puerto Blest*	Rescue displacement of stranded people (located out-of-threat)	No ground accessibility; complete disruption of shipping	One large tourist catamaran	TC	Post impact and long term response	Total evacuation of 8 people to Bariloche	Lack of foreseen planning; hazardous conditions for shipping; feasible larger number of potential evacuees (peak season)

(-To be continued-)

(-Continued-)

Table 1 Summary of water evacuation case studies. NP: National Parks; PNA: Prefectura Naval Argentina; CLER: Comité Local de Emergencias Rurales; TC: Tourism company; PTW: Private tourism workers; SIEN: Sistema Integrado de Emergencias de Neuquén; CP: Civil Protection; NRA: National Roads Authority.

Event	Case study	Type of procedures	Reasons to initiate response actions	Transport resources	Organization	Timing	Evacuation degree	Evacuation constrains
4.2 The 2011-2012 Cordón Caulle volcanic eruption 4.3 The 2015 Calbuco volcanic eruption	4.3.1 Aid through the Lácar-Nonthué Lakes during extensive road disruptions	Social assistance and displacement of people stranded or sheltered in-place	Complete disruption of limited ground accessibilities; partial disruption of shipping	Single coastguard ship (specifically intended for these procedures)	PNA; associated with NP and a TC	Trans to post impact and long term responses	No written records on people and supplies displaced	Lack of foreseen planning; hazardous conditions for shipping; sustained and severe wind-remobilization of ash
4.3 The 2015 Calbuco volcanic eruption	4.3.2 Isolation-risk scenarios in the Huechulafquen & Epulafquen Lakes	Not applicable	Exposure to proximal to distal volcanic hazards	Available fleet: one large tourist catamaran; smaller passenger ships	Available physical and human resources: NP; TC; PTW	Not applicable	Not applicable	Lack of foreseen planning; limited ground accessibilities; lack of knowledge on volcanic hazard' effects on water transport networks
4.4 The 2019 geo-meteorological crisis in Villa La Angostura	4.4.1 Nocturnal withdrawal of day time visitors	Preventive displacement of transient stranded visitors	Complete disruption of ground accessibility; disruption of critical services; no resources for shelter	Three large tourist passenger ships (Bariloche)	PNA; NP; SIEN; CP; NRA; two TC (Bariloche)	Immediate and short to long term response	Total evacuation of ~800 day-time visitors to Bariloche	Lack of foreseen planning; difficulties for navigating at night and extreme weather; difficulties for sheltering transient groups (peak season); involvement of practitioners unrelated to emergency management
	4.4.2 Transport of stranded tourists and residents by catamarans	Preventive and protective displacements of transient stranded visitors (and residents)	Idem 4.4.1	Two large tourist catamarans (Villa La Angostura); one tourist ferry barge serving as floating mobile wharf	Two TC	Trans impact and short to long term responses	Partial evacuation of ~12.800 totaling passengers to Bariloche (first week) and *Puerto Huemul* (next 3 weeks)	Lack of foreseen planning (evacuation routes and water transport resources); specific difficulties for managing large groups of tourists
	4.4.3 Transports by private small ship-cruises	Idem 4.4.2	Idem 4.4.1	~10 (at most) private small ship-cruises	PTW; coordinated with NP	Idem 4.4.2	Partial evacuation of ~1.200 passengers to Bariloche (first week); and ~2.400 to *Puerto Huemul* (next 3 weeks)	Idem 4.4.2
	4.4.4 Continuance of passenger transport services	Return and disaster economic recovery efforts	Complete disruption of ground accessibility; need for recover livehood and economy	Idem 4.4.2 Idem 4.4.3	Idem 4.4.2 Idem 4.4.3	Trans to post impact recovery responses	Idem 4.4.2 Idem 4.4.3	Lack of foreseen planning; specific difficulties for managing large groups of tourists

This typology provided a useful framework for summarizing and evaluating these remarkably contrasting cases, and were set as follows: • Type of procedure (based on, but not restricted to: Perry 1978, 1985, 1991; Leonard 1985; McLoughlin 1986; McCool et al. 2003; Lindell et al. 2006; Marrero et al. 2010; Tobin et al. 2013; Kolen and Helsloot 2014; and references therein). • Specific reasons for initiating (or refraining from initiating) response actions (e.g., Quarantelli 1980; Leonard 1985; Vogt and Sorensen 1992). • Transport resources implemented (number, type, and size of ships employed). • Organizations (if any) involved in the evacuation procedure, including local agencies, private tourism companies, etc. • Evacuation timing (in relation to disaster impact) and comparative lengths (amount of time that evacuees are expected to spend away from their homes) (Tierney et al. 2002; Urbina and Wolshon 2003; Zimmerman et al. 2007). • Specific remarks on the evacuation degree, and the number of residents, transient evacuees, livestock, and supplies transported (Drabek 1995; Tobin et al. 2013; Wilson et al. 2012b). • Evacuation failures, constraints and complexities arosen (e.g., Vogt and Sorensen 1992). • And key achievements accomplished. By presenting these cases orderly together (Strauss and Corbin 1990; Charmaz 2000; Glaser and Strauss 2017), we were able to identify key common issues that recurrently had an impact on both the efficiency and effectiveness of procedures. These insights are enumerated in section 5.1 as critical knowledge gaps that must be addressed in order to plan future water-based responses in North Patagonia. We conclude by presenting practical recommendations for emergency managers and other parties involved in planning or executing water evacuations, which are listed in section 5.2, based on different fundamental principles or functions of community emergency preparedness (Lindell and Perry 2007; and references therein).

4 Results: Summary of Case Studies

4.1 Case study 1: The 2008 Chaitén volcanic eruption

The Chaitén volcano (42.8° S, Chile) began erupting explosively (VEI: 4; Watt et al. 2009) without significant precursory activity on 2 May 2008 (Carn et al. 2009; Watt et al. 2009). The successive eruptive plumes dispersed rhyolitic products across the Andes and over Argentinean territory causing a wide range of immediate to long-lasting environmental, social and economic impacts on both Chilean and Argentinean Patagonia (e.g., Martin et al. 2009).

4.1.1 Maritime evacuations in Chaitén town (Chile)

In Chile, the eruption prompted mass evacuations of people from the town of Chaitén, where over 5000 citizens were successfully evacuated by marine transport shortly before the city was completely inundated by lahars (Tomsen et al. 2014). However, several ships suffered problems when facing the volcanic ashfall and floating pumice (Wilson et al. 2012a).

4.1.2 Assistance of sparse communities through Los Alerces' lakes

Lakes within Los Alerces region are located up to 85 km away from the volcano and were affected by 1 mm to 4 mm of ashfall (Watt et al. 2009). During the first days after the onset of the eruption, every tourist facility in Los Alerces evacuated on vehicles towards neighboring towns, and recreational lake activities were completely interrupted for almost six months, until the following summer season. Authorities remaining on site held various visitations onboard of coastguard ships to the sparse communities inhabiting the surroundings throughout sporadic sailings. Regrettably, there were no written records of these procedures, detailing the number of sailings and supplies transported. Similarly to what happened with boats in Chile (See section 4.1.1), two ships fishing in Menéndez Lake (Fig. 1) lost functionality when forcing their way through a perishable coating of floating pumice the morning after the eruption began. Despite these examples of ships failing both in Chile and Argentina, water transport was still regarded as a plausible resource for evacuating or assisting people in presence of volcanic ash by the following events affecting North Patagonia (See sections 4.2 and 4.3).

4.2 Case study 2: The 2011-2012 Cordón Caulle volcanic eruption

On 4 June 2011, 41 years since its last major eruption and following two months of precursory activity (OVDAS-SERNAGEOMIN 2011), the Cordón

Caulle (40.5° S, Chile) generated a Plinian eruption (VEI ~4-5; Bonadonna et al. 2015) with associated stratospheric eruptive columns (Castro et al. 2013). Heavy ashfalls were dispersed towards the east and southeast (Castro et al. 2013; Collini et al. 2013; Alloway et al. 2015), severely affecting large areas of Argentina, with important and prolonged volcanic ashfalls and remobilization events (Fig. 3). Eruptive activity continued intensely throughout June and into July; and it was not until August 2012 that OVDAS-SERNAGEOMIN reported the end of the emission of volcanic ash. The eruption and tephrafall widely damaged and interrupted critical infrastructure services in the region, including ground transport networks (Wilson et al. 2013). Destructive mass-wasting events, triggered by intense precipitations and involving tephra deposits (*secondary lahars*; Córdoba et al. 2015) were widely reported throughout the region severely interrupting ground-based transport, even in distal areas from the volcano, in the Patagonian steppe. The extensive disruption of critical services in Villa La Angostura and the uncertainties associated to the lack of official indications (Outes et al. 2015; Wilson et al. 2013) prompted the spontaneous self-evacuation of a large number of citizens by car during the first stages of the eruption (there are no official numbers). These procedures were strongly hindered by harsh conditions for driving during the first two weeks, primarily because of low visibility.

4.2.1 Evacuation and assistance of the Perilago rural area

Situated 50 km southeast from the eruptive center, Villa La Angostura was the most affected Argentinean locality, exposed to tephra thicknesses ranging between 150 mm and 170 mm (Alloway et al. 2015). However, even thicker ashfall deposits mantled the communities inhabiting in the *Perilago* (See section 2.2), closer to the volcanic center. Our first record of lacustrine retreat from the *Perilago* relates to a group of 9 volunteers, working on the building of the mountain refugee *El Dormilón* (Fig. 3). After hearing the extremely loud explosions at the beginning of the eruption, the workers rushed on foot to the western shore of the lake, later arriving in Villa La Angostura in two *RIBs* (rigid inflatable boats) overflowing with coarse pumice.

Lake authorities in Villa La Angostura, acknowledging the feasible situation of isolation for the rural communities on the *Perilago*, initiated a spontaneous and unsuccessful first attempt of withdrawal of the endangered families, soon before the beginning of the ashfall on the city. A two-member crew onboard of a high-speed *RIB*, headed towards the nearest family located in *Bahía Colorado* on the afternoon of 4 June (Fig. 3). Navigating half the way to destination, the crew encountered the first ashfall over the lake along with extremely loud electrical discharges over the waters. Visibility on the lake dropped to almost zero due to both, airborne and floating tephra, and very soon the outboard motor failed for the first time. The fully computerized system for navigation and intercoms sustained flashovers when exposed to airborne ash. The engines functionality was intermittently interrupted until failing completely close to the destination. The crew managed to row the boat to the shore and take refuge for the night at the addressed family house. The inoperative boat had to be later towed back to Villa La Angostura (Fig. 6). On the same day, a second ship, heading to the rescue of the first one, lost functionality too, near *Puerto Bosque de Arrayanes* (Fig. 3), where the crew took refuge at the housekeeper cottage. Finally, a third ship was unexpectedly resilient to the volcanic ash effects, attaining to assist the crew stranded in *Bosque de Arrayanes*.

These attempts initiated as spontaneous and unplanned evacuations of the populations closest to the volcano. However, in the short term these attempts of evacuation progressively turned into operations of aid and assistance by lacustrine transport, coordinated by the *Local Committee for the Rural Emergency* (*CLER*; Anselmi et al. 2012). The strategy was modified mostly on account of the families' reluctance to leave their farms and animals, and further difficulties arising from logistical constraints for mobilizing people and livestock. Social and agricultural assistance included the distribution of bottled drinking water for livestock and human consumption, bales of hay and the transport of livestock (Fig. 7). These operations were handled by *El Patagón*, a ferry barge belonging to one of the main tourist companies in Villa La Angostura, along with supporting ships from *Prefectura Naval Argentina* (Fig. 7).

One of the main reasons prompting the attempt of evacuating the communities on the *Perilago* relayed on the already identified extremely vulnerable infrastructure conditions that would inhibit the possibility for sheltering in place. This included the

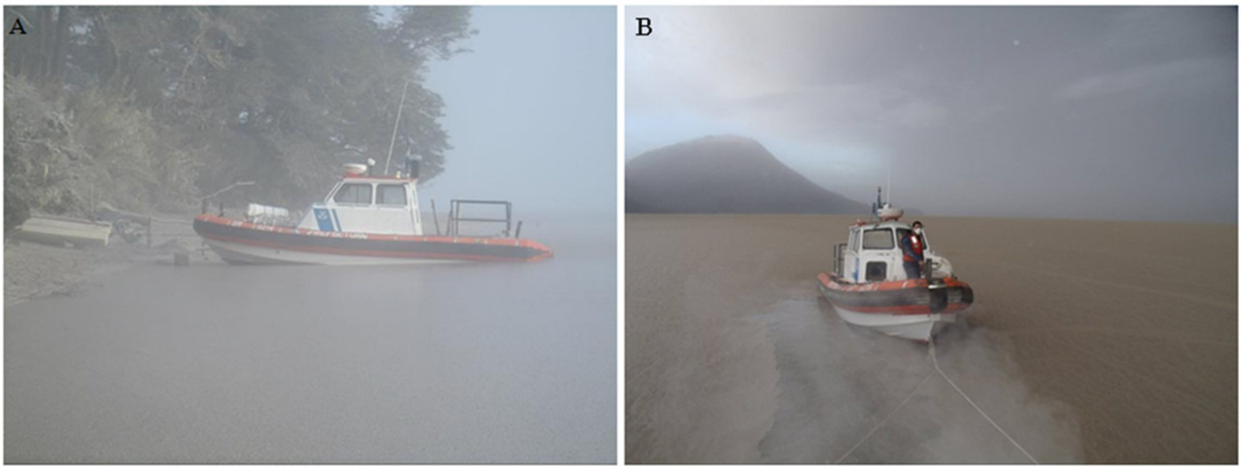

Fig. 6 First attempt of evacuation of rural communities in the Perilago, during the 2011 volcanic eruption. Photos courtesy of Prefectura Naval Argentina from Villa La Angostura. A) Dysfunctional speedboat stranded in Bahía Colorado, on the Perilago, 4 June 2011; B) Dysfunctional speedboat towed back to Villa La Angostura the following day after losing total functionality, 5 June 2011.

Fig. 7 Evacuation and assistance of isolated communities in the Perilago, during the 2011 volcanic eruption. Photos courtesy of Prefectura Naval Argentina from Villa La Angostura.

stream-fed drinking water supplies, completely disrupted since the beginning of the ashfall (Wilson et al. 2012a; Outes et al. 2015). The lack of accurate livestock census, associated to the restricted and widely open farming style within the National Park, was also a significant deficiency for coordinating the response actions and quantifying the animals to be evacuated. Unfortunately, no written records regarding the relocation or sale of livestock and goods were officially registered in the compulsion of the crisis (Anselmi et al. 2012; Outes et al. 2015).

4.2.2 Surveillance trips & aid of rural communities in Traful Lake

Situated about 65 km east from the volcano, Villa Traful and its surroundings were affected by almost 50 mm of tephra thicknesses (Alloway et al. 2015). Similarly to the *Perilago* (See sections 2.3 and 4.2.1), there are a number of small groups of coastal communities farming sparsely along the northern shores of Traful Lake, a remote area mostly inaccessible by ground transport (Fig. 2). In the absence of communications, two emergency sailings were separately deployed for surveying the situation in the northern shores of the lake, transporting bottled drinking water and supplies. A first *RIB* operative on site departed from Villa Traful for assisting the nearby communities about a week after the beginning of the eruption, once given better conditions for sailing in the area. A second *RIB* had to be towed by truck from Villa La Angostura´s surroundings and launched to the lake from its northwestern end for assisting communities on the northern branch of the lake. Both ships sustained engine failures due to the persistence of pumice in the water, requiring manual clearances of engines in the midst of the navigations. Still, all communities refused to leave the northern shores of the lake, preferring to cope with the volcanic ashfall sheltering on site. In this region, the response strategy for the rural crisis included the immediate transport and sale of livestock before death or quality degradation, mitigating the negative effects of the eruption on livestock activities.

4.2.3 Strandings in Puerto Blest

Puerto Blest is a famous tourist destination located on the western branch of Nahuel Huapi Lake, on the way to the Pérez Rosales pass. Tourist trips sail daily from *Puerto Pañuelo* to *Puerto Blest*. Being the only inhabited location in a radius of tens of kilometers, it is only attainable by means of lacustrine navigation (Fig. 2; Fig. 3).

During the 2011-2012 Cordón Caulle eruption, neither ashfall nor floating pumice was reported specifically at *Puerto Blest*, sitting about 60 km south of the eruptive center. Bariloche however, located 100 km southeast of the volcano, was draped with tephra deposits of 30 mm to 45 mm thick (Alloway et al. 2015) (Fig. 3). Owing to the harsh conditions for sailing near Bariloche and *Puerto Pañuelo*, due to primary ashfalls and the southeastwards drift of massive floating pumice rafts (Fig. 8) *Prefectura Naval Argentina* imposed a one-week-long restriction for shipping operations in the area. Consequently, 8 workers were stranded for 8 days in *Puerto Blest*, incapable of returning. The stranded staff was later evacuated to Bariloche by the catamaran *Victoria del Lago* (Fig. 8), once given better conditions for sailing. Four other Argentinean officers stranded in *Puerto Frías* (Fig. 3) attained to walk out safely towards Chile.

At the time of the day when the ashfall began in Bariloche, no daytime visitors remained at *Puerto Blest*, resulting on the stranding of only the rotating working staff. Moreover, the *Puerto Blest* Hotel was not hosting guests regularly at the time, thus no overnight-stays aggravated the number of stranded people. However, since 2015 the Hotel accommodates visitors and passengers travelling to/from Chile. Currently, a maximum of 650 people (including about 50 overnight-stays of tourists and staff) can stay at *Puerto Blest* simultaneously during summer seasons. Hence, forthcoming events compromising the navigability on the lakes could represent a completely different scenario of strandings, owing to the feasible larger number of potential evacuees (See section 5.1).

4.3 Case study 3: The 2015 Calbuco volcanic eruption

Almost four years after the 2011 Cordón Caulle eruption, the Calbuco volcano (41.3° S, Chile) reawakened on April 2015 in an intense sub-Plinian eruption (VEI: 4; Romero et al. 2016) with little pre-warning indications (Romero et al. 2016). The eruption comprised two major sub-Plinian pulses,

Fig. 8 Volcanic ashfalls and pumice rafts disrupting the navigability on the southeastern Nahuel Huapi Lake, after the Cordón Caulle eruption, in June 2011. A) Large yachts and catamarans moored in Puerto Pañuelo covered by a thin layer of volcanic ash; second in the foreground, the catamaran Victoria del Lago (seating 300 passengers) withdrew the stranded staff from Puerto Blest eight days later. Photo courtesy of Martín Pereira; B) Massive pumice rafts drifting towards the Bariloche city center shores.

occurring on 22 and 23 April, and a third and minor pulse occurring later on 30 April (Romero et al. 2016). The eruption dispersed ashfalls mainly towards the northeast (Romero et al. 2016) affecting regions of North Patagonia previously impacted by the 2011-2012 Cordón Caulle eruption.

4.3.1 Aid through the Lácar & Nonthué Lakes during extensive road disruption

The area around the Lácar & Nonthué Lakes (Fig. 2), located up to 80 km away from the Cordón Caulle and 170 km away from the Calbuco volcano, was significantly affected by the two eruptions, receiving about 2-4 mm (Alloway et al. 2015) and 7-12 mm of ashfall thicknesses, respectively.

During the Cordón Caulle eruption, and based on the warnings from Villa La Angostura's authorities (See section 4.2.1), all types of shipping were restricted as a precaution on the lakes in the area. Simultaneously, vehicle driving was strongly discouraged due to the appalling conditions of roads and the heavy remobilization of ash caused by passing vehicles. Hence, lake authorities in San Martín de los Andes took over all transport of people and supplies in the areas around the Lácar & Nonthué Lakes, by means of a single small *RIB* that remained operational during the volcanic crisis. For months, this single ship handled the transport and the assistance of the various families and communities sitting sparsely on the shores of these lakes, during the interruption of the tourist shipping services that regularly visit these remote sites. Again, the lack of written records on this type of operation prevents a more detailed analysis regarding evacuation and assistance procedures. After the 2015 Calbuco eruption, lake activities were interrupted for only two days, the time it took for clearing the ashfall accumulated in San Martín's port.

4.3.2 Isolation-risk scenarios in the Huechulafquen & Epulafquen Lakes

The Huechulafquen & Epulafquen Lakes (Fig. 2) were found to be the most affected lakes after the 2015 ashfall event, receiving ashfall thicknesses ranging from 3 mm in *Puerto Canoa* to over than 15 mm towards the east (Fig. 9). These remote lakes also bear tourist shippings departing daily from *Puerto Canoa*, an overrun tourist port accessed only via a single gravel road. Still, the ashfall event (extremely disruptive for vehicles) did not prompt the need for any particular emergency water transport in the area. However, in other respects, the Huechulafquen & Epulafquen Lakes are located immediately southwards the active stratovolcano Lanín, on the border of Argentina and Chile. Further in-depth isolation-risk analysis is required for these sites, on the basis of its exposure to a wider range of volcanic hazards (See section 5.1).

4.4 Case study 4: The winter 2019 geo-meteorological crisis & evacuations from Villa La Angostura

On the night of 20 July 2019, the biggest snowstorm registered in Villa La Angostura since 1994, covered the *Ruta de los Siete Lagos* (Fig. 2)

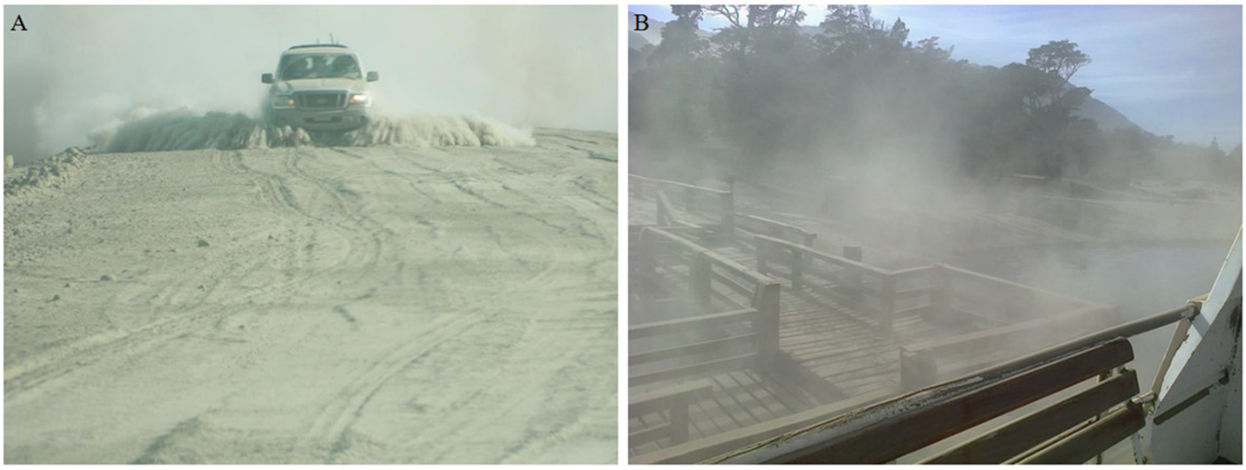

Fig. 9 Effects of ashfalls on transport networks in the Huechulafquen & Epulafquen Lakes area, after the 2015 volcanic eruption. A) Passing vehicle over ashfall deposited on the gravel Provincial Route 61, heading to Puerto Canoa. Photo courtesy of Hostería Paimún staff; B) Wind-remobilization of volcanic ash at Puerto Canoa; view from onboard the tourist catamaran José Julián. Photo courtesy of Catamarán José Julián.

with snow and fallen trees. The snowstorm accumulated thicknesses of 120 cm and was followed by heavy rainfalls, covering road surfaces and snow with ice. The fall of trees caused a 16 days-long disruption of electricity supply in the city, which also prompted the enhanced requirement of incoming fuel-tanker trucks to supply electricity generators. A grave traffic accident, involving a tanker trunk, caused not only the road obstruction but also a wide oil spill and a severe wildfire. Consequently, the northwards way-out of the city remained intermittently disrupted for many weeks. Some neighborhoods also experienced disruptions on the drinking-water supplies, due to systems' dependences on electrical power (Wilson et al. 2013). Fallen trees disrupted communications and severely damaged a number of vehicles and buildings, and a fire resulted in the complete destruction of a residential house.

Fig. 10 Rockfall blocking the access between Villa La Angostura and Bariloche for almost a month, during winter 2019. Photo courtesy of Carlos Tavalla.

Fig. 11 Night evacuation of day-time visitors from Puerto Modesta Victoria to Bariloche, 23 July 2019. Photo courtesy of Prefectura Naval Argentina from Villa La Angostura.

Simultaneously, a decrease on natural gas supply was also reported within different sites of the city.

Two days after the beginning of the snowstorm, a large and rapid rock topple (Hungr et al. 2014) fell directly over the National Route 40 roadway (Fig. 10) southwards Villa La Angostura and near *Puerto Huemul* (Fig. 2). The collapse of a detached 40 meters-high wall of rock, with an estimated volume of 1.000 m^3, completely disrupted the traffic towards Bariloche and the Bariloche Airport for 29 consecutive days. Remediation works were hindered by the impairing adverse weather conditions, along with the need for finding best-practice methods, as the main gas piping supplying the city runs only 50 cm deep along the road shoulder. Remediation and stabilization works were initiated later on September, causing further occasional traffic disruptions. These two simultaneous events completely blocked the two main connecting roads to Villa La Angostura, isolating the city by all means of ground transport for an entire month.

The climatic emergency was managed by a local Emergency Operations Committee, which was also handling the affluence of *Hantavirus Pulmonary Syndrome* period. During the first weeks, two overburdened evacuation centers assisted residents and stranded tourists. Rural communities were aided by means of a helicopter and a special health service aircraft. A municipal alert regarding the social, economic and environmental emergency was issued on 24 July and lasted for two months.

4.4.1 Nocturnal withdrawal of day-time visitors by large passenger-ships

On the first night of the total land-based isolation, about 800 day-time visitors (touring in buses through Villa La Angostura and San Martín de los Andes) were evacuated to Bariloche through an exceptional nocturnal operation by means of three large tourist passenger-ships that regularly sail from *Puerto Pañuelo*: the yacht *Modesta Victoria* and the catamarans *Cau-Cau* and *Gran Victoria* (Fig. 11). The Nahuel Huapi Lake open waters lack of beaconing and usually the nocturnal navigation is strictly restricted. The basis for the decision to perform this night evacuation relied on the severe disruption of critical infrastructure services and difficulties on accommodating such a large number of people in an already overcrowded destination during the winter peak season.

The three passenger-ships in *Puerto Pañuelo* initiated the navigation heading to find the group of tourists in the afternoon of the same 23 July. The slow process of boarding in Villa La Angostura, hampered by the lighting outages and extreme weather conditions, ended near midnight. Tourist guides in site collaborated on the management of the groups of people, and *Prefectura Naval Argentina* assisted specifically on the lantern lightning for boarding processes and ship maneuvers.

4.4.2 Transport of stranded tourists and residents by catamarans

Three days after the confinement of the city, the two companies managing large passenger-ships in Villa La Angostura began to coordinate the periodic withdrawal of stranded people out of the city by means of the catamarans *Patagonia Argentina* and *Futaleufú* (Fig. 5). For the first six days both catamarans transported passengers from the city center ports to *Puerto Pañuelo*, near Bariloche, on a respectively single-daily-travel across the Nahuel Huapi Lake (Fig. 12). Notwithstanding, this path is lengthy (over 2 hours), expensive and extremely liable to risky wind conditions, which were forecasted for the following days. Thus, 6 days later, the evacuation path was modified, sailing from Villa La Angostura to *Puerto Huemul*, located close to the rock toppling, over 20 km southeastwards the city (Fig. 3). As there is no wharf serving large ships in *Puerto Huemul*, the passengers boarding and disembarking were assisted by usage of the ferry barge *El Patagón*, serving as a floating-mobile wharf (Fig. 12). The navigation from Villa La Angostura to the new disembarking site at *Puerto Huemul* was greately shortened, and each catamaran increased the frequency to two daily travels. The evacuation process was then completed from *Puerto Huemul* to Bariloche, or the Bariloche Airport, by means of ground transport. However, the stretch of land between *Puerto Huemul* and the National Route 40 was an impassable path for vehicles. Therefore, for the first days, the evacuation process implied a 700 meters-long snowy or muddy uphill walk, carrying baggage in severely adverse meteorological conditions. Remediation works undertaken a week later allowed the access of vehicles

Fig. 12 Transport of stranded tourists and residents from Villa La Angostura during the winter 2019. A) Boarding of tourists at Puerto Modesta Victoria, during the first week of the isolation; B, C) Boarding of tourists through a ferry barge serving as a mobile wharf in absence of pier facilities at Puerto Huemul. Photos courtesy of Roxana Cerda; D) Reconditioned uphill walk, between Puerto Huemul and the National Route 40, for vehicle access. Photo courtesy of Carlos Tavalla.

from the route to the lakeshore, facilitating the evacuation processes (Fig. 12).

These navigations were carried out with the tourist companies' regular existing staff, and an extra agent coordinating the land transports; boarding of passengers was also assisted by local and national authorities. The Provincial government later covered the costs for these free transports. Both companies estimated that each catamaran transported about 6.300 and 6.500 passengers respectively, during the 26 days of ground-access isolation until the restitution of passability on the National Route 40, on 20 August.

4.4.3 Transports by private small ship-cruises

Immediately after the total confinement of the city, tourist private providers at Villa La Angostura also initiated the transport of stranded people through small-ship cruises and boats, habitually navigating to nearby destinations. These atypical shippings, through unusual water routes, were lead by about four suppliers, transporting an average of ten passengers each to *Puerto Pañuelo* for over a week. However, this lengthy lane through open waters posed an extremely expensive recourse and a risky venture for small boats. For these reasons, most providers opted out these navigations at the beginning of the catamarans services (See section 4.4.2); and the remaining suppliers handling relatively larger boats also tailored its shipping lanes along with the catamarans to *Puerto Huemul* (Fig. 3). Differential private transports operated daily at full capacity until the restoration of the ground-based transport. Additionally, authorities carried out medical referrals and social assistances for the rural communities on the *Perilago* by usage of speedboats.

4.4.4 Continuance of passenger transport services

Once coped with the climatic emergency, and critical services were reinstated, the city initiated a strong campaign for recovering tourist activity. The initial lacustrine withdrawal efforts slowly turned into the main bias of influx of tourists to the restored city, and the only resource for citizens working out of Villa La Angostura, and vice versa. Lacustrine tours, usually handled by the larger catamarans, were managed in replacement by smaller particular boats sailing with reduced numbers of customers, in order to cope with the economic crisis. Large passenger-ships operating in Bariloche also initiated atypical and occasional transports of tourists from Bariloche to the still isolated but restored Villa La Angostura. Various organizations and Provincial government provided economic support to aid with the restoration of activities in the city and the also affected Villa Traful.

5 Discussion and Recommendations

5.1 Knowledge gaps and future directions

Local authorities and communities conducted several efforts in order to cope with the different crises described previously. However, a number of difficulties arose during the evacuation and assistance processes. This review allowed us to identify a number of shortfalls that should be addressed for planning forthcoming water evacuations, enumerated below. Collectively, these insights examine the susceptibility of North Patagonian communities to a range of natural hazards, and their capability to deal with them through water transport means.

- The lack of an integrated outlook of the different natural hazard scenarios in the region. North Patagonia is exposed to a wide range of different natural hazards that might directly endanger or isolate populations by disrupting transport networks (this work), triggering the necessity for evacuating or assisting refugees via water transport. A better understanding of the type, severity, location, and timeline of events would aid in determining what specific response would be most appropriate (Vogt and Sorensen 1992; Perry and Lindell 2004; Murray-Tuite and Wolshon 2013).

A further challenge is the multi-hazard characteristic often exhibited by the case studies (Table 1). Various volcanic and non-volcanic threats can occur simultaneously or sequentially, affecting societies differently and prompting the need for complex response mechanisms (Wilson et al. 2012a). Importantly, different hazards and different post-event environments pose remarkably different constraints for managing evacuations, assistance, returns, or recovery efforts via water transport (Table 1).

While not part of the addressed case studies, forest fires affecting the wildland/urban interface has been also widely reported in North Patagonia (e.g., Veblen et al. 2009) and require specific attention for planning water evacuations. Wildfire risk in the area appears to be increasing under a regional trend towards warmer temperatures, increased lightning ignitions and urban sprawl (Veblen et al. 2011; SAyDS 2014). Most recently, a severe wildfire initiated in March 2021 in southern Río Negro Province, consumed a vast swathe of forestland and affected severely a number of settlements in North Patagonia. Limited land-accessibility has been addressed constraining evacuations and fire-fighting actions. Less frequent threats, as seismicity and associated phenomenons (such as subaqueous landslides and lacustrine tsunamis) has been previously identified affecting localities and tourist sites in the region (Chapron et al. 2006; Villarosa et al. 2009, 2013; Córdoba et al. 2015; Beigt et al. 2016, 2019) and also need to be considered for planning responses.

In contrast to many other threats (Murray-Tuite and Wolshon 2013), the majority of North Patagonian cases (Table 1) occurred as a result of short to no-notice events (Wilson-Goure et al. 2006; Noh et al. 2009; Murray-Tuite and Wolshon 2013). Although quick responses are critical for saving lives and mitigating losses, hurried waterborne responses in trans to post-impact environments (Tierney et al. 2002) resulted in additional evacuation-related risks (See sections below).

• The absence of a clear identification of sites with a greater risk of isolation, and the corresponding development of resources for evacuating these sites alternatively by lake. Evacuations entail considerations of spatial concerns and territorial systems (D'Ercole and Metzger 2009; Defossez et al. 2017; Leone et al 2019), especially if the location of the event influences the decision to evacuate or not (e.g., Hughey 2008; Tomsen et al. 2014; Leone et al. 2019). In North Patagonia, limited land-based accessibilities strongly governed both the necessity and the possibility of evacuating via water transport (Table 1). As such, emergency management must be based not only on hazards-related data, but also on depicting territorial vulnerabilities (in the water and land domains) and functional infrastructure features (as adequate port facilities, ships and preset-paths for safe evacuation) that allow evacuating these areas.

For example, the currently increased accommodation capacity at the remotely located *Puerto Blest* (See section 4.2.3) urge the necessity to address the management of a feasible larger number of stranded tourists. Forthcoming disruptions of water-based accessibilities, or hazardous scenarios threatening *Puerto Blest* site, would require the readiness of resources enabling the shelter in-place of an overcrowded group of people, or alternative evacuation strategies. In other respects, although the 2015 Calbuco volcano eruption did not trigger any cases of evacuations at the Huechulafquen & Epulafquen Lakes (See section 4.3.2), the circumstances could be critically more unfavorable when facing forthcoming hazards (mostly if associated with the nearby Lanín volcano), owing to the existence of a number of coastal settlements, great influx of tourists and a single access road to *Puerto Canoa* (Fig. 2). Many other semi-insulated places of limited access, frequent on the coasts of North Patagonian lakes, lack of suitable resources that could make water-based evictions possible. For example, the *Península de San Pedro* (Fig. 3), an inhabited suburb extending near Bariloche, is accessible solely by a single entry paved road and lacks of sizing port facilities.

Hence, plan development (fundamentally if water transport is required) should integrate specific plans for each individual community (e.g., Perry and Lindell 2004) considerng ground-based accessibility issues (D'Ercole and Metzger 2009; Defossez et al. 2017; Leone et al. 2019); the identification of low-mobility groups (Urbina and Wolshon 2003), with regard to the possibility of accessing ground or water-based transport resources; and possible worst-case scenarios assumpions (e.g., Golding and Kasperson 1988).

• The absence of a clear (intra and inter organizational) coordination among the different parties and jurisdictions involved in risk and emergency management.

It has long been recognized that response activities are substantially enforced by an effective interorganizational coordination among diverse groups (some formally constituted, others volunteer), and that one of the most difficult challenges that stakeholders usually face is to ensure that these organizations work effectively together (Dawson 1993; Neal 1993; Perry and Lindell 2004; Cronin et al. 2004; Alexander 2007; King 2008; etc.). Due to the primarily tourist-nature of the most important water transport resources in North Patagonia, many private entities got unexpectedly involved in response and recovery actions (Table 1). Emergency plan development in the region needs to address the close involvement of local water transport professionals and tourism organizations, including their available physical and human resources (ships, ports, facilities, and specialized personnel), and their capabilities for managing large groups of visitors.

Another emerging issue is the lack of a clear delimitation of the scopes of the different parties involved in risk and emergency management (Table 1). This is particularly the case within national parks and protected natural areas, where a clear overlap has been repeatedly identified between the numerous institutions formally or unofficially involved (such as National Parks, *Prefectura Naval*, *Protección Civil*, *Vialidad Nacional*, emergency committees, the private sector, etc) and various authority levels (national, provincial, municipal, and the various park's jurisdictions) for managing water evacuations in different urban environments (Cross 2001). These constraints were further elucidated in the case of simultaneously managing multiple transport networks disruptions (See sections below). Importantly, failing to accomplish the full range of emergency coordination favours impromptu and autonomous responses by potential evacuees, posing additional risks (e.g., Sorensen 2000; Grothmann and Reusswig 2006; Kolen et al. 2013), which are exacerbated in water domains (Table 1; See sections below).

Intra-organizational constraints (Vogt and Sorensen 1992) included the complete and repeated lack of written documentation, including formal or unofficial evacuation (or recovery) plans, records of previous experiences, or accurate census data (for rural and tourist activities). In addition, although not reflected in Table 1, there is a frequent turnover of personnel with first-hand experience and knowledge of previous cases.

• Recognizing and acknowledging the critical influences of demographic characteristics on evacuation procedures.

The influence of pre-emergency population attributes (psychological, demographic, and social characteristics) on response actions has been extensively studied in the past (e.g., Kroll-Smith and Drabek 1988; Morrow 1999; Chakraborty et al. 2005; Bolin and Kurtz 2018). Local authorities consistently proved to be clear about the great demographic variabilities in North Patagonia. However, incorporating collectivelly all these shifting and widely different population-related features (inherent to such a particular region as North Patagonia) represents critical complexities for planning forthcoming water evacuations. For example, despite the lack of communications and long-lasting disruption of critical services during the 2008, 2011, and 2015 volcanic ashfalls, many poorly censored rural communities were paradoxically sheltered and assisted in-place, due to the initial constraints on moving via water transport, and their reluctance to leave animals and houses (See sections 4.1.2, 4.2.1, 4.2.2, and 4.3.1). Hence, evaluating not only the location but also the vulnerability of critical infrastructure services (e.g., Wilson et al. 2012a) in both urban and rural environments (Table 1) plays a part in determining the necessity and viability of evacuating via water transport, as well as influencing authorities and evacuees' decision-making processes.

Evacuations in areas with seasonal peaks are difficult (Murray-Tuite and Wolshon 2013). Among the greatest limitations for planning clear responses in Patagonia is the enormous diurnal and seasonal variation in the number and location of potential evacuees, owing to the great influx of tourist visitors. This type of situation-specificity is critical for effective planning, as time of the day or time of the year may limit (water or land-based) evacuation-route options, transportation resource availability, navigability conditions, etc.

Tourists are often more vulnerable and less prepared for evacuating (e.g., Matyas et al. 2011; Aliperti et al. 2020; Wachtel et al. 2021). Several peculiar features arose regarding the complexity of tourist groups involved in these waterborne procedures (Table 1). For example, many stakeholders interviewed, particularly and emphatically recalled many obstacles arising from the management of tourists' luggage during the winter 2019 water evacuation in Villa La Angostura (Fig. 12). Interviewees repeatedly highlighted how passenger's bulky luggage limited the capability onboard, hindering and lengthening the processes of boarding, navigating and disembarking, which also curtailed the daily frequency of trips. For smaller boats, luggage tied up on top of the ships diminished their stability, a key point during the transfers crossing open waters. Further difficulties arose from transporting luggage on foot from the lakeshore, at *Puerto Huemul*, to the route (Fig. 12).

Developing strategic plans should be hence strengthened by considering accurate information about the size of the procedure to plan for, and particular social and physical vulnerabilities of exposed populations in order to better determine possible alternative waterborne responses.

• The lack of knowledge about vulnerability characteristics of water transport networks, facing different hazardous scenarios.

During an emergency, functional transportation is one of the most critical components of a region's infrastructure network, as it facilitates the movement of people, livestock, and supplies (Amdal and Swigart 2010; Tomsen et al. 2014; Wilson et al. 2012a). As any type of response will take place under conditions that differ from normal transportation (Holguin-Veras et al. 2007), it is critical to ensure the resilience of logistics during emergencies (Godschalk 2003; Valentine 2003). In the past, maritime and fluvio-lacustrine transport was widely regarded (and implemented) as a viable transport resource for managing natural disaster events (e.g., Wilson et al., 2009; Amdal and Swigart 2010; Tomsen et al. 2014; PAHO 2021). However, different volcanic hazards caused by recent eruptions significantly limited evacuations in Patagonia, as volcanic ash severely impacted ship and port functionality (Table 1). The nescience about the possible consequences of navigating during and after an ashfall event not only hampered evacuation efforts, but also posed additional threats to in-route stakeholders and evacuees.

Furthermore, even years after these eruptions, sustained wind and fluvial remobilization of tephra deposits continued to affect the navigability of many lakes in the region. For example, during the 2019 ground isolation of Villa La Angostura (See section 4.4), eight years after the Cordón Caulle volcanic eruption, a smaller passenger-ship with ten tourists onboard blew its engine while crossing a thread of floating pumice close to a stream mouth near the *Perilago* (Fig. 3). On the other hand, many impromptu measures udertaken to mitigate the effects of volcanic ash on shipping proved partially effective in preserving the functionality of water transport (Table 1). Hence, developing of emergency plans must be accompanied by a better understanding of the potential effects of volcanic ash (and other volcanic hazards) on water transport, and the actual effectiveness of different mitigation and remediation strategies. All of this has prompted our investigation into the potential impacts of volcanic eruptions on water transport systems, which is currently in the bias of publication (Salgado et al. *in prep*).

5.2 Recommendations for planning water evacuations

The disregard of lacustrine navigation as a formal evacuation resource resulted in improvised procedures rather than an orderly and stage process. Our comprehensive assessment depicts some of the various elements and staged practices that ought to be orderly considered by those involved in crisis management when devising a water-based evacuation procedure (Lindell and Perry 2007); which are summarized below:

• The identification and characterization of all the potential threats menacing the region, based on previously surveyed hazard-related data and resulting in overarching hazard maps that consider possible multi-hazard scenarios.

• The regional assessment of land-based territorial accessibilities, attempting to identify sites prone to ground-isolation risks, and liable to require the readiness of alternative means of transport.

• The regional assessment of population-at-risk, attempting to identify the highly variable vulnerabilities that might hasten or hinder the evacuation procedure (or conversely, the suitability of sheltering in-place). In North Patagonia, this is particularly the case for rural communities and tourist groups.

• The reckoning of population-at-risk, attempting to size the extent of potential transports (accounting for people, livestock and goods). In North Patagonia, this is particularly the case for the poorly censored livestock in rural areas, the sharp variations of tourist affluences, and the ongoing unplanned urban and tourist developments.

• The design of detailed and comprehensive evacuation plans, formally considering alternative water transport resources. All levels of concerned jurisdictions should be involved in developing comprehensive evacuation strategies, clearly establishing responsibility scopes and communication channels between scientific institutions, stakeholders/authorities, and the private sector. Evacuation schemes should specially: address where the evacuees will meet and embark; devise safe paths and suitable destination points; establish where the evacuees will be housed (either in-place or at destination points); determine what vehicles (ships) and human resources will be used, evaluating its capabilities and its associated efficiencies; foresee when and how an evacuation call will be announced;

and outline the minimum conditions and viable means for a safe returning. Planning should also consider preparations for emergency and non-routine shippings, as nocturnal lake navigations or the transit through unconventional water routes, and consider in adition post-vent recovery strategies (e.g., Philips 2013).

- The identification of available transport resources and the development of lacking infrastructure required to fulfill successfully the evacuation procedures. This includes suitable port facilities strategically located, the availability of ships or watercrafts, and adequate evacuation routes. Most noticeably, existing and projected ports in the region need to be fully integrated with further surface transport networks (routes, airports) and other critical facilities (major cities, hospitals and evacuation centers). As discussed before, all infrastructure and operations concerned should be matched with a clear understanding of the possible effects of exposure to natural hazards, and the knowledge about effective mitigative strategies.
- Finally, evacuation plans must be clearly communicated to all of the parties potentially involved: including those who might exceptionally have a role assisting in the procedures (as tourist companies, tourist guides, captains and sailors, private suppliers, etc.).

5.3 Lessons relevant to North Patagonia and other areas at risk

Although this is not the first assessment of communities' preparedness and general transport resources for emergency management, a review of the available literature revealed that there have been no prior studies particularly investigating cases of water evacuations (or emergency responses) in North Patagonia Argentina. This region was an ideal scenario for this assessment, not only because of the large number and variety of recent cases to address, but also because of the peculiar and dissimilar range of challenges that arose, simultaneously impeding the success of such a specific response strategy. This investigation, then, indentified the influence of many well-known difficulties in managing emergencies via ground-based transport (e.g., Vogt and Sorensen 1992), but specifically in cases of waterborne responses. In addition, new issues have been recognized that did not emerge in previous studies, indicating the need for greater attention to specific areas missing in evacuation planning research, most particularly in North Patagonia. It is important to note that each case presented a variety of constraining elements, whose comparisons significantly expanded our understanding of water transport capabilities for managing disasters. Given the low probability of events necessitating evacuation in a given area (Murray-Tuite and Wolshon 2013), this limited history of such events in Patagonia represents a valuable experience (for researchers, responders, and policymakers alike) from which to learn and improve the development of emergency plans (taking into account water transport).

This research provides realistic insights for assessing the actual benefits of evacuating by ship in comparison to other modes of transport. A key finding of this work is how functional water transport can significantly reduce pre-existing territorial accessibility constraints and disruptions, while also supporting alternative protective actions (such as sheltering in-place) through water assistance trips for vulnerable and low mobility groups, also favoring post-event recovery actions. Lake transport, on the other hand, demonstrated significant limitations in supporting mobility during and long-after the occurrence of volcanic ashfall events. More research should be conducted in North Patagonia and worldwide to better understand the benefits and drawbacks of mobilizing people, livestock, and supplies in such conditions.

By depicting how effectively lake transport responded, and by having knowledge about how different interacting components constrained these procedures, we provide quantitative and qualitative empirically proven insights and better justified suggestions for supporting the development of transport/evacuation simulation models through the lakes of the region. Importantly, no modeling-based inputs on the effective capacity of existing water transport infrastructure in North Patagonia for disaster management have been proposed or assessed to date: our contribution represents the first step in that direction. Planning on the basis of only past experiences is insufficient because of environmental, social, and economic changes (Romero Lankao and Qin 2011); for example, the continuing growth of tourism and populations in coastal zones places pressure on existing water transport resources, and constrains planning for future responses. These simulation models for waterborne transport and evacuations can refine the emergency assessment achieved, by prognosing future responses.

While this paper evaluates case studies at specific hazards and locations (difficult to extrapolate to other threats and regions; Marrero et al. 2010), empirical lessons from this research on theoretical and practical concerns provide valuable information on the feasibility of managing crises through lacustrine transport in a range of scenarios and limitations.

6 Conclusions

This contribution presented an overview of recent local-scale evacuation case studies in North Patagonia via water transport. These procedures included the displacement of urban residents, tourists, rural families and livestock; various operations for assisting people and livestock sheltered in-place; and different recovery activities. Given the distinctive characteristics of the study region, North Patagonia represents an ideal scenario for assessing water evacuation cases and influencing factors. The reconstruction of the cases was mainly based on in-person meetings, interviews and field observations. By presenting these cases orderly together, through an eight-stage typology for summarizing and assessing water evacuation-data, we were able to recognize common and recurrent issues affecting these specific types of procedure. The most relevant complexities identified referred to: deficient hazard-related knowledge, regarding previous events prompting the need to respond via water transport; limited ground-based accessibilities; inter and intra-organizational issues (most importantly for tourist regions and natural reserves); and a glaring lack of knowledge about the vulnerability characteristics of water transport networks, facing different natural hazards. We present an enumeration of forthcoming quests to solve that need to be addressed (highlighting present constraints and prospective research developments) and recommendations for planing water evacuations. We expect that our findings serve as a valid methodology and test case relevant for emergency planning in other costal settlements, especially in remote and mountainous regions, with similar accessibility limitations or tourist imprints. Importantly, this review and assessment of cases is the first of its kind for North Patagonia; we expect that a better understanding of these experiences will contribute to building resilience in this and other regions facing different geoenvironmental hazards.

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