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Impacts on water transport networks after three widespread volcanic ashfalls in Andean Patagonian lakes

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ABSTRACT

Although the impacts of volcanic ashfall on air transport and land transport networks are well documented, little information exists about volcanic ash effects on water transport. Three recent widespread ashfall events severely affected the extensive shipping activity that takes place in the many lakes of Andean Patagonia, Argentina. By means of impact assessment fieldtrips, meetings, semi-structured interviews, and expert consultation, we surveyed and categorized impacts of volcanic ash on ships, ports and shipping activities, also assessing most effective mitigation strategies undertaken, including clean-up actions. To better catalogue type and severity of impacts, we expand on available damage scales developed for critical infrastructure, to include more specific details about water transport systems. Our contribution ultimately aims to communicate to emergency managers, and the volcanological and nautical communities, the most likely outcomes from explosive volcanic eruptions on shipping, along with best-practice advice for mitigating adverse effects.

RESUMEN

Si bien los efectos de las caídas de ceniza volcánica sobre los sistemas de transporte aéreo y terrestre han sido ampliamente investigados, existe poca información que refiera específicamente a los impactos de la ceniza sobre el transporte naval. Tres eventos de caídas piroclásticas recientes han afectado severamente la profusa actividad náutica de varios lagos Andino-Patagónicos de Argentina. Por medio de visitas de reconocimiento, entrevistas semiestructuradas, y consultas con expertos, hemos podido relevar y sistematizar los impactos de la ceniza sobre embarcaciones, puertos y la navegación, evaluando también la efectividad de distintas estrategias de mitigación implementadas. Con el fin de poder categorizar tipo y severidad de impactos, hemos elaborado sobre escalas de daño en infraestructura crítica disponibles, para incluir detalles más específicos referidos al transporte naval. Esta contribución pretende comunicar a los gestores de la emergencia y a las comunidades volcanológica y náutica acerca de las posibles consecuencias del volcanismo explosivo sobre la actividad, aconsejando también sobre las mejores prácticas para la mitigación de adversidades.

KEYWORDS: Volcanic risk; Tephrafall; Pumice rafts; Chaiten; Cordon Caulle; Calbuco.

1 INTRODUCTION

1.1 Background

Water transport, whether for trade, fishing, research, military, or recreational purposes, has been vital in the development of civilizations, affording societies greater connectivity than traveling over land [Burns 2018]. Nowadays, water transport is still an essential part of worldwide economies, accounting for about 80 % of total international trade [UNCTAD 2020]. While maritime transport has been traditionally regarded as the primary means for transporting parts and finished goods on a global scale [Song and Panayides 2015], extensive inland shipping is still an important resource for trade, commerce, and pleasure [Branch and Robarts 2014; UNCTAD 2020], also facilitating movement in regions with limited accessibility [Salgado et al. 2022]. The basic function of a water transport network can be broadly schematized as the movement of people (*passengers*), animals, or goods (*cargo*) by means of different types of water vehicles (*ships*); [Law 20.094; REGINAVE 2019] via oceans, rivers, canals, reservoirs, and lakes (*waterways*), or the development of any other specialized water-based activity. Regardless of their gauge, location, and serviceability, shipping activities depend on a great variability of infrastructures at the interface between land and water (*port sites*) that provide secure harboring and gateways into inland environments, as shipping is typically integrated into larger transport networks. Ports usually comprise one or more wharves, machinery, and accompanying infrastructure that ensure the easy movement of passengers and cargo [e.g. Branch and Robarts 2014; Song and Panayides 2015; Burns 2018].

Worldwide, volcanic ashfalls have been extensively documented to affect road networks, rail, and aviation [e.g. Blong 1984; Casadevall 1994; Guffanti et al. 2009; 2010; Wilson et al. 2012; Blake et al. 2017; 2018], as networks can be vast and cover large areas of territory, increasing their exposure to volcanic hazards [Wilson et al. 2014]. During volcanic crises,

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functional transport is critical for societies, as it may be required for permitting accesses for emergency services, evacuation, or enabling immediate to long-term recovery of affected sites [Blong 1984; Wilson et al. 2014; Blake et al. 2017]. Additionally, detrimental consequences for other infrastructure sectors may occur if they are critically dependent on transport [Wilson et al. 2012]. Water transport has proved vital during volcanic (and non-volcanic) crises in remote, insular, or sparsely populated regions, with frail and/or restricted ground accessibilities [Komorowski et al. 2016; Leone et al. 2019; Salgado et al. 2022].

In Andean Patagonia, Argentina, recent and widespread ashfall events, associated with three major explosive volcanic eruptions [VEI ≥ 4; Newhall and Self 1982] occurring within the Andean Southern Volcanic Zone [33° S–46° S; Stern 2004], have caused serious impacts on the extensive water transport activities across the many lakes of the region. These events involved instances of ships breaking down during risky rescue attempts [Salgado et al. 2022] and the sinking of moored boats. Moreover, at the time of the current study, ten years after one of the largest Andean eruptions in recent decades, the ongoing remobilization of massive deposits of tephra still poses significant hazards for shipping and port infrastructure across the region.

Despite the large number of cases locally and globally reported for volcanic hazards affecting nautical activities, the volcanological and nautical literature have not yet systematically documented or assessed the impacts and vulnerabilities of water transport networks for either volcanic ashfalls or any other volcanic hazard [Blong 1984; Wilson et al. 2012; Wilson et al. 2014; Blake et al. 2018]. To address this knowledge gap, here we document and assess the effects of volcanic ash on water transport, elaborating on the impacts observed in Patagonian lakes after the 2008 Chaitén, the 2011–2012 Cordón Caulle, and the 2015 Calbuco volcanic eruptions. We first provide a brief overview of the chronology of each eruption, focusing on the different volcanic hazards observed at the most-affected sites, where impacts on water transport were surveyed (Section 3). Separately, we offer a thorough reconstruction of the events that took place at each of these sites, compiling detailed narratives on the most relevant effects of volcanic ash on shipping, provided as Supplementary Material 1. Particularly, all the consequential emergency response actions handled by different lake transport resources have been summarized and evaluated by Salgado et al. [2022]. Based on these observations, we develop a novel and systematic catalogue of volcanic ashfall impacts on ships, port sites, and nautical activities (Section 4). This includes impact data not only for the direct effects of primary fallouts, but also from secondary phenomena such as *pumice rafts*, sedimentation and mass-wasting processes, fluvial and aeolian remobilization of tephra deposits, etc. We further provide a summary of the mitigation and remediation actions undertaken (including clean-up efforts) evaluating the effectiveness of each strategy in attenuating the effects of volcanic ash (Section 5). Finally, we assess relationships between observed impact data and varying hazard intensities controlling the type, severity, timing, and duration of impacts. On that basis, we expand on Wilson et al. [2014] *damage and disruption states* from volcanic ashfalls on critical infrastructure, to include more specific details on water transport (Section 6). Our contribution ultimately aims to communicate to emergency managers, policymakers, stakeholders and the volcanological and nautical communities, the most likely outcomes from explosive volcanic eruptions on shipping and associated infrastructure, along with best-practice advice for mitigating and remediating adverse effects from volcanic ashfalls.

1.2 Study area

Argentinean Andean Patagonia is a vast and sparsely populated territory, located in southern South America. Endowed with exceptional natural resources, the region is a worldwide famous tourist destination. This region comprises the southern section of the Andes and a cluster of natural reserves, comprised of the major *Lanín*, *Nahuel Huapi*, and *Los Alerces* National Parks (Figure 1, 2, and 3), plus other smaller protected areas. This north-to-south-trending passage crosses a series of glacial lakes, many of them extending eastwards to extra-Andean Patagonia. Most cities, villages, and tourist destinations are sparsely located on the shores of these lakes.

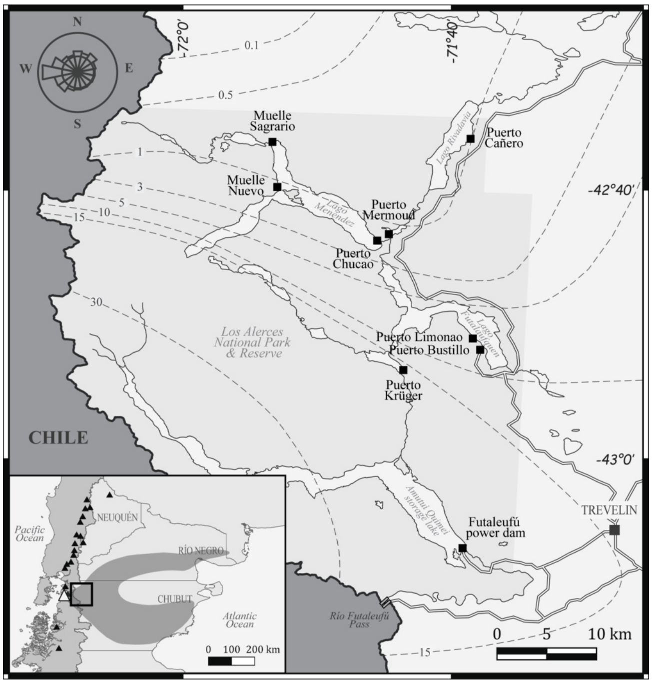

Figure 1: The Chaitén 2008 volcanic eruption and tephra fall distribution map (isopachs in millimeters, based on Watt et al. [2009] and Alfano et al. [2011]) in *Los Alerces* National Park and Reserve (area in gray), and location of the most-affected port sites. At the top left, the wind rose charts the relative distribution of annual wind (origin) direction frequencies. Bottom left, tephra fall distribution >0.1 mm.

The study region is located downwind of the Southern Volcanic Zone, an active volcanic arc comprising over 60 Holocene volcanoes, with over 400 historical eruptions confirmed since 1558 [Global Volcanism Program 2013] (the locations of these historically active volcanoes are shown in Fig-

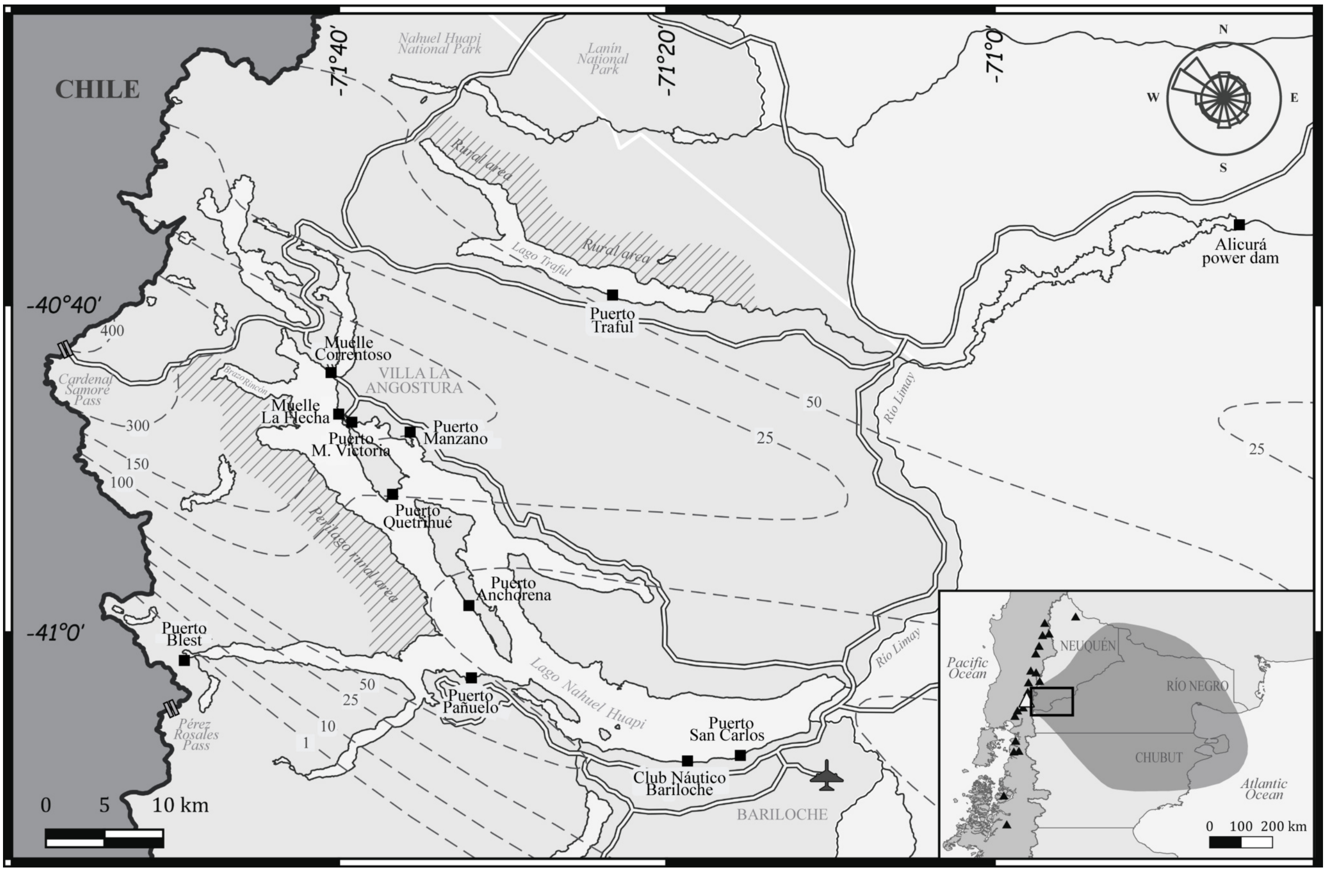

Figure 2: The Cordón Caulle 2011–2012 volcanic eruption and tephra fall distribution map (isopachs in millimeters, based on Villarosa and Outes [2013] and Alloway et al. [2015]) in the *Nahuel Huapi* National Park (area in gray), and location of the most-affected port sites. At the top right, the wind rose charts the relative distribution of annual wind (origin) direction frequencies. Bottom right, tephra fall distribution >1 mm.

ure 1, 2, and 3). Hence, Argentinean Patagonia is a territory recurrently affected by volcanic ashfalls, resulting from explosive volcanic eruptions and the eastward atmospheric dispersion of pyroclastic material transported by the extra-tropical regional flow of westerlies [e.g. Villarosa et al. 2006]. These events have affected extensive areas of Argentinean territory in recent times, causing substantial impacts on urban environments, rural communities and farmland, and tourist destinations, including water transport networks.

1.3 Lake transport in Patagonia

Originally, all infrastructure associated with water transport was introduced for developing regional and international trade, and the movement of people in the absence of well-developed ground transport networks. However, since the 1940s, economic activities have gradually shifted to tourism, which is now the main source of regional wealth [Bandieri 2011]. Lacustrine outings, sport fishing, and water sports are currently the most common activities in these lakes, entailing daytime excursions of up to hundreds of passengers. Cargo shipping has been reduced to the transport of supplies through small service ships to sites with limited access. Because of this economic alignment, most of the original relatively small wooden wharves were later upgraded or entirely rebuilt, and many other new ports, ships, naval routes, and associated infrastructure were specifically introduced for servicing the massive influx of visitors. The most important port sites within the region, where impacts were surveyed, are summarized in Table 1. In particular, some of these sites are in remote areas that can only be accessed through lake transport. There are also small rural communities farming on the shores of these lakes which have a vital reliance on water transport for fulfilling basic needs, as many do not have ground access to any urban centers [Anselmi et al. 2012; PNNH 2019; Salgado et al. 2022].

Nautical activities are supervised by *Prefectura Naval Argentina*, the national marine authority and security force [REGINAVE 2019], and the corresponding National Parks headquarters [e.g. PNNH 2019]. Herein, inland vessels (which are commonly classified by their measurements, area of navigation, means of propulsion, number of hulls, etc. [Rawson and Tupper 2001; Tupper 2004; Molland 2008]) will be referenced in the way they are classified by the corresponding authority [Table 2; REGINAVE 2019].

2 METHODOLOGY

Impact data has been sourced from direct field observations, and numerous role-driven consultations with a range of af-

Table 1: Attributes of the most important inland port sites in Patagonia, where volcanic ash impacts were surveyed. [Continued on next page]

Lake	Port site	Location	General characteristics	Access	Size and structure	Capability	Material
Lago Futalaufquen and Krüger	Puerto Bustillo	42° 16’ 05" S 72° 12’ 20" W (Lago Futalaufquen)	Built in 1937 for timber commerce; destroyed in 1970 by a flooding event and promptly rebuilt; reconditioned in 2003 exclusively for mooring tourist and official authorities’ ships.	Single gravel road access	Gable-roofed mooring base: 30 m × 15 m. Depth: 3 m	Ships <30 m length	Reinforced concrete and wood
	Puerto Limonao	42° 51’ 50" S 71° 37’ 25" W (Lago Futalaufquen)	Built in 1937 for wood commerce; partially destroyed in 1970 by a flooding event and rebuilt in 1975; currently serves as a departure point for various tourist sailings	Single gravel road access	L-shaped pier: 30 m and 10 m long. Depth: 3 m	Ships <30 m length	Wood
	Muelle Krüger	42° 53’ 26" S 71° 43’ 49" W (Lago Krüger)	Wharf built in 1937 for wood commerce; currently serves as destination site for tourist outings sailing from Puerto Limonao	By navigation only	I-shaped small wooden pier	Ships <30 m length	Wood
Lago Verde	Puerto Mermoud	42° 43’ 23” S 71° 44’ 54” W	Built in 1940 for tourism; currently serves as destination site for tourist outings sailing from Puerto Limonao	By a 1 km-long footpath access	I-shaped pier: 35 m long	Ships <30 m length	Wood
Lago Menéndez	Puerto Chucao	42° 34’ 53” S 71° 35’ 41” W	Built in 1940 for tourism; destroyed in 1999 by a fire and rebuilt next to the old ruins; currently serves as a tourist departure point	By a 2 km-long footpath	T-shaped pier: 30 m long. Depth: 3 m	Sits only smaller ships	Wood
	Muelle Sagrario	42° 45’ 13” S 71° 45’ 64” W	Stopover wharf built in 1940 exclusively for tourism; currently serves as destination site for tourist outings	By navigation only	I-shaped pier: 25 m long. Depth: 3 m	Sits only smaller ships	Wood
	Muelle Nuevo	42° 40’ 14" S 71° 53’ 01" W	Stopover wharf built for tourism; currently serves as destination site for tourist outings sailing from Puerto Chucao	By navigation only	I-shaped small wooden pier	Sits only smaller ships	Wood
Lago Nahuel Huapi (southern)	Puerto San Carlos	41° 07’ 55" S 71° 18’ 30" W (Bariloche)	Built in 1935 for wood and wool international commerce (Chile). Fully re-built in 1991, after a fire in 1958 and the 1960 earthquake and tsunami-wave. Currently inoperative for larger passenger ships	Very easily accessed by all type of vehicles	Two main docks: 112 m and 108 m long within a L-shaped breakwater structure	Ships <30 m length	Concrete
	Club Náutico Bariloche	41° 07’ 43" S 71° 20’ 51" W	Civil association with legal status for sport and recreational shipping. Founded in 1947 within Puerto San Carlos, and displaced to its current location in 1964, after the 1960 earthquake and tsunami-wave	Very easily accessed by all type of vehicles	Ship-base with multiple docks, within a 200 m-long breakwater structure	Hundreds of smaller ships and motorsails; ships <42 m length	Concrete, wood, iron-mesh floating docks
	Puerto Pañuelo	41° 03’ 07" S 71° 31’ 50" W	Built within a natural harbor between 1965 and the 1980s for regional and international tourism, after the 1960 destruction of Puerto San Carlos. The only concrete wharf was built in 1985	Very easily accessed by all type of vehicles	Seven I- and T-shaped piers:between 14 m and 35 m long. Depth: 5–8 m	Ships <50 m length Handling ~350.000 passengers annually	Wood and concrete
	Puerto Blest	41° 01’ 27” S 71° 48’ 49” W	Built in 1937 along with a hotel and rebuilt in 2002 for national and international tourism	By navigation only	Two I- and T-shaped piers: about 23 m long. Depth <4 m	Ships <20–30 m length	Wood and iron
	Muelle Cántaros	41° 01’ 04” S 71° 49’ 15” W	Private and artificial wharf built in 1958 for tourism		L-shaped pier: 40 m and 30 m long. Depth <4 m	Ships <20–30 m length	Wood

Table 1 [cont.]: Attributes of the most important inland port sites in Patagonia, where volcanic ash impacts were surveyed.

Lake	Port site	Location	General characteristics	Access	Size and structure	Capability	Material
Lago Nahuel Huapi (northwestern)	Muelle La Flecha	40° 46’ 57” S 71° 39’ 39” W (Villa La Angostura)	Private and artificial wharf built in mid-1970s and later enlarged for tourist sailings to Península de Quetrihué	Road access, for small vehicles	I-shaped pier: 110 m long. Depth: 2.5–6 m	Ships <50 m length	Wood
	Puerto Modesta Victoria	40° 46’ 58” S 71° 39’ 26” W (Villa La Angostura)	Built in the early 1940s for connecting Villa La Angostura and Bariloche; reconditioned in 1972 and rebuilt in 2001	Road access, for small vehicles	T-shaped and roofed doble decker pier: 55 m long. Depth: 6–10 m	Ships <50 m length	Wood
	Bahía Manzano	40° 47’ 58” S 71° 35’ 50” W	Built in 1907 and reconditioned in 1955 for tourism, water sports and mooring rentals	Road access, for small vehicles	Multiple small piers within a large natural harbor bay	Sits only smaller ships	Wood
	Puerto Quetrihué	40° 51´ 27" S 71° 36´ 52" W (Península Quetrihué)	Built in 1942, and later reconditioned as a stopover port and tourist destination site (Bosque de Arrayanes National Park)	By navigation only (12 km-long footpath)	I-shaped pier:80 × 6 m. Depth: 7–8 m	Ships <30 m length	Wood
	Puerto Anchorena	40° 58’ 15" S 71° 31’ 23" W (Isla Victoria)	Built in 1974, exclusively as a tourist destination site	By navigation only	Ushaped pier: 50 m long within a natural harbor bay. Depth: <4 m	Ships <40 m length	Wood
Lago Traful	Puerto Traful	40° 39’ 13” S 71° 23’ 58” W (Villa Traful)	New and more sophisticated wharves rebuilt for tourism near the old port	Single gravel road access	Two I- and T-shaped docks, 70 m and 60 m long forming a small bay next to a revetment	Sits only smaller ships	Wood
Lago Lácar and Nonthué	Puerto San Martín	40° 09’ 42” S 71° 21’ 31” W (S. M. de los Andes)	Built in 1937 for regional and international wood commerce or vehicle transport towards Puerto Hua Hum; completely rebuilt in 1998 for tourism	Very easily accessed by all type of vehicles	Y-shaped pier: 60 m long. Depth: ~3 m	Ships <30 m length	Wood
	Puerto Don Bruno	40° 10’ 27” S 71° 26’ 02” W (Quila Quina)	Built in 1937 and re-built in 1999; currently used as a tourist destination, stopover and sport fishing.	Single gravel road access	I-shaped pier: 40 m long. Depth: ~3 m	Ships <30 m length	Wood
	Puerto Hua Hum	40° 07’ 19” S 71° 39’ 14” W (Lago Nonthué)	Built in 1937 for regional and international wood commerce or vehicle transport towards San Martín de los Andes); reconditioned in 2003 exclusively for tourism	Single gravel road access	L-shaped pier: 60 m long	Ships <30 m length	Wood and concrete
	Puerto Chachín	40° 08’ 34” S 71° 39’ 07” W (Lago Nonthué)	Currently disable due to deterioration	Single gravel road access	I-shaped pier: 30 m long	Ships <30 m length	Wood
Lago Huechulafquen and Epulafquen	Puerto Canoa	39° 45’ 10" S 71° 30’ 05" W (Lago Huechulafquen)	Built after 1937 for goods transport towards Puerto Encuentro (Lago Epulafquen); rebuilt in 1992 exclusively for tourism	Single gravel road access	L-shaped pier: 30 m long. Depth: ~5 m	Ships ~15 m length	Reinforced wood

Table 2: Classification of inland vessels, according to *Prefectura Naval Argentina* [REGINAVE 2019, and amending legislations].

Ship typology (Inland vessels)	General attributes	Examples
Primary passenger ship	Ships with capacities >12 passengers, and overall lengths >17 m; including yachts, catamarans, and small ship-cruises	Figure 8, 13; Figure S4, S6, S9
Secondary passenger ship	Ships with capacities >12 passengers, but overall lengths <17 m; including yachts, catamarans, and small ship-cruises	Figure 4
Smaller ship	Ships with capacities <12 passengers, regardless overall lengths; including small ship-cruises, speedboats, rigid inflatable boats (RIBs), motor-sailors, etc.	Figure S1, S7
Service ship	Any other class of ship or watercraft fulfilling specialized services; including cargo and supply ships, ferry barges, dredging-ships, etc.	Figure S2
Non-motorized ship	Sailboats, sailing-yachts, rowing-boats, canoes, etc.	

Table 3A: Summary of impacts observed following the Chaitén 2008 eruption at some of the most relevant affected sites, indicating tephra fallout main characteristics (primary tephra depth, grain-size, composition) and waterborne tephra characteristics (formation and fate of (PR) pumice rafts, inputs of (FR) fluvial remobilized tephra, etc.); (NA) not applicable; (NS) not studied, or not identified; (?) unconfirmed or inferred impact.

Affected site / area	Tephra fallout deposit	Waterborne tephra	Capsizing	Roll, pitch, heave & stability issues	Abrasion of deck surfaces & components	Corrosion of metallic deck frames & devices	Deterioration & other damage to deck surfaces	Contamination of fuel & lubricating oils	Damage/disruption to air-supply reliant equipment	Volcanic ash ingress into ship interiors	Effect on electricity ntws & navi-comm devices	Impact to centralized navi-com computers	Impacts on engine's cooling systems	Damage to propulsion & transmission systems	Impacts on waterjets	Damage to hulls frames	Damage & deterioration to port infrastructure	Damage to port machinery & equipment	Disruption to critical infrastructure services	Ground accessibility issues	Entries of PR into harbors or critical sites	Freezing of PR	Sedimentation (including remobilization) issues	Ships requiring clean-up	Ports land-side domains requiring clean-up
Ports in northern Los Alerces	0.1–2 mm of very fine-grained rhyolitic ash	Very thin PR formed in-situ, followed by the eastward drift of thin coarser PR affecting eastern ports*					✓						✓					NA	✓	✓	✓			✓	
Ports in southern Los Alerces	2–17 mm of very fine-grained rhyolitic ash				✓	✓	✓		✓	✓			✓		✓		✓	NA	✓	✓	✓			✓	✓
Futaleufú dam & storage lake	>30 mm** of very fine-grained rhyolitic ash	Drifting and formed-in-situ PR remained suspended >8 weeks†			✓	✓	✓	NS	NS	NA			✓		NA		NA	NA	✓	✓	✓		✓	✓	NA

* tephra depth or PR thickness estimated by eyewitnesses
** tephra depth inferred by isopach maps
† Wilson et al. [2012]

fected parties. Consultations were carried out through a great number of in-person meetings and semi-structured interviews [e.g. Longhurst 2016], which were then continued by frequent remote feed-back. Semi-structured interviews rely on asking a set of predetermined questions within a specific thematic framework while allowing interviewees to elaborate on different facets of the research question, which may not have been planned to explore beforehand [Longhurst 2016]. A total of 62 interviewees from 26 different entities were consulted. Ethical permission was not required as interviewees were consulted in their professional roles and discussions only covered technical issues. The broad group of respondents comprised various lake authorities and officers from different institutions, such as *Prefectura Naval Argentina*, National Parks headquarters, Civil Protection, Nautical Clubs, etc. Interviewees also spanned staff from numerous lake tourism companies, tourism

Table 3B: Summary of impacts observed following the Cordón Caulle 2011–2012 eruption at some of the most relevant affected sites, indicating tephra fallout main characteristics (primary tephra depth, grainsize, composition) and waterborne tephra characteristics (formation and fate of (PR) pumice rafts, inputs of (FR) fluvial remobilized tephra, etc.); (NA) not applicable; (NS) not studied, or not identified; (?) unconfirmed or inferred impact.

Affected site / area	Tephra fallout deposit	Waterborne tephra	Capsizing	Roll, pitch, heave & stability issues	Abrasion of deck surfaces & components	Corrosion of metallic deck frames & devices	Deterioration & other damage to deck surfaces	Contamination of fuel & lubricating oils	Damage/disruption to air-supply reliant equipment	Volcanic ash ingress into ship interiors	Effect on electricity ntws & navi-comm devices	Impact to centralized navi-com computers	Impacts on engine's cooling systems	Damage to propulsion & transmission systems	Impacts on waterjets	Damage to hulls frames	Damage & deterioration to port infrastructure	Damage to port machinery & equipment	Disruption to critical infrastructure services	Ground accessibility issues	Entries of PR into harbors or critical sites	Freezing of PR	Sedimentation (including remobilization) issues	Ships requiring clean-up	Ports land-side domains requiring clean-up
Puerto Canoa	Trace amounts*	PR not observed*					✓		✓						NA			NA	NS					✓	
Puerto San Martín	2–4 mm of fine-grained rhyolitic ash	Very thin PR formed in-situ, followed by the eastward drift of thin PR*					✓	✓	✓	✓			✓		✓				✓	NA	✓			✓	✓
NW Lago Nahuel Huapi	>170 mm of lapilli to very fine-grained rhyolitic ash	Large PR rapidly drifting away; large sustained inputs of FR ash	✓	✓	✓	✓	✓	✓	✓	✓	(?)	✓	✓		NA	✓	NA	NA	✓	✓	NA		✓	✓	NA
Ports in Villa La Angostura	150–170 mm of lapilli to very fine-grained rhyolitic ash	Large PR rapidly drifting away, or accumulating on downwind shorelines	✓	✓	✓	✓	✓	✓	NA	✓	(?)	✓	✓		✓	✓	✓	✓	✓	NA	✓			✓	✓
Bahía Manzano			✓	✓	✓	✓	✓	✓	NA	✓	(?)	✓	✓		✓	✓	✓	✓	✓	NA	✓			✓	✓
Puerto Traful	~50 mm of medium to fine- grained rhyolitic ash	PR rapidly drifting away		✓	✓	✓	✓	✓	✓	✓			✓		✓		✓		✓	✓			✓	✓	✓
Puerto Blest & Muelle Cántaros	Trace amounts*	PR not observed*													NA					NA					
Puerto Pañuelo	45–50 mm of medium to coarse-grained rhyolitic ash	Thin PR formed in-situ, followed by the southeastward drift of thicker (~35 cm)* and coarser (lapilli) PR		✓	✓	✓	✓	✓		✓			✓	✓	NA	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Club Náutico Bariloche	35–40 mm of medium to coarse-grained rhyolitic ash	Thin PR formed in-situ; occasional entries of (lapilli) PR with easterly wind; moderate inputs of FR ash		✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	NA	✓	✓	✓	✓	NA	✓	✓	✓	✓	✓
Puerto San Carlos	35–40 mm of medium to coarse-grained rhyolitic ash	Thin PR formed in-situ; occasional entries of PR with easterly wind; shore deposits far exceeding 40 cm thick		NS	✓	✓	✓	✓	NA	NA			✓	✓	✓	✓	✓		✓	NA	✓	(?)	✓	✓	✓
Alicurá dam & storage lake	~20 mm of medium to fine- grained rhyolitic ash	Sizable PR formed in-situ, followed by great and sustained fluvial drift inputs (max ~45 cm)			✓	✓	✓	NS	NS	NS			✓		NA		NA	NA	NA	✓	✓	✓	✓	✓	NA

* tephra depth or PR thickness estimated by eyewitnesses

Table 3C: Summary of impacts observed following the Calbuco 2015 eruption at some of the most relevant affected sites, indicating tephra fallout main characteristics (primary tephra depth, grain-size, composition) and waterborne tephra characteristics (formation and fate of (PR) pumice rafts, inputs of (FR) fluvial remobilized tephra, etc.); (NA) not applicable; (NS) not studied, or not identified; (?) unconfirmed or inferred impact.

Affected site / area	Tephra fallout deposit	Waterborne tephra	Capsizing	Roll, pitch, heave & stability issues	Abrasion of deck surfaces & components	Corrosion of metallic deck frames & devices	Deterioration & other damage to deck surfaces	Contamination of fuel & lubricating oils	Damage/disruption to air-supply reliant equipment	Volcanic ash ingress into ship interiors	Effect on electricity ntws & navi-comm devices	Impact to centralized navi-com computers	Impacts on engine's cooling systems	Damage to propulsion & transmission systems	Impacts on waterjets	Damage to hulls frames	Damage & deterioration to port infrastructure	Damage to port machinery & equipment	Disruption to critical infrastructure services	Ground accessibility issues	Entries of PR into harbors or critical sites	Freezing of PR	Sedimentation (including remobilization) issues	Ships requiring clean-up	Ports land-side domains requiring clean-up
Puerto Canoa	~3 mm of fine-grained dacitic-andesitic ash	PR not observed			✓	✓	✓	✓	NA	✓			✓		NA			NA	NS	✓			✓	✓	
Puerto San Martín	7–12 mm of fine-grained dacitic-andesitic ash	Very thin PR formed in-situ, followed by the eastward drift of thin PR			✓	✓	✓	✓	✓	✓			✓		✓		✓		✓	NA	✓			✓	✓
Puerto Traful	~5 mm of fine-grained dacitic-andesitic ash	Very thin PR rapidly drifting away*					✓		✓								✓			✓				✓	
Ports in Villa La Angostura	~1 mm of fine-grained dacitic-andesitic ash	PR not observed							✓											NA				✓	

* tephra depth or PR thickness estimated by eyewitnesses

guides, freelancers, port managers, official crews and seafarers, ship-owners, sailing coaches, maintenance staff, divers, volunteers, craftsmen, etc. Field visits and meetings also included guided mechanical inspections of machinery, equipment, and infrastructure affected by volcanic ash, led by official nautical technicians and ship mechanical specialists. Most interviews were carried out between 2019 and 2021. However, this investigation is part of wider and continuing research on the effects of volcanic activity in Patagonia Argentina, initiated during the 2008 volcanic crisis, which included scientific advice to emergency committees and local and national authorities [e.g. Leonard et al. 2009; Stewart et al. 2009; Wilson et al. 2009a; b; c; 2012; Villarosa and Outes 2013; Wilson et al. 2013; Beigt et al. 2016; Craig et al. 2016; Stewart et al. 2016; Salgado et al. 2022].

Data from interviewees broadly referred to: (1) a general description of the situation at each site before, during, and after being impacted by volcanic hazards; (2) specific data about the direct effects of ash on each affected asset; (3) the possible identification of vulnerable or resilient aspects for each affected element; (4) actions undertaken in advance or in response to the volcanic crises, including clean-up methodologies applied; (5) sources of shipping disruption; (6) specific upgrades incorporated and lessons learned after each event; and when appropriate, its proven effectiveness after repeated experiences; and (7) particular references focused on the impacts resulting from fluvial and aeolian remobilization events of tephra deposits. The design of interview schemes and impact-data processing were informed by technical experts' advice and supporting literature on nautical sciences, maritime engineering, and ship architecture.

Fieldwork included not only a survey of volcanic ash effects on lake transport, but also the measurement of tephra depths at each affected site (synchronously and long after each volcanic eruption), providing first-hand data about volcanic hazards intensity metrics and the fate of volcanic ash deposits subjected to different remobilization agents [e.g. Wilson et al. 2011; Durant et al. 2012; Villarosa and Outes 2013; Alloway et al. 2015; Reckziegel et al. 2016; Beigt et al. 2019; Beigt and Villarosa 2022]. Collectively, these data allowed us to characterize and systematize volcanic ash impacts on water transport resources.

3 OVERVIEW OF CASE STUDIES

The following subsections present a chronological synopsis of each eruptive event, briefly describing the associated hazards that have affected the nautical activity. Separately, we offer a reconstructive compilation of case studies that narratively details all the observed immediate-to-long-term consequences of each volcanic eruption on lake transport, provided as Sup-

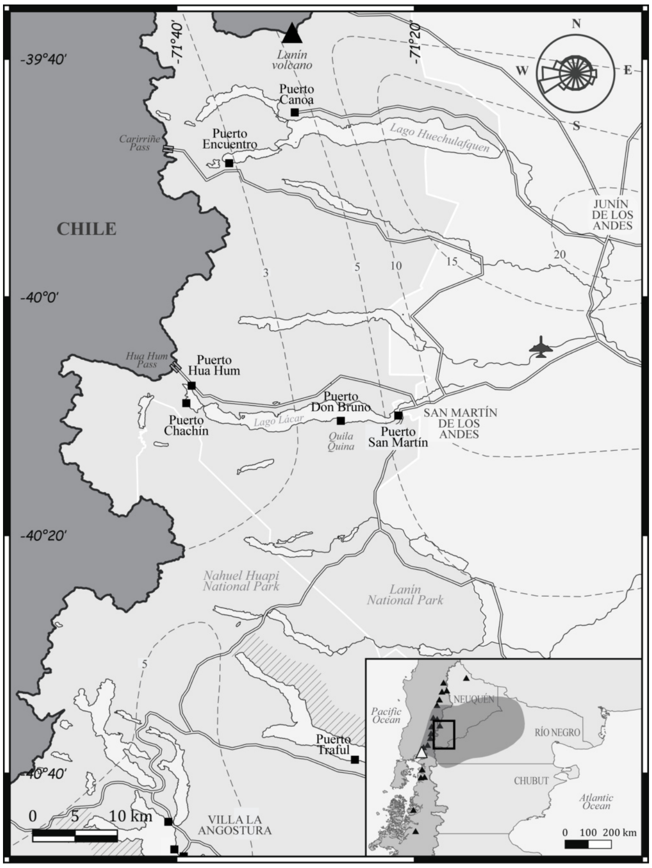

Figure 3: The Calbuco 2015 volcanic eruption and tephra fall distribution map (isopachs in millimeters) in the *Nahuel Huapi* and *Lanín* National Parks (areas in gray), and location of the most-affected port sites. At the top right, the wind rose charts the relative distribution of annual wind (origin) direction frequencies. Bottom right, tephra fall distribution >0.1 mm.

Figure 4: Example of a heeled-over secondary passenger ship, moored at *Bahía Manzano* (northwestern *Lago Nahuel Huapi*) after the 2011–2012 Cordón Caulle volcanic eruption. Photo courtesy of Carlos Tavalla.

plementary Material 1. The occurrence of the most relevant impacts (systematized in Section 4) at each site or region is indicated in Table 3A, 3B, and 3C.

3.1 The 2008 Chaitén eruption

The Chaitén (42.8° S–72.6° W, Chile) volcanic eruption began with a strong explosive phase (VEI: 4 [Watt et al. 2009; Alfano et al. 2011]) on 2 May 2008 without significant precursory activity [Castro and Dingwell 2009; Lara 2009; Watt et al. 2009]. Explosive activity was most energetic during the first week, producing eruptive columns that reached a maximum height of 30 km [Watt et al. 2009]. The successive eruptive plumes dispersed rhyolitic products across the Andes and over Argentinean territory, with tephra deposition occurring over 1000 km away from the source [Watt et al. 2009; Alfano et al. 2011; Durant et al. 2012]. Explosive activity continued throughout the following months with much lower plume heights and little evidence of measurable ash fallout in Argentina [Watt et al. 2009]. The extensive ashfalls caused immediate to long-lasting environmental, social, and economic impacts on Chilean and Argentinean Patagonia [e.g. Martin et al. 2009; Stewart et al. 2009; Wilson et al. 2009a; b; Stewart et al. 2011; Wilson et al. 2012], including water activities in *Los Alerces* National Park and Reserve (Figure 1).

Los Alerces fluvio-lacustrine basin comprises a chain of glacial lakes connected by short river courses. The largest ports (Table 1), lodgings, and campsites sit on the eastern shores of *Lago Rivadavia*, *Lago Verde*, *Lago Menéndez*, and *Lago Futalaufquen*, from where various tourist ships sail daily during the summer season. These ports, located up to 85 km away from the volcano, were affected by up to 15 mm of fine-grained rhyolitic ash (Figure 1). Even though all tourist facilities were almost entirely evacuated throughout the first days [Salgado et al. 2022], and shipping remained completely disrupted for almost six months, the ashfall caused widespread damage to berthed ships and ports. Visits of coastguard ships to the sparse communities inhabiting the surrounding were also slowed down by effect of volcanic ash. To the south of *Los Alerces* National Park, over 30 mm of fine-grained ash fell around the *Amutui Quimei* storage lake, upstream of the 448 MW *Futaleufú* power dam, located 90 km away from the volcano (Figure 1). Pumice fragments remained suspended in the lake for over eight weeks [Wilson et al. 2012] making the operability of supporting ships more difficult. Across the Andes, volcanic ashfalls also caused widespread impacts on maritime shipping, on the Chilean coast around the Chaitén township [Wilson et al. 2012].

3.2 The 2011–2012 Cordón Caulle eruption

On 4 June 2011, after two months of precursory activity, the Cordón Caulle (40.5° S–72.1° W, Chile) generated a Plinian eruption [VEI ~4–5; Bonadonna et al. 2015] with associated stratospheric eruptive columns [Castro et al. 2013; Schipper et al. 2013]. The initial phases, and intermittent sub-Plinian fountaining activity, continued intensely into July, declining to Vulcanian blasts by January 2012 [Alloway et al. 2015], while the emission of volcanic ash persisted until August 2012 [SERNAGEOMIN 2010]. Enormous volumes of rhyolitic ash [Alloway et al. 2015] blanketed large areas of Argentina [Collini et al. 2012; Schipper et al. 2013] causing widespread damage and economic losses [e.g. Wilson et al. 2013; Hayes et al. 2015; Craig et al. 2016; Elissondo et al. 2016; Stewart et al. 2016; Beigt et al. 2019]. Thick deposits of primary and remobilized tephra accumulated over the *Nahuel Huapi* and *Lanín* National Parks, affecting nautical activities in a great number of lakes, including the larger and heavily navigated *Lago Nahuel Huapi* (Figure 2).

The northwestern region of the *Lago Nahuel Huapi* fluviolacustrine basin was affected by the most sizeable accumulation of tephra [Villarosa and Outes 2013; Alloway et al. 2015], including the heavily navigated areas around Villa La Angostura, a tourist village located 50 km away from the eruptive center (Figure 2) and impacted by between 150 and 170 mm of lapilli to very fine–grained rhyolitic ash. All tourist passenger ships managed to return to the city amidst almost zero visibility that same afternoon, after which shipping was suspended for 45 consecutive days. In this region, the sinking of ships as large as primary passenger ships possibly stood out as one of the most striking consequences of the eruption (Figure 4). Various evacuation attempts failed because of the effects of volcanic ashfall and pumice rafts on ships, although water transport resources proved vital for managing post-event recovery actions in the *Perilago* [Figure 2; PNNH 2019], a rural area on the western shores of the lake, inaccessible by ground transport [Salgado et al. 2022]. Despite large rafts of pumice were rapidly dragged away by prevailing winds, many inconveniences persisted over time, even a decade after the eruption, associated with the fluvial remobilization of large deposits of tephra. Similar scenarios were also observed in *Lago Traful* (Figure 2), a smaller lake located over 50 km away from Cordón Caulle, which received up to 85 mm of medium to fine-grained ash at its western end [Villarosa and Outes 2013; Alloway et al. 2015]. On the southern shore of the lake sits Villa Traful (Table 1; Figure 2), a very small but heavily visited port hamlet, where ~50 mm of medium to fine-grained ash accumulations were measured accumulating near the port.

The southern shore of the *Lago Nahuel Huapi* was affected by primary ashfall thicknesses increasing steeply towards its middle central part (Figure 2). In this area, *Puerto Pañuelo*, *Club Náutico Bariloche*, and *Puerto San Carlos* (Table 1; Figure 2) stand as three of the largest and most transited port sites, where various and severe volcanic ash impacts were surveyed. These ports are located between 75 and 100 km away from the Cordón Caulle and received up to 50 mm of medium to coarse-grained ash. Lake authorities prohibited shipping for eight days (although commercial shipping only restarted several months later), stranding eight workers in *Puerto Blest* (Table 1; Figure 2), a tourist destination only accessible via waterways [Salgado et al. 2022]. During the first few days, the direct fallout of finer ash created a very thin coating of floating pumice over the lake. However, shipping conditions worsened dramatically throughout the following weeks, as wind dragged immense volumes of thicker and coarser pumice rafts, causing severe impacts on ships and the ports' *sea-side* domains. This situation triggered various improvised measures amongst port authorities to halt the ingress of pumice rafts into the harbors (Section 5). In this part of the lake, many setbacks associated with ash sedimentation and fluvial remobilization processes caused severe and long-lasting issues in port environments.

The effects of pumice rafts were not restricted to lacustrine environments: large masses of floating pumice also drifted along the *Río Limay*, the single outflow from *Lago Nahuel Huapi*, reaching the 1.050 MW *Alicurá* power dam (Figure 2), where pumice raft thicknesses of over 40 cm were measured. The dam sits 110 km away from the volcano and was also impacted by the primary fallout of about 20 mm of medium to fine-grained ash [Villarosa and Outes 2013; Alloway et al. 2015]. Supporting ships in the reservoir were likewise affected by both primary ashfalls and pumice rafts.

3.3 The 2015 Calbuco eruption

Almost four years after the Cordón Caulle eruption, the Calbuco volcano (41.3° S–72.6° W, Chile) reawakened in April 2015 with an intense sub-Plinian eruption [VEI: 4; Romero et al. 2016; Van Eaton et al. 2016]. Beginning with little warning [SERNAGEOMIN 2015; Arzilli et al. 2019], the eruption comprised two major pulses, occurring on 22 and and 23 April, with associated stratospheric eruptive columns [SERNAGEOMIN 2015]. A third and minor pulse occurred later on 30 April, generating lower columns [SERNAGEOMIN 2015; Castruccio et al. 2016; Romero et al. 2016]. The predominantly northeast dispersion of ash [Castruccio et al. 2016; Romero et al. 2016; Van Eaton et al. 2016] impacted a region of Patagonia previously affected by the 2011–2012 ashfall, and the most affected lakes were found to be the *Lago Lácar and Nonthué*, and the *Lago Huechulafquen and Epulafquen* (Figure 3).

In the span of only four years, the *Lago Lácar and Nonthué* region was significantly impacted by both ashfall events, receiving different ashfall thicknesses, grain sizes, and compositions, including differing durations of ash emissions or wind-remobilization events. During the 2011–2012 Cordón Caulle eruption, *Puerto San Martín* (Table 1; Figure 3), located about 80 km away from the volcano, was affected by 2 to 4 mm of fine-grained rhyolitic ash [Villarosa and Outes 2013; Alloway et al. 2015], while between 7 and 12 mm of fine-grained dacitic-andesitic ash were measured after the subsequent 2015 eruption around the port, located 170 km away from the Calbuco volcano (Figure 3). This port serves a small number of larger passenger ships, on which many rural communities living in the lakes' surroundings depend for commuting into the city [Salgado et al. 2022]. Despite the milder and discontinuous ashfalls received during 2011–2012 (in comparison to the succeeding eruption), nautical activities sustained a longer period of disruption due to the persistent emission of volcanic ash and wind-remobilization events. In both cases, all primary passenger ships in the lake remained moored and uncovered at *Puerto San Martín*, and although thin coatings of floating pumice dragged by westerly winds reached the site, no associated effects were reported.

Northwards, on the northern shore of *Lago Huechulafquen* sits *Puerto Canoa* (Table 1; Figure 3), a remote but much-visited port handling a single catamaran, plus many other smaller ships. During the 2011–2012 Cordón Caulle eruption, only trace amounts of very fine ash reached the area, and no damage was reported. However, these lakes were the most affected by the 2015 Calbuco eruption, receiving up to 15 mm of ash at their eastern ends (Figure 3). *Puerto Canoa*, located almost 200 km away from the volcano, received 3 mm of fine-grained dacitic-andesitic ash, sufficient to cause some sort of damage to berthed and uncovered ships.

4 SUMMARY OF VOLCANIC ASH IMPACTS ON WATER TRANSPORT

Ships, ports, and nautical activities across the study area were differently affected by a range of volcanic ash-induced impacts. Based on our observations (Supplementary Material 1; Table 3A–3C), the following subsections sum up the most relevant effects of volcanic ash on the numerous elements that make up a water transport system, cataloguing and systematizing volcanic ash impacts on ships and shipping (Section 4.1), and port sites and services (Section 4.2). Impacts associated with fluvial remobilized ash (Section 4.3) and the risks related to subaqueous mass-wasting processes and tsunami waves (Section 4.4) are discussed separately. Some additional impacts, not observed in Patagonia but inferred or suggested by interviewees and experts, are briefly mentioned throughout these sections.

4.1 Impacts on ships and shipping

Ships and shipping in Patagonia have been impacted by the effects of both airborne (Section *4.1.1* to Section *4.1.5*) and waterborne ash (Section *4.1.5* to Section *4.1.9*), whether as pumice rafts, suspended, silted, or remobilized ash.

4.1.1 *Effects of ash-loading on seaworthiness*

Volcanic ashfalls can lead to significant additional loading on ships, which may in turn plunge the ship's waterline and compromise its *seaworthiness*. The seaworthiness refers to the ship's capability to travel safely, accomplishing minimum standards of floatability, seakeeping, stability, watertight integrity, maneuverability, etc [e.g. Marzi and Broglia 2018; Wilson 2018].

Moderate and uneven loads associated with heavy ashfall deposition (Table 3A–3C) have been observed to tilt, pitch, and heave various berthed ships in Patagonia, causing the breakage of moorings. However, the capsizing of ships as large as primary passenger ships was possibly the most striking consequence for shipping of explosive volcanic eruptions in the region (e.g. Figure 4).

It is important to note that we could only find a few isolated cases of ships capsizing in the region (Section S2.1, Supplementary Material 1), and since vessels may be rolled or founded for various reasons [Belenky et al. 2019], further reconstructive data and estimations are needed for fully determining if ash-loading (e.g. from ash thicknesses as sizable as 170 mm; Table 3B) would be sufficient for compromising the ship's stability on itself. For example, uneven loads over a large and one-sided deck, with little air draft, will favor heeling and the consequential ingress of water into dry watertight spaces, which is usually cleared by emergency bilge suction valves. These systems are required for passenger ships of any size and are usually driven by emergency generators [Molland 2008; REGINAVE 2019]. These systems were observed to frequently fail, because of the direct effect of volcanic ash and sustained periods of ship inoperability. The extra weight of volcanic ash accumulations can also increase substantially due to rain, splashing, and snow deposition. This was a frequently reported issue in Patagonia, given the rainy, cold, and windy winter seasons during which all these volcanic ashfalls occurred.

4.1.2 *Damage to deck surfaces and equipment*

Volcanic ash can cause different types of deterioration on decks, and damage any uncovered equipment exposed to airborne ash and/or ash deposition (e.g. Figure 5).

Figure 5: At the top, effects of volcanic ash on motor-sailors at *Club Náutico Bariloche* (*Lago Nahuel Huapi*) after 2011–2012 Cordón Caulle volcanic eruption. Photos courtesy of *Club Náutico Bariloche*. Below, deep abrasion on the *Catamarán José Julián* wind glasses, in *Puerto Canoa* (*Lago Huechulafquen*), requiring full replacement after the 2015 Calbuco volcanic eruption. Photo courtesy of *Catamarán José Julián*.

Primary ashfalls have been observed to cause extensive abrasive damage to various types of exposed surfaces and frameworks (Table 3A–3C). For example, wooden decks, frames, and cabins have required sanding, painting, or even replacement in uncovered ships. Windscreens of cabins have sustained deep abrasion due to volcanic ash accumulations, even to the point of requiring full replacement. Primary ashfalls have been observed to cause accelerated and widespread corrosion of metallic frames and components (Table 3A–3C), diminishing their life span and requiring enhanced maintenance, painting, or even substitution. In particular, any components of ships designed specifically for maritime navigation (such as galvanized or zinc-plated components) proved to have greater resilience against the abrasive and corrosive effects of ash than other painted components. Uncleared volcanic ash on decks have been the cause of other problems (Table 3A–3C) such as rot, mold, and mildew on plastic, fiberglass, and wood frames due to deposits holding moisture. Other issues reported on ship decks included the development of slippery surfaces and icy coatings; damage to wires and chain cables; induration of ropes; and collapse of sailcloth-cabins in smaller ships after heavy ashfalls. Although not reported in Patagonia, heavy ashfalls might be a source of structural damage to larger ships' superstructure.

Few instances of airborne ash damaging deck equipment have been reported in Patagonia (Table 3A–3C). Occasionally, volcanic ash has caused the contamination of fuel and lubricating oils in exposed tanks and equipment. Similar to ground transport, airborne ash has compromised equipment reliant on air-supplies by blocking air inlets and filters or damaging fans, leading to overheating, although few instances were reported in Patagonia, because of halts on shipping and extensive cleaning before resuming activities (Section 5). On the other hand, this could be a critical issue for larger ocean-going vessels, where constant supplies of fresh air are vital for sustaining positive pressures within enclosed spaces (such as passenger, working, or housing areas, and machinery rooms or cargo spaces) and halting the ingress of harmful gases.

4.1.3 *Volcanic ash ingress into ships' interiors*

Fine volcanic ash can easily ingress into the ship's interiors and cause critical damage to sensitive equipment. In Patagonia, there were various instances of volcanic ash entering into enclosed spaces (Table 3A–3C), but few impacts were recorded, even for significant ashfalls with frequent wind resuspension. We suggest that precautionary halts on shipping activities and extensive clearances of ash (Section 5) played a part in restricting impacts to interiors. However, ash entering the living space of a catamaran completely ruined furnishing upholsteries, requiring full replacement (e.g. Section S3.2, Supplementary Material 1). Fine ash ingress into machinery rooms has also been observed to compromise the physical and chemical properties of fuel and lubricating oils. In all cases, those involved in clean-up emphasized the laborious challenge of removing accumulated ash from the ship's interior and sensitive equipment before resuming activities (Section 5).

4.1.4 *Damage to power systems, electronic devices and computers*

The contamination of power systems with particulate matter is a common issue on ships, resulting in insulation breakdown, leakage currents, and earth faults [Taylor 1996]. Curiously, there have been no known impacts on such networks by the cause of ash deposition, beyond the occasional failure of emergency electric generators (Table 3A–3C; Section *4.1.1*), even though volcanic ash typically become highly conductive when wet [e.g. Wardman et al. 2012; Wilson et al. 2012], and humid conditions prevail in ship environments. Once more, in almost every documented case where shipping activity was stopped and clean-up took place, this type of impact has been avoided. Similarly, few impacts were observed for navigation and communication (*navi-comm*) electronic devices (Table 3A–3C), whether exposed on decks (Section *4.1.2*) or housed inside cabins (Section *4.1.3*), facilitating navigation with reduced visibility (Section *4.1.5*). On the other hand, centralized *navi-comm* computers proved extremely vulnerable to the effects of volcanic ash [Salgado et al. 2022]. Increasingly, modern ships tend to boast more integrated and automated controls that result in centralized computer-aided systems for navigation and communications [Song and Panayides 2015]. The loss of functionality in such systems, by the effect of volcanic ash ingress into cabins, has been the cause of risky and irreparable failures in sailing (Section S2.1, Supplementary Material 1) and even berthed or moored ships (Section S2.3, Supplementary Material 1). Volcanic ash can affect computers in a variety of ways, which could not be specifically determined for case studies. We refer the reader to Gordon et al. [2005] and Wilson et al. [2012] for more details on volcanic ash effects on computer systems and electronic equipment.

4.1.5 *Loss of visibility, navigability, and positioning*

Reduced visibility due to both primary and remobilized ash affects all modes of surface transport [e.g. Guffanti et al. 2009; 2010; Wilson et al. 2012; Blake et al. 2018]. For lake transport, reduced atmospheric visibility has likewise been a source of long-lasting disruptions in all operational domains, including disruption to ground accessibility to port sites [Salgado et al. 2022]. Waterborne ash has also been a source of visibility issues, since extensive pumice rafts and shore deposits can fully blanket the water surface, shorelines, bedrock features, and even signal and beaconing. In Patagonia, airborne and waterborne visibility issues hindered water-based emergency response actions [Salgado et al. 2022] and caused costly incidents for ships maneuvering in compromised harbor basins (Section S2.3, Supplementary Material 1). In all cases, ships encountering primary ashfalls and extensive pumice rafts circumvented visibility issues through navigation equipment withstanding the effects of volcanic ash (such as GPS, radars, sonars, compasses, anemometers, etc).

Although not reported in this study, volcanic ashfalls might be a source of signal strength attenuation, as with dust storms [Saleh and Abuhdima 2011] causing loss of navigation and communication data [e.g. Wardman et al. 2012; Wilson et al. 2012; Cragg 2022]. However, these occurrences are poorly and inconsistently documented [Wilson et al. 2014]. For example, while radio communications were totally disrupted during the 1912 Novarupta-Katmai eruption [Hildreth and Fierstein 2012], VHF and UHF radio stood as the most reliable form of communication throughout the 2011–2012 Cordón Caulle emergency, since cellphone networks experienced problems due to overloading [Wilson et al. 2013]. Cragg [2022] discusses how positioning referencing data strength might also be attenuated because of wet ash deposition over GPS antennae.

4.1.6 *Blockage and damage to engine's cooling systems*

Engine malfunctioning due to ash clogging engines' cooling systems stood as one of the most common and often reported impact on any type and size of motor-ship (Table 3A–3C).

Most types of marine engines, including diesel engines [Molland 2008; Woodyard 2009], require some sort of cooling, enabling metal components to retain their mechanical properties when exposed to high temperatures. Most modern ocean-going vessels operate with a centralized system that uses *seawater* for cooling a supply of cooling-liquids, which in turn circulates around internal passages within the engine and other separate systems, reducing the amount of equipment in contact with seawater and avoiding corrosion and contamination issues. On another hand, the cooling of smaller outboard engines (Figure 6) or larger ships' engines outside marine environments (Figure 7) relies on open systems that circulate *seawater* pumped from a suction inlet directly through the entire engine, which is then discharged overboard.

Waterborne ash can easily affect cooling systems at multiple system stages. Coarse fragments have been observed to clog *seawater* inlets, impeding water entrances (Figure 6), while smaller fragments can skip regular outer filters, or even extra pre-filters installed at water intakes (Section 5), and clog the inner stages of the cooling system. In larger primary passenger ships, thin pumice fragments have largely clogged inner regular and extra (Section 5) water strainers and have been observed blocking radiators and the thinner piping that constitute larger and more sophisticated systems, more laborious to clear and repair (Figure 7). Abrasive fragments had also damaged internal components in the cooling system, such as pump impellers, requiring replacement.

The sudden loss of functionality of engines represented a grave source of risk for unguarded crews, navigating amid volcanic ashfall events [Salgado et al. 2022] or even years after the eruption (Section 4.3). For larger ocean-going vessels, waterborne ash might similarly clog water inlets and internal circuits from the various services that rely on *seawater* supplies.

4.1.7 *Damage to propulsion and transmission systems*

Waterborne ash can easily damage different elements from *propulsion* and *transmission* systems (Table 3A–3C). Most common propulsion systems in modern ships include different variations of screw propellers, consisting of a submerged rotating propeller-shaft and a boss with several helical blades attached to it [Molland 2008; Woodyard 2009; Carlton 2018]. In larger ships, the propeller's power of movement is transmitted from the engines to the propellers by way of a transmission system made up of connecting shafts. Several fixed bearings support the rotating shafts' loads and transfer the thrust from the propeller to the ship. These bearings carry the shafts through bearing-pads mounted in holders or carriers, arranged to pivot, or tilt. Some sections of the transmission system sit sealed within the hull's frame, while some others sit submerged outboards in contact with water, which acts as a cooling and lubricating agent. Waterborne ash can wear any of these submerged sections from the propulsion and transmission systems.

In *Puerto Pañuelo* for example, unscheduled audits held in 2011 (during the eruption) were carried out *in situ* by divers, to check the status of these submerged elements, finding no visible impacts (Section S2.3, Supplementary Material 1). However, during the following inspection in dry docks in 2012, extremely severe wear was verified on the rubber bearing-pads that carry the submerged shafts, requiring immediate replacement (Figure 8). On the other hand, few effects were identified on *white metal* (a series of metal alloys) bearings. Such impacts on propulsion and transmission systems can continue for years after primary ashfalls, due to the abrasive effect of ash remobilized from settled deposits in the lakebed (Section S2.3, Supplementary Material 1). Importantly, the corresponding inspections necessary to identify such impacts represent complex and expensive procedures that must be performed on ships pulled out of the water or drawing upon divers. Without proper attention, many further and serious problems can result. Waterborne ash may also compromise the integrity of other submerged moving components, such as propellers, steering gears, bow-thrusters, or stern tubes.

4.1.8 *Blockages and damage to waterjets*

Aside from screw propellers (Section *4.1.7*), other forms of propulsion include *waterjets*, a system in which water is drawn through a ducting system by internal pumps (plungers, centrifugal or axial pumps) and expelled aftwards through a nozzle exit at high velocities, thrusting the ship forward [Carlton 2018]. Waterjet systems tend to be used where other forms of propulsion are not feasible (e.g. due to immersion and draught issues) and have found considerable application on small high-speed ships, while their application to larger crafts is rapidly growing [Carlton 2018]. Volcanic ash rapidly blocked waterjet inlet pipes or channels and damaged pumping systems by developing hard and compact blockages when navigating in the presence of waterborne ash, rendering Patagonian high-speed ships inoperable almost immediately (Table 3A–3C). However, in many cases, the use of waterjets during the successive volcanic ashfalls was preventatively, by common sense, avoided by authorities and emergency managers.

4.1.9 *Abrasion, corrosion, and algal growth on hulls*

The abrasive action of high loads of floating ash can cause the wear of the ship's underbody. For many metallic hulls, scrapings have also been accompanied by corrosion. In *Puerto Pañuelo* for example, the frequent encounter of primary passenger ships with enduring pumice rafts caused a rare deep abrasion mark on many hulls' bows, above the waterline where the swell usually breaks (Section S2.3, Supplementary Material 1). Additionally, a strongly accelerated algae growth was widely reported after the 2011–2012 volcanic ashfall in many lakes of the region [Modenutti et al. 2013], causing the accelerated formation of biofoulings or hard crusts on hulls and port infrastructure submerged or exposed to water splashing.

4.2 Impacts on port sites and port services

Port sites and services in Patagonia were impacted by the effects of both airborne ash, causing damage and disruption in

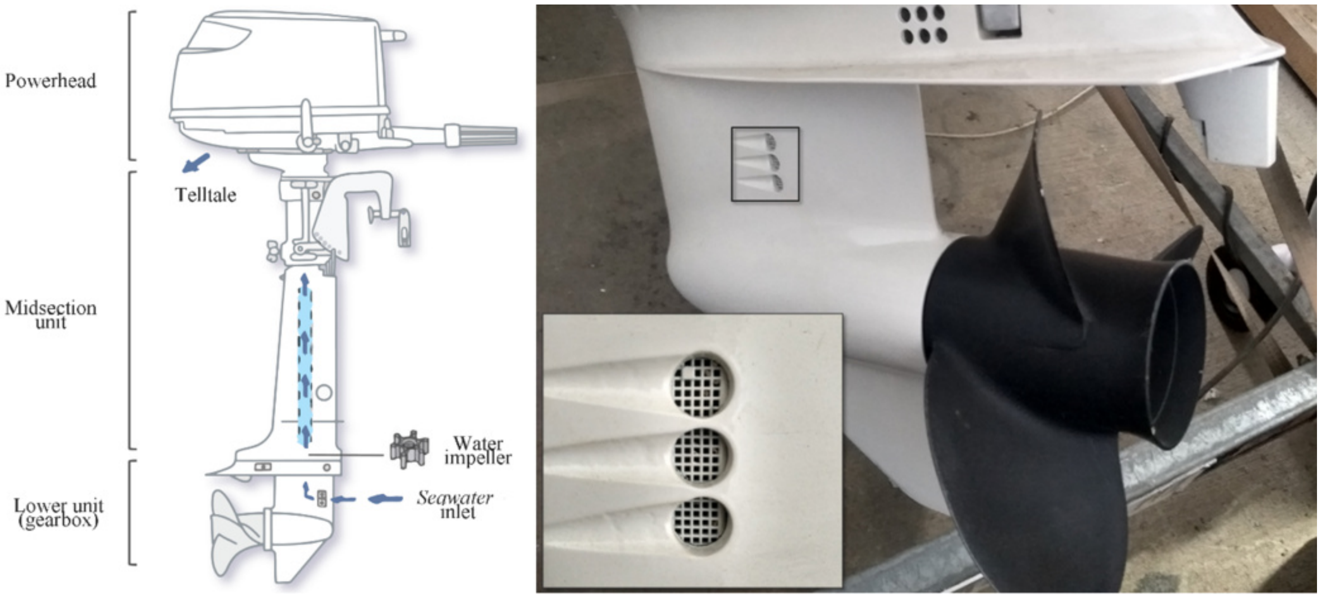

Figure 6: To the left, a schematic diagram of an outboard engine, illustrating the seawater circulation pattern through the cooling system. To the right, pumice fragments stuck in the seawater inlet in the "*Tsunami*" ship's outboard engine, after a field trip (in northwestern *Lago Nahuel Huapi*) held in October 2021, a decade after the 2011–2012 Cordón Caulle volcanic eruption).

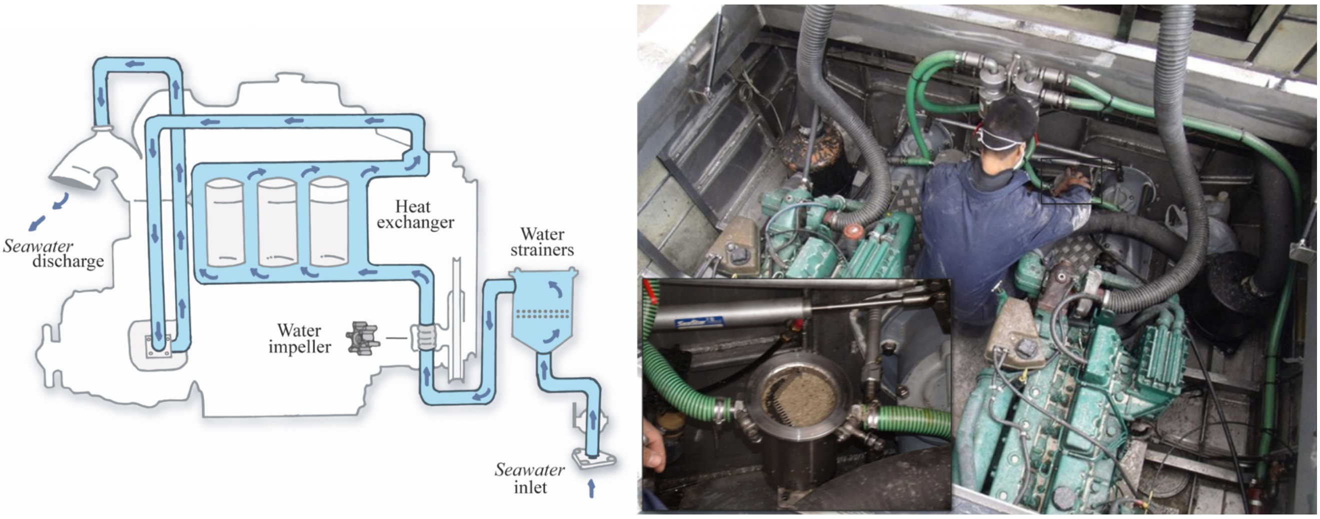

Figure 7: To the left, a schematic diagram of a marine diesel engine, illustrating the seawater circulation pattern through an open cooling system.To the right, manual clearances of pumice from clogged strainers in a primary passenger ship at *Puerto Pañuelo* (*Lago Nahuel Huapi*) during the 2011–2012 Cordón Caulle volcanic eruption. Photo courtesy of Martín Pereira.

all operational domains (Section *4.2.1*), and waterborne ash, whether as pumice rafts, suspended, silted, or remobilized ash, causing impacts on the ports' *sea-side* domain (Section *4.2.2* to Section *4.2.4*).

4.2.1 *Effects on port infrastructure and machinery*

Primary ashfalls had mild effects on ports' infrastructure, causing some degree of deterioration of exposed surfaces, the corrosion of metallic components, the development of slippery surfaces, etc. (Table 3A–3C). Wharves and docks, being particularly flat horizontal and wide structures, would tend to be most vulnerable to the effects of increased ash-loading. However, even the greatest accumulations of ash measured in remote and maintenance-free wharves—with loads intensified by rain, splashing, and snow—were not enough to cause structural damage to port infrastructure as it was reported for residential buildings in the region, including roof collapses [Wilson et al. 2013]. Most floating docks, possessing the lowest resistances to increased loads, did not sustain ash accumulations on their iron mesh reticulated surfaces. On the other hand, primary ashfalls caused severe damage to exposed machinery and equipment for passengers and cargo handling. At *Club Náutico Bariloche*, the 2011–2012 Cordón Caulle eruption affected various cranes, two crawlers, and a ship elevator, which required deep cleaning or even replacement (Section S2.3, Supplementary Material 1). Even minor ashfalls were the cause of long-lasting disruptions to port services due to ground

Figure 8: Detail image of corroded bearing-supports and worn rubber bearing-pads that carry the submerged tail shafts in the *Catamarán Victoria Andina*, identified in dry docks during 2012. Photos courtesy of Martín Pereira.

Figure 9: Massive pumice rafts generated after the 2011–2012 volcanic eruption entering the inner basin of Puerto San Carlos in Bariloche (*Lago Nahuel Huapi*).

accessibility issues (vital for the management of emergencies [Salgado et al. 2022]), the disruption of critical infrastructure services, and the clean-up of volcanic ash accumulations from ships and ports.

4.2.2 *Entry of pumice rafts into harbors*

Large masses of floating pumice can easily enter downwind open harbors (Table 3A–3C), causing disruption to port logistics on the *sea-side* domain because of diminished waterborne visibility, the risk of clogging ships' cooling systems, and sedimentation issues (Figure 9). This was particularly the case for the various ports that sit on the *Lago Nahuel Huapi* southeastern shore, after the 2011–2012 ashfall (Section S2.3, Supplementary Material 1). Great volumes of pumice rafts covering the surface of the lake were observed for several weeks. Most of this floating material accumulated on open shores exposed to the wind or in wind-protected bays, producing thick deposits of lapilli and ash in both, surface and subaqueous environments. In *Puerto Pañuelo*, the direct fallout of fine ash during the first days of the eruption created a very thin coating of floating pumice over the harbor's bay. However, harboring conditions worsened dramatically throughout the following weeks, as the wind dragged immense volumes of thicker and coarser pumice rafts straight into the open natural harbor. The successive accumulation of pumice on the inner part of the bay rapidly prograded, silting up the harbor and damaging berthed ships. In many cases, managers on-site improvised the usage of containment booms to prevent entries of pumice rafts into harbors' basins and other critical sites (Section 5). Large masses of pumice rafts have also been observed drifting along tributaries and outflow rivers (Section 4.3), causing damage and disruption to downstream critical sites and shipping (Section S1.2, S2.4, Supplementary Material 1).

4.2.3 *Freezing of pumice rafts*

For regions with extreme climates, low temperatures can freeze wet pumice, forming consolidated masses difficult to remove. Frozen pumice rafts and shore deposits have been seen hampering harboring logistics in Patagonia (Table 3B). In *Puerto Pañuelo*, frozen pumice rafts blocked a small service ship on the inner part of the harbor, which had to be liberated by breaking the surrounding sheet of frozen pumice with shovels (Section S2.3, Supplementary Material 1). At the

Alicurá power dam, the occasional freezing of pumice rafts hindered the managers' attempt to divert away from the generation units to the spillway the floating mass of harsh pumice by the usage of containment booms (Section S2.4, Supplementary Material 1). Possibly, the humidity contained in pumice fragments and the inhibition of wave movement due to the floating pumice-coating contributed to the development of these singular masses identified in southern *Lago Nahuel Huapi* and *Río Limay*.

4.2.4 *Sedimentation and draft losses*

The deposition of massive volumes of volcanic ash in harbor basins and lake shores after explosive volcanic eruptions poses negative effects for nautical activity (Table 3A–3C). Input of ash can result from primary ashfalls, the drifting of pumice rafts, and fluvial discharges, and from other secondary phenomena such as lahars or long shore drift. Volcanic ash build-up in harbors' lake floors can compromise the suitable widths and draughts for accommodating larger ships in basins and channels, as it was widely reported in southeastern *Lago Nahuel Huapi*. In 2011–2012, low-stand lake levels in many Patagonian lakes worsened draft loss issues, particularly in *Puerto Traful* and *Puerto Pañuelo* (Section S2.2, S2.3, Supplementary Material 1). Severe reduction of water depths can require unscheduled dredging and difficult remediation works (Section 5). In 2021, regular dredging works at *Club Náutico Bariloche* and *Puerto Pañuelo* still remove great amounts of settled ash from the 2011–2012 Cordón Caulle volcanic eruption (Figure 10). Sedimentation in harbors poses a long-term issue as settled ash is easily remobilized by the traffic of ships, lengthening the potential damage of re-suspended pumice to shipping (Figure 11). In view of this, the disposal of volcanic ash resulting from clean-up operations into lake basins, or in sites prone to remobilization, should be strongly discouraged (Section 5).

On another hand, the massive accumulation of shore deposits of ash, can also affect beaches usually committed to the embarkation and disembarkation of smaller ships. This situation was widely observed in northwestern *Lago Nahuel Huapi* (Section S2.1, Supplementary Material 1), where various beaches, much visited during the summer season for recreational shipping, were severely affected by the sedimentation of large amounts of loosely consolidated ash to lapilli-sized tephra deposits, representing potential hazards to slope failure during post-eruption years, which can, in turn, generate tsunami-like waves (Section 4.4).

4.3 Impacts of fluvial remobilized ash

Unconsolidated deposits of pyroclastic material in subaerial environments are subject to erosion, remobilization, and redeposition caused by different fluvial processes, affecting water transport in several ways. Major inputs of fresh volcanic debris can cause substantial geomorphic changes in volcanic ashfall-affected watersheds leading to flooding, channel aggradation, migration, and avulsion [Hayes et al. 2002; Segschneider et al. 2002; Major et al. 2016], or the development of secondary lahars [e.g. Córdoba et al. 2015]. Such processes threaten water transport functionality by compromising inland (fluvial) waterways, or by affecting nearby and downstream infrastructure (e.g. road networks and port accessibilities). For example, storm events occurring soon after the 2011–2012 Cordón Caulle eruption in northwestern *Lago Nahuel Huapi* remobilized massive volumes of ash to lapilli-sized tephra through rivers and streams in near-vent watersheds, causing severe damage to roads, bridges, and residential buildings (Section S2.1, Supplementary Material 1).

On another hand, remobilized ash, eroded from upland watersheds, may also drain towards downstream water bodies causing damage and disruption to ships and ports (e.g. through sedimentation issues in harbor basins; Section *4.2.4*). Although not part of the case studies, the fluvial remobilization of pyroclastic material generated after the August 1991 Hudson (45.9° S–72.9° W, Chile) Plinian eruption [VEI: 5; Naranjo et al. 1993] also caused significant impacts on lake transport. A ferry terminal, formerly located close to the mouth of the *Río Ibáñez*, in *Lago General Carrera* (or *Lago Buenos Aires*, in its Argentinean part), had to be later relocated because of the significant deposition of fluvial-reworked pyroclastic materials from upland watersheds, which received over 2 meters of ash [Wilson et al. 2009c]. This ferry barge played an essential part in the evacuation of livestock during the 1991 volcanic crisis, similar to the situation described for northwestern *Nahuel Huapi* in 2011 (Section S2.1, Supplementary Material 1). Secondary processes also caused considerable damage to Chilean port infrastructure during the 2008 Chaitén eruption. Proximal ashfall deposits remobilized by rainstorms that followed the main explosive phase of the eruption triggered complex and continuous lahar-floods that buried much of the town of Chaitén [Major et al. 2016], including the old harbor of *Puerto Chaitén* [Rodríguez Torrent et al. 2016]. Subsequently, the persistent input of sediment from the *Río Chaitén* to the port town's bay [Major et al. 2016] posed long-term draft issues for a major floating ferry dock that serves the regional maritime transport system, requiring intensive dredging between 2010 and 2012.

The entrance of fresh fluvial remobilized pumice into the lakes instigates the development of renewed pumice rafts, threatening passing ships (Section *4.1.6*). Thin threads of floating pumice were largely reported by fishers and sailors near river mouths in watersheds affected by all these three explosive eruptions, mostly during the Patagonian (rainy) winter season, with some examples of engine losses occurring even eight years after the main primary ashfall. Fluvially remobilized ash entering lacustrine basins can also flow as density currents, transporting suspended sediments in the form of hyperpycnal or hypopycnal currents [e.g. Beigt et al. 2019, and references therein]. These currents were detected transporting pyroclastic material by means of a suspended-sediment collector installed at the *Pireco* and *Totoral* rivers' prodelta in *Brazo Rincón* (Figure 2) during the last months of the 2011–2012 eruption [Beigt et al. 2019]. These hypopycnal currents probably explain the patches of pumice suspended at shallow depths identified by sailors in the area, causing the occasional clogging of ships' engines (Section S2.1, Supplementary Material 1). Massive volumes of floating and suspended pumice may also divert away from lacustrine basins through outflow

Figure 10: Aerial view of *Puerto Pañuelo*, before the volcanic eruption (February 2011) at the top left; and ten years later (November 2021) at the top right. The dashed line indicates the position of the gabion wall constructed to retain tephra dredged from the bay since 2011. Below, dredging works in *Puerto Pañuelo*, many years after the 2011–2012 volcanic eruption, still removing great amounts of settled tephra from the inner basin (May 2019).

rivers, affecting downstream waterways and infrastructure. During the 2011–2012 Cordón Caulle volcanic eruption, large masses of floating pumice drifted along the *Río Limay* (Section S2.4, Supplementary Material 1), the single outflow from *Lago Nahuel Huapi*, reaching the 1.050 MW *Alicurá* power dam, where pumice raft thicknesses of over 40 cm were measured (Figure 12).

All these various secondary syn- and post-eruptive processes can be sustained for prolonged periods of time after explosive eruptions (especially during heavy rains and the snow

Figure 11: Remobilization of subaqueous ash deposits at *Puerto Canoa* (*Lago Huechulafquen*) by action of the *Catamarán José Julián* propellers, many months after the 2015 Calbuco volcanic eruption.

melting season), posing long-lasting threats to shipping and harboring activities, even a decade after the primary ashfall events.

4.4 Subaqueous mass-wasting processes and tsunami waves

Fluvio-lacustrine waterways recurrently affected by the deposition of pyroclastic material are prone to the occurrence of subaqueous mass-wasting phenomena and associated landslide-induced tsunami waves [e.g. Chapron et al. 2006; Villarosa et al. 2009; Beigt et al. 2016; 2019], threatening water activities and infrastructure on the lakes' shores.

The re-sedimentation of large amounts of loosely consolidated ash deposits at overloaded and over steepened subaqueous slopes represents potential hazards to slope failure during post-eruption years [Beigt et al. 2019], which can, in turn, generate tsunami-like waves [e.g. Kremer et al. 2015; Brothers et al. 2016]. Many similar phenomena have been registered in various volcanic ashfall-affected Patagonian lakes in recent years [Beigt and Villarosa 2022].

In other respects, volcanic ash may be involved in the development of failure planes [Wiemer et al. 2015] or act as failure planes themselves in earthquake-triggered subaqueous landslides [Harders et al. 2010]. A massive mass-movement triggered by the 1960 Valdivia earthquake [Mw 9.5; Kanamori 1977] generated a tsunami wave that impacted *Puerto San Carlos*, causing the collapse of the harbor pier, the sinking of moored ships, and the end of two lives [Chapron et al. 2006]. Villarosa et al. [2009] found that the failure was probably induced by the presence of a non-cohesive surface (tephra layer?) that acted as a sliding surface. In this region, earthquake-triggered subaqueous landslide risks (and associated tsunami wave-risks) can persist for long periods after volcanic ashfall events since these lakes are frequently subjected to seismic shaking [Beigt et al. 2019]. After the 2010 Concepción earthquake [Mw 8.8; Duputel et al. 2012], for example, a small pier near *Puerto Canoa* was found still in one piece, sunk in seven meters of water.

5 MITIGATION AND RECOVERY: SUMMARY AND ASSESSMENT OF STRATEGIES

The management of water transport resources during the succeeding volcanic ashfalls included a wide range of mitigation and recovery actions. Despite the region being affected by three major eruptions in just seven years, all these efforts were mostly improvised and poorly communicated amongst the affected parties, and port and ship managers repeatedly disclosed having little or no warning and advice. In this section, we discuss all these measures undertaken and their relative effectiveness in attenuating the effects of volcanic ash.

By far, the mandatory cessation of shipping activities, and housing secondary and smaller ships in dry docks, prevented the greatest damage to ships and kept passengers and crews out of danger from volcanic ash encounters. However, functional water transport paradoxically proved to be a vital resource for managing volcanic crises and assisting with post-event recovery [Salgado et al. 2022].

Protecting berthed, moored, and out-of-water ships with canvas or sailcloth covers and outboard engines with plastic bags also proved useful in avoiding the excessive accumulation of volcanic ash on open decks, halting the ingress of fine ash into ships' interiors, and averting damage to engines and frail equipment.

Many improvised measures were used by ship managers to avoid clogging of the engines' cooling systems. The usage of pre-filters at water intakes, such as rudimental mesh filters, or additional inner strainers installed in larger ships, proved to be a very effective strategy to prevent blockages and damage to the engine, although not infallible. For larger ships, sailing at limited speeds was tested to allow the proper performance of extra filters. However, inadequate cooling due to low rates of *seawater* flow causes significant reductions in the lifespan of numerous engine components, leading to irreversible damage. The possibility to bypass parallel cooling circuits, allowing seafarers to clean one clogged strainer while the other remained in function, represented traits of resilience for larger ships while navigating through ash-contaminated waters, without the need to stop cooling. For smaller outboard motors, the stream of water flowing from the telltale (Figure 6) was used to visually monitor an adequate rate of cooling water flow, with relative success. The deeper *seawater* inlets on outboard motors appeared to confer resilience to the effects of pumice rafts [Salgado et al. 2022]. It is important to note that no additional filtration can be installed in waterjets because of the extremely high water flow they require.

Entries of pumice rafts into harbors and other critical sites can be partially halted using *booms*, containment lines of floaters similar to those deployed for oil spills (e.g Figure 12). In Patagonia, the setup of these barriers evinced inconsistent results. In *Puerto Pañuelo* for example (Section S2.3, Supplementary Material 1), booms proved inadequate for halting the ingress of immense volumes of pumice rafts dragged by winds straight into the natural open harbor. Meanwhile, several barriers installed at the *Alicurá* dam (Section S2.4, Sup-

Figure 12: Drafting of floating pumice down the *Río Limay* during the 2011–2012 Cordón Caulle volcanic eruption, and lines of floating barriers attempting to halt and divert away pumice rafts close to the *Alicurá* power dam during the first days of the eruption (below) and the following weeks (at the top right).

plementary Material 1) only partially fulfilled their intended function of diverting pumice rafts to the spillway, in the weeks following the primary ashfall. Conversely, a shorter barrier intermittently set up at *Club Náutico Bariloche* (Section S2.3, Supplementary Material 1) between the harbor's breakwater and the shoreline's revetment was considered widely successful in avoiding the entrance of pumice rafts to the bay when the wind blew occasionally from the east (Figure 9). In all these three cases, great accumulations of settled ash on the ports' *sea-side* domain required laborious and expensive dredging work for managing water-depth and remobilization issues. The input of waterborne ash into harbors can endure even decades after the primary ashfall event (related to the drifting and sinking of pumice rafts, fluvial discharges, shoreline processes, etc.), which prolongs the need for remediation and increases the demand of more intricate works. In *Puerto Pañuelo*, remediation works entailed the construction of a gabion wall to retain the bulk of volcanic ash dredged from the harbor and hurled to the beach, avoiding re-entry into the water (Figure 10).

In all cases, even the smallest accumulations of ash on ships and ports required complete removal before resuming full operational capacity (Table 3A–3C). In Patagonia, various clean-up methods have been used, depending on the amount of ash fallen, the characteristics of the ash (as in some cases, wet deposits became cementitious and hard to remove), the type of asset affected, and the availability of clean-up resources. The different strategies undertaken ranged in complexity from coordinated operations, combining dry (shovels, brooms, cloths, vacuums) and wet methods (ballast or bilge pumps, firefighting systems from port sites, or the same ships) (e.g Figure 13), to instances where the wind and rain themselves were allowed to clear ash from ships (mainly in cases of negligible ashfall) and ports (mainly in remote or difficult-to-access sites). The clearance of large accumulations of ash proved essential in avoiding the effects of ash-loadings on the ships, also extenuating rot and abrasive and corrosive damage to decks and halting the ingress of fine ash into the ship interiors. In such cases, volcanic ash required careful clean-up (including vacuums, low-pressure compressed air, and dry and damp cloths) before resuming activities to avoid damage to frail electronic equipment. In various cases, clean-up operations were severely delayed because of disruption of ground access to affected sites (Table 3A–3C).

Figure 13: Volcanic ash clean-up in *Puerto Pañuelo* (*Lago Nahuel Huapi*), and thin coating of floating pumice developed in-situ in the background (05/06/2011). Photo courtesy of Martín Pereira.

The ash removed from ships, ports, and urban environments was occasionally and unfortunately dumped into lakes near port sites (e.g Section S2.2, S2.3, S3.1, Supplementary Material 1). Considering that these loose deposits are easily remobilized by water currents and passing ships, posing long-lasting threats to shipping and harboring activities for even decades after the primary ashfall, these actions should be strongly discouraged.

All of these attempts to reduce asset damage were considerably refined by repeated practice, but they were also poorly planned, registered, and communicated among the parties affected. This paper represents the first written record and discussion of experiences on the subject. In essence, it must be observed that this assessment provides the foundation for working on engineered solutions to increase asset resilience to volcanic ashfalls.

6 DISCUSSION AND CONCLUSIONS

This paper has summarized and assessed the most significant consequences of three recent and widespread volcanic ashfalls on Andean Patagonian lake transport. Impacts on ships and port sites, and mitigation and recovery strategies undertaken, were surveyed by means of direct field observations at most affected sites, in-person meetings and semi-structured interviews, and an invaluable transdisciplinary contribution from a range of engineering and nautical expert collaborators. Disruption and physical damage to the different elements that make up a typical water transport network resulted not only from primary ashfalls but also from other secondary phenomena such as pumice rafts, sedimentation processes, and wind and fluvial remobilization of tephra deposits that extended the hazard footprints and prolonged the adverse effects of volcanic ash over time, even a decade after the main eruptive event. Importantly, even relatively small ashfalls were sources of widespread and long-lasting disruption to nautical activity because of a wide range of impacts, including ship malfunctioning; deteriorated conditions for shipping and harboring; downtimes due to clean-up, maintenance, repair, or remediation; and disruption of critical services or ground accessibility to port sites.

6.1 Summary of findings

The most relevant impacts from primary ashfall on ships were: (1) effects of ash-loading on ships' seaworthiness, including capsizing; (2) damage to exposed surfaces and equipment on deck; (3) volcanic ash ingress into ships' interiors, and failure of integrated and computerized *navi-comm* systems; and (4) difficult navigability conditions (and disruption) caused by airborne and waterborne visibility degradation. The most relevant impacts from pumice rafts and waterborne ash on ships were: (5) blockage and damage to the engine's *seawater* cooling systems; (6) damage to propulsion and transmission systems; (7) blockage of water ducts and damage to waterjet impellers and stators; and (8) accelerated abrasion, corrosion, and algal crusting on hulls' frames.

The most relevant impacts from primary ashfalls on the ports' land-side domain were: (1) direct damage to port infrastructure and exposed machinery for ship, cargo, and passenger-handling; and (2) disruption to port services because of reduced airborne visibility, disruption to port's critical infrastructure services, ground accessibility issues, clean-up, etc. The most relevant impacts surveyed on the ports' *sea-side* domain included: (3) entries of pumice rafts into open harbors causing disruption to harboring activities (including the occasional freezing of floating and shore pumice in cold climates); (4) sedimentation and remobilization issues in harbors' bays, including lake-floor build-up and draft losses; and (5) sedimentation and remobilization issues in beaches committed to the embarkation and disembarkation of smaller ships. In addition, further secondary phenomena such as the fluvial remobilization of tephra deposits, and mass-wasting-related hazards (including the generation of associated tsunami-like waves) have also been widely observed affecting ships and port sites (in all domains), which required a separate analysis.

Amidst all the mitigating strategies undertaken, (1) housing ships in dry docks and (2) precautionarily halting all shipping activities prevented by far the greatest damage to ships and hazardous incidents. Other strategies frequently observed included (3) covering berthed, moored, and pulled-out-of-water ships with canvas or sailcloth drapes; (4) various improvised measures for avoiding clogging of the engine's cooling system (e.g. usage of additional filtering instances, shipping-speed restrictions, visual monitoring of the outboard engine's telltales); and (5) the installation of booms to halt the entrance of pumice rafts into harbors. Remediation of affected sites included (1) the complete removal of ash accumulated on decks and ship interiors, and (2) port sites, before resuming full operational capacity (including various clean-up strategies); (3) the repair or replacement of damaged components and infrastructure from ships and ports; (4) dredging work for removing settled ash and managing water depth issues; (5) various renovation and refitting works in port environments to avoid remobilization issues and entries of ash into the harbor (e.g. diversion of watercourses, construction of gabion walls, etc); and (6) other remediation works beyond port areas (e.g. clearing ground accesses). The relative effectiveness of such measures was already discussed in the previous section (Section 5), laying the groundwork for developing engineered solutions to increase the resilience of ships and ports to volcanic ash.

6.2 Damage and Disruption States proposal

Observed volcanic ash impacts span a wide range of consequence-severities that range from no- or nuisance-impact to the extreme cases of total asset loss. To better systematize such a large and varied dataset of impacts, we offer a common and system-specific damage scale [Blong 2003] for lake transport networks, primarily based on Wilson et al. [2014] *Damage and Disruption States* from volcanic ashfalls to critical infrastructure. Similarly, our proposed four-level impact scale presents various descriptors for physical damage and disruption to different ship elements (Table 4A) and two distinct port domains (Table 4B), separated into relative levels with increasing severity: Level 0, no damage; Level 1, cleaning required; Level 2, repair required; and Level 3, replacement required, or financially expensive repair [Wilson et al. 2014]. This system allowed us to effectively compress the extensive impact descriptions elaborated in Supplementary Material 1 and to better depict the gradational nature of impacts severity, not outlined in Table 3A–3C.

Additionally, Wilson et al. [2014] associate each level of damage with a hazard-specific intensity metric range (tephra thicknesses for volcanic ashfalls) over which impacts were observed to occur, based on an accumulation of impact assessment research on different sectors, supported by lab-based experimentation and expert judgment. When examining the empirically observed impact-data presented above, its relationship with the quantifiable amounts of ash received, whether as primary ashfall or waterborne ash (Table 3A–3C), suggests once more the existence of hazard intensity thresholds patterning the severity of impacts on different water transport elements. By grouping distinct types and severity of impacts observed at various affected sites, we were able to recognize and associate preliminary ranges of hazard intensity measures to our damage scale proposal, indicated in Table 4A and Table 4B as tephra depth ranges and relative abundance of waterborne ash. In cases of absence of empirical data (Section 6.1) expert judgment was sought. Volcanic ashfall impact groups were defined by continuous values of hazard intensities, producing sharp thresholds. Logically, different thresholds were derived for each ship element and port domain, since systems responded differently to a specific intensity of hazard. We refer the reader to Wilson et al. [2014] for a comprehensive review of volcanic hazard impacts to critical infrastructure, and for a detailed explanation on how the impact model on which is based our damage and disruption scale proposal was elaborated; and to Blong [2003] for an in-depth review of different scales and indices used to describe natural hazards and their impacts.

6.3 Limitations, implications, and future directions

Despite the robust dataset over which this proposal is based (which includes three major volcanic eruptions and tens of inland ports or hundreds of different types of ships affected), our impact model presents ample limitations and biases that should be considered, as we acknowledge insufficient evidence to derive unequivocal and well-founded hazard intensity thresholds. This is particularly the case for the effects of volcanic ash loading on ships' seaworthiness and port infrastructure, since very few instances of ships' capsizing were reported in Patagonia, and no structural damage was observed on port infrastructure. Unlike prior assessments [e.g. Jenkins et al. 2014; Wilson et al. 2014], suggested thresholds are based on available observational data and expert consultation, and more observations, experimentation, and/or numerical modeling are required to better estimate the amounts of ash that would be necessary to cause such impacts. A further source of bias refers to the various mitigation actions adopted during each volcanic ashfall event, primarily associated with precautionary halts in water activities, which masked the occurrence of impacts that would, otherwise, have been expected.

Another major problem concerns determining the most appropriate intensity metrics for pumice rafts and other waterborne ash-related hazards, which were observed to cause significant damage to water transport, aside from primary ashfall. Accordingly, a preliminary rough division for increasing amounts of waterborne ash was introduced in our damage scale proposal (Table 4A; Table 4B). This includes: (1) the absence of waterborne ash; (2) the presence of scarce fragments in the water; and (3) heavy loads of waterborne ash (whether it be as a result of pumice rafts developed *in situ*, the drifting of floating or suspended ash, fluvial remobilization processes, etc). These qualitative terms leave hazard intensity values undefined, which can lead to ambiguity [Blong 2003]; however, it facilitates the goal of maximizing the scale's applicability. No type of differentiation was made regarding the origin of waterborne ash, given the similarities observed in consequential impacts on ships and ports, and the difficulties in establishing the source of waterborne ash while several hazards were occurring simultaneously.

Despite the fact that our systematic review is limited to evaluating volcanic ash impacts on small and mostly tourist networks, results can provide fundamental and replicable insights for larger fluvio-lacustrine networks and lay the foundations for evaluating volcanic ash impacts on maritime transport systems. We expect that continued application of our impact scheme to case studies will improve the accuracy of hazard intensity thresholds (by incorporating consideration for numerous factors external to the ashfall characteristics) and impact descriptors (by incorporating systems with different vulnerabilities), a fundamental step towards developing universal damage state schemes. Additionally, we expect that further methodological approaches commonly used in natural hazard vulnerability assessments (such as experimental, analytical, and hybrid approaches), applied to water transport systems, will refine and strengthen the proposed thresholds.

While this assessment goes a long way towards finding comprehensive hazard intensity thresholds, our early system-

Table 4A: Proposed impact scale for different ship elements, based on the *Disruption and Damage States* suggested by Wilson et al. [2014] for tephra fall impacts to critical infrastructure; (NA) not applicable.

Ship elements		Level 0	Level 1	Level 2	Level 3
		No damage	Cleaning required	Repair required	Replacement, expensive repair
Seaworthiness	Thresholds	<30 mm ashfall	30–150 mm ashfall	>150 mm ashfall	
	Impacts	No damage. No disruption	Moderate plunge of waterlines, reducing ship's seaworthiness and ability to transit in shallow water, or causing possible heeling and breakage of moorings in berthed ships	Hazardous plunge of waterlines, causing possible heeling, entries of water into watertight spaces, capsizing, or sinking. Favored in uncovered and poorly maintained ships with large, open, and one-sided decks, little above the waterline; or malfunctioning of emergency bilge pump systems	
Deck equipment, surfaces & components	Thresholds	<0.1 mm ashfall	0.1–5 mm ashfall	5–170 mm ashfall	>170 mm ashfall
	Impacts	No damage. No disruption	Possible development of slippery surfaces, icy coatings, indurations of ropes. Clogging of air intakes and filters in equipment relying on air supplies. Possible damage to exposed equipment (especially with moving parts) and disruption of HVAC systems. Difficulties in deck operations	Possible scraping and/or corrosion to metallic frames, abrasion to wind glasses, and rot, mold, or mildew due to tephra holding moisture. Possible contamination of fuel and lubricating oils. Ash ingress into machinery, cargo, control, and accommodation spaces and damage to HVAC systems. Possible collapse of sailcloth-cabins. Impracticable deck operations	Complete burial of deck. Extensive damage to deck equipment and possible structural damage. Completely inoperable
Navi-com devices & computers	Thresholds	<1 mm ashfall	1–50 mm ashfall	>50 mm ashfall	
	Impacts	No damage. No disruption	Apparent resilience of electronic devices waterproof-enclosed or housed inside cabins (anemometers, radars, sonars, GPS, VHF radios). Reduced functionality until clean-up	Possible damage to exposed control and communication equipment. Note: centralized and computerized navigation and communication systems proved extremely vulnerable to airborne ash, immediately failing, and rendering ships inoperable at much lower ashfall thicknesses	
Systems dependent on seawater supply	Thresholds	No waterborne tephra	Scarce fragments of waterborne tephra	Heavy loads of waterborne tephra	
	Impacts	No damage. No disruption	Possible clogging of water inlets or filters, and damage to impellers and piping from seawater cooling systems, causing engines' stoppages (requiring clearance and reboot). Immediate damage to waterjets' pumps	Immediate clogging of water inlets or filters, and damage to impellers and piping from seawater cooling systems, causing engines' overheating and ruin. Waterjets completely inoperable. Possible failure of firefighting, ballast, or domestic-water systems in larger ships	
Propulsion & transmission systems	Thresholds	No waterborne tephra	NA	Scarce fragments to heavy loads of waterborne tephra	
	Impacts	No damage. No disruption	NA	Damage to submerged moving parts from screw propeller systems (worn of rubber bearing pads, abrasion and deterioration of shafts and propellers, damage to control devices, etc), compromising the control and manoeuverability of ships after long-term exposures, and causing shipping disruption until repaired or replaced	
Hulls	Thresholds	No waterborne tephra	Scarce fragments of waterborne tephra	Heavy loads of waterborne tephra	NA
	Impacts	No damage. No disruption	Possible light scrapings on the stern at waterline levels after long-term exposures. Possible development of algae crusting on surfaces in contact with water, requiring clean-up. Ships' downtimes until cleaned or repaired	Possible scrapings and deep abrasion marks (accompanied by corrosion in metallic frames) after long-term exposures. Ships' downtimes until repaired for avoiding holing of hulls' frames	NA

Table 4B: Proposed impact scale for different port operational domains [Leitner and Harrison 2001], based on the Disruption and Damage States suggested by Wilson et al. [2014] for tephra fall impacts to critical infrastructure.

Port setting		Level 0 No damage	Level 1 Cleaning required	Level 2 Repair required	Level 3 Replacement, expensive repair
Land-side domain	Thresholds	<0.1 mm ashfall	0.1–5 mm ashfall	5–150 mm ashfall	>150 mm ashfall
	Impacts	No damage. No disruption	Reduced airborne visibility (in all operational domains). Light damage to cargo and passenger-handling machinery. Clogging of air intakes and filters in equipment relying on air supplies. Possible development of slippery surfaces, icy coatings, indurations of ropes. Disruption of critical infrastructure services and limited ground-based accessibilities	Severe damage to cargo and passenger-handling machinery. Possible deterioration of exposed surfaces (abrasion, corrosion, rot, mold, and mildew due to tephra holding moisture, etc). Possible ingress of ash into accommodation spaces, or structural damage to port's superstructures. Port downtimes until remediation	Possible structural damage port superstructures, including buildings' roof collapse.[*] Complete burial of land-transport networks.[**] Completely inoperable
Sea-side domain	Thresholds	<0.1 mm ashfall	0.1–20 mm ashfall	20–200 mm ashfall	>200 mm ashfall
	Impacts	No damage. No disruption	Reduced airborne visibility (in all operational domains). Blanketing of signaling, beaconing, water-surface, bedrock features and shorelines. Harbor's downtimes until cleaned/cleared	Fully blanketing of port sea-side domain's features. Harbor's downtimes until remediation (at risk of further incidents). Others: possible deterioration of beaches committed for stranding smaller ships; enhanced mass-wasting processes related-risks; etc	Possible structural damage to docks, wharves, and berthing structures due to ashfall vertical loading. Others: inability to strand smaller ships in affected beaches
	Thresholds	No waterborne tephra	Scarce fragments of waterborne tephra	Heavy loads of waterborne tephra	Massive pile-up of waterborne tephra
	Impacts	No damage. No disruption	Reduced waterborne visibility. Blanketing of water-surface, bedrock features and shorelines. Harbor's downtimes until cleaned/cleared	Sedimentation and remobilization issues in harbors' basins and canals,[**] requiring dredging. Fully blanketing of port sea-side domain's features. Harbor's downtimes until remediation (at risk of further incidents). Others: freezing of pumice rafts; possible deterioration of beaches committed for stranding smaller ships; enhanced mass-wasting processes related-risks; etc	Filling and possible abandonment of harbors' basins and canals.[†] Others: inability to strand smaller ships in affected beaches

[*] e.g. Spence et al. [2005]; Wilson et al. [2013]; Jenkins et al. [2014], etc.

[**] Wilson et al. [2014]

[†] e.g. Blong [1984]; SMEC International Pty Ltd [1997]; this paper.

specific damage scale proposal represents an evidence-based and valuable resource for stakeholders, authorities, and emergency managers. This is not only because of the current lack of empirical and theoretical knowledge on the subject, but also because water transport has proved crucial for managing emergency response actions during various volcanic crises in the region [Salgado et al. 2022], despite being extremely vulnerable to volcanic ashfalls (even in terms of life-safety concerns [this paper]). A better understanding of the most likely outcomes of navigating in the presence of volcanic ash would guide decision-makers to determine the most appropriate course of action and avoid, if possible, hazardous encounters with volcanic ash. Since volcanic ashfalls are generally infrequent and somewhat exotic events, and the global development of ships, ports, and waterways is likely to continue to increase, the improved knowledge of impacts resulting from explosive volcanic eruptions (and how to deal with them) will certainly enhance transport networks' resilience to volcanic ash hazards, an immensely valuable step towards reducing the impacts of volcanic eruptions on societies.

AUTHOR CONTRIBUTIONS

PAS conceptualized the main research idea, led field interviews and data collection, and wrote the original draft with input from GV, DB, VO, CS, and FB. GV and VO provided invaluable input from first-hand experience during each of the volcanic crises addressed, leading scientific assistance programs for local and provincial authorities. DB and GV advised on the risk assessment of subaqueous mass-wasting processes and tsunami waves. CS provided extensive and fundamental counseling on volcanic ash impact assessment. FB provided vital inputs and validation on nautical subjects. GV and DB led and managed funding acquisitions. All authors contributed to reviewing and editing the final manuscript.

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DATA AVAILABILITY

The full narratives on the most relevant effects of volcanic ash at each affected site, on which this impact catalogue and assessment is based, are included as Supplementary Material alongside the online version of this article.

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