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Review

Volcanic hazard impacts to critical infrastructure: A review

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ABSTRACT

Effective natural hazard risk assessment requires the characterisation of both hazards and vulnerabilities of exposed elements. Volcanic hazard assessment is at an advanced state and is a considerable focus of volcanic scientific inquiry, whereas comprehensive vulnerability assessment is lacking. Cataloguing and analysing volcanic impacts provide insight on likely societal and physical vulnerabilities during future eruptions. This paper reviews documented disruption and physical damage of critical infrastructure elements resulting from four volcanic hazards (tephra fall, pyroclastic density currents, lava flows and lahars) of eruptions in the last 100 years. We define critical infrastructure as including energy sector infrastructure, water supply and wastewater networks, transportation routes, communications, and critical components. Common trends of impacts and vulnerabilities are summarised, which can be used to assess and reduce volcanic risk for future eruptions. In general, tephra falls cause disruption to these infrastructure sectors, reducing their functionality, whilst flow hazards (pyroclastic density currents, lava flows and lahars) are more destructive causing considerable permanent damage. Volcanic risk assessment should include quantification of vulnerabilities and we challenge the volcanology community to address this through the implementation of a standardised vulnerability assessment methodology and the development and use of fragility functions, as has been successfully implemented in other natural hazard fields.

Contents

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1. Introduction

The aim of natural hazard risk assessment is to evaluate the extent and nature of risk in a particular area by evaluating potential hazards that together could harm people, property and services (UNISDR, 2009). Risk assessments are an integral part of the risk management process (Fig. 1) and comprise hazard, exposure and vulnerability assessments (Marzocchi et al., 2012). Recent natural disasters such as the Eyjafjallajökull eruption in Iceland (2010), the Tōhoku earthquake and tsunami in Japan (2011), Hurricane Sandy in the USA (2012) and Typhoon Haiyan in the Philippines (2013) highlight the need for effective natural hazard risk management and sustainable development (UNISDR, 2014). Various studies have identified society's increasing vulnerability to disasters as a consequence of population expansion in hazardous areas and increasing economic and environmental strains (Rougier et al., 2013). Risk assessment and management are essential for identifying, avoiding and minimising losses associated with natural hazard impacts. Using quantitative risk assessment provides a numerical estimation of risk which can facilitate comparisons between different natural hazards and locations and allow prioritisation of risk mitigation strategies to increase society's resilience to these hazards. Risk mitigation strategies can be broadly classified as:

(1) Land-use planning (citing) used to decrease exposure of people, buildings and infrastructure to natural hazards.
(2) System and component design to improve resilience if exposed to natural hazards
(3) Contingency planning (i.e., preparedness and response) used to reduce the impacts of natural hazards and decrease restoration and recovery times.

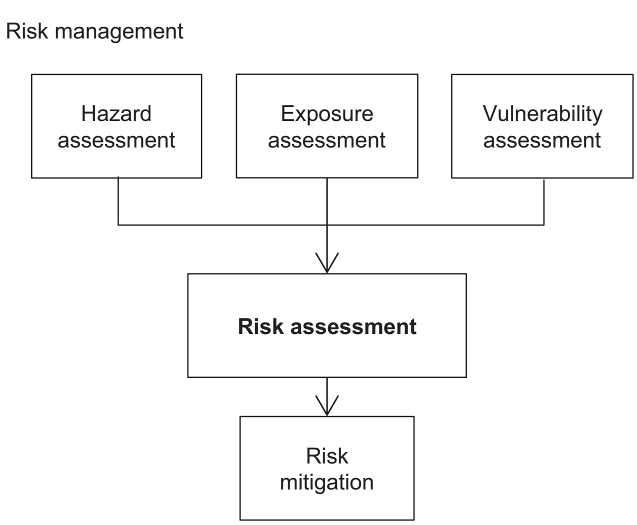


Fig. 1. Schematic description of components and process followed during natural hazard risk management.

A challenge for volcanic risk assessment is the multi-hazard characteristic of volcanic eruptions (Sparks et al., 2013). Tephra falls, pyroclastic density currents (PDCs), lava flows and lahars can occur simultaneously or sequentially and over differing spatial and temporal scales, potentially adversely affecting society (see Table 1 for hazard descriptions). The threat to society is considerable: there are at least ~600 million people living in areas that could be affected by volcanic eruptions (Auker et al., 2013). As populations increase in volcanically active areas, exposure and vulnerability to volcanic hazards will increase (Chester et al., 2000). However, pre-emptive hazard assessment, volcanic monitoring, early warning, crisis management and other mitigative strategies can reduce the impact on society (Sparks et al., 2013). For example, the number of likely fatalities was reduced by two orders of magnitude during the

Table 1
Description of hazard origin, transport, composition, primary damaging characteristics and common hazard intensity metrics for tephra falls, pyroclastic density currents (PDCs), lava flows and lahars.

Hazard	Hazard characteristics	Primary damaging characteristics	Hazard intensity metric (HIM) definitions
Tephra fall	• *Origin*: explosive volcanic eruptions or fire fountaining as a result of magma fragmentation. • *Transport*: dispersed in convective eruption plumes up to 40–50 km vertically and thousands of kilometres laterally.[a,b,c] • *Composition*: vitric (volcanic glass), crystalline and/or lithic particles. Blocks and bombs (>64 mm in diameter), lapilli (2–64 mm) and ash (<2 mm).[d]	• *Loading*: relates tephra thickness and bulk density. Increased loading leads to structural damage of buildings and infrastructure.[e] • *Thickness*: similar to loading and generally decreases exponentially with distance from the vent.[f] • *Dispersal*: tephra can be dispersed over wide extents. Tephra deposits may be eroded and remobilised by wind and/or water for long periods post-eruption.[g] • *Grainsize*: smaller particles are dispersed further from the vent and can penetrate smaller openings than larger particles. • *Surface chemistry*: tephra particles have surface coatings of soluble salts as a result of scavenging in volcanic plumes.[h] Salts may be released upon contact with water, resulting in water contamination.[i] Acidic coatings may cause corrosion of metals.[j] • *Abrasiveness*: tephra is highly abrasive due to the hardness and angular morphology of individual particles.[k]	• *Thickness* (common unit: mm): accumulated thickness of tephra fall. • *Static load* (common units: kg/m^2, kPa): mass of tephra per unit area on a surface. Indicates load on an object in the vertical direction. • *Particle density* (common unit: kg/m^3): the density of individual particles influences their mobility and settling rate in liquids. • Surface chemistry (common unit: mg/kg dry weight for individual elements): concentration of soluble salt layer on the surface of tephra particles. • *Grainsize:* particle size distribution of tephra at a particular site. • *Moisture content* (common unit: vol. %): water content of tephra deposit. Influenced by plume dynamics, environmental conditions during and subsequent to deposition. • *Hardness*: particle hardness influences abrasiveness of tephra deposits. • *Atmospheric concentration* (common unit: $\mu g/m^3$): concentration of tephra particles suspended in air. Is relevant for aircraft safety, visibility and human health.
PDC	• *Origin*: (1) collapse of an unstable eruption column, (2) directed blast, (3) low pyroclastic fountaining, and (4) lava dome collapse.[b,l,m] • *Transport:* gravity-driven flows which accelerate down slope at velocities up to 300 m/s[n] and travel distances of tens of kilometres.[o] • *Composition:* mixtures of generally hot volcanic ejecta and gas.[p]	• *Dynamic pressure:* relate the flows density to its velocity. Dynamic pressures can be on the order of tens of kilopascals[q] enough to damage or destroy buildings and infrastructure. • *Run-out distance:* PDCs can flow distances of tens of kilometres, are generally confined to valleys,[o] although overtopping can unpredictably occur.[m] • *Temperature:* may reach 1100 °C[m], sufficient to burn common building materials.[r] • *Abrasiveness:* pyroclastic material is highly abrasive and in combination with high flow velocity can cause significant abrasion to impacted surfaces.	• *Dynamic pressure* (common unit: kPa): the kinetic energy per unit volume of the flow which changes with flow density and velocity. Used to infer lateral impacts. • *Velocity* (common unit: m/s): velocity of the PDC during emplacement. Can be used instead of dynamic pressure if PDC density is unknown. • *Temperature* (common unit: °C): temperature of the PDC at emplacement. • *Thickness of deposit* (common unit: mm): thickness of the PDC deposit after emplacement has ceased.
Lava flow	• *Origin:* outpourings of molten rock from volcanic vents or fissures. • *Transport:* flows emplaced as a dynamically continuous unit elongated downslope. Lengths are typically <10 km and velocities ~10's km/h, although higher velocities are documented.[s] • *Composition:* the majority of flows are basaltic in composition although high silica and non-silicate flows occur.[s,t]	• *Morphology*: flows tend to travel along confined paths as cohesive, sometimes massive, units (10 m thick) which impact and inundate objects in the flow path. Flows solidify on cooling. • *Temperature*: are between 800–1200 °C[s] during eruption, sufficient to ignite fires.	• *Presence of lava*: whether lava is present at a particular location, regardless of lava flow depth. • *Depth of flow* (common unit: mm): depth of the solidified lava flow. • *Dynamic pressure* (common unit: kPa): the kinetic energy per unit volume of the flow which changes with flow density and velocity. Used to infer lateral impacts. • *Velocity* (common unit: m/s): velocity of the lava flow during emplacement. Can be used instead of dynamic pressure if flow density is unknown. • *Temperature* (common unit: °C): temperature of the flow. Ambient temperature around flow margins is equally important for infrastructure damage considerations.

			• *Cooling duration* (common units: hours, days): time that it takes for a lava flow to cool sufficiently to reinstate infrastructure on top of flow.
Lahar	• *Origin*: (1) eruption of hot pyroclastic material onto ice or snow, (2) eruptions through crater lakes, (3) breakout of crater lakes or other water bodies, and (4) rainfall after eruptions of voluminous tephra.[u] • *Transport*: gravity-driven flows which travel downslope at velocities of 10 m/s and travel 10's km.[b] • *Composition*: slurry of volcaniclastic material (i.e., tephra) and water other than normal streamflow.[v]	• *Velocity*: can travel at high velocities which can partially damage or destroy buildings and infrastructure in flow path. • *Erosive*: commonly erosive which can destabilise structures (e.g., bridge piers and abutments) located in or near to flow channels. • *Run-out distance*: can travel for long distances and inundate large areas. • *Depth*: commonly up to tens of metres in valleys and thin veneers outside of valleys[w] which is sufficient to bury infrastructure and sometimes inundate buildings and structure. • *Temporal*: lahars may occur post eruption ("secondary") for many years as rain remobilises pyroclastic material, prolonging hazard impact.[x]	• *Dynamic pressure* (common unit: kPa): the kinetic energy per unit volume of the flow which changes with flow density and velocity. Used to infer lateral impacts. • *Velocity* (common unit: m/s): velocity of the lahar during emplacement. Can be used instead of dynamic pressure if lahar density is unknown. • *Thickness of deposit* (common unit: mm): thickness of the lahar deposit remaining after emplacement. • *Depth of flow* (common unit: mm): depth of the lahar during emplacement. Depth of flow can be greater than deposit thickness.

[a] Carey and Bursik (2000).
[b] Parfitt and Wilson (2008).
[c] Lockwood and Hazlett (2010).
[d] Cashman et al. (2000).
[e] Spence et al. (1996).
[f] Johnston (1997).
[g] Wilson et al. (2011).
[h] Óskarsson (1980).
[i] Witham et al. (2005).
[j] Oze et al. (2013).
[k] Wilson et al. (2012b).
[l] Branney and Kokelaar (2002).
[m] Nakada (2000).
[n] Wilson and Houghton (2000).
[o] Valentine and Fisher (2000).
[p] Burgisser and Bergantz (2002).
[q] Clarke and Voight (2000).
[r] Blong (1984).
[s] Kilburn (2000).
[t] Griffiths (2000).
[u] Waitt (2013).
[v] Smith and Fritz (1989).
[w] Vallance (2000).
[x] Gran et al. (2011).

1991 eruption of Mt. Pinatubo, Philippines when thousands of people were evacuated prior to the climactic eruption (Sparks et al., 2013). The death toll since 1900 from volcanic eruptions is small compared to other natural hazards; for example, in that time period there were ~280,000 fatalities from volcanic eruptions (Auker et al., 2013) compared to >2 million from earthquakes (Holzer and Savage, 2013). However, disruption, damage and economic loss from volcanic eruptions are considerable, although hard to quantify (Sparks et al., 2013). One aspect of modern society that is commonly and sometimes severely disrupted and damaged by volcanic hazards is critical infrastructure (Blong, 1984; Wilson et al., 2012b), the focus of this paper. Critical infrastructure is defined as a network of man-made systems and processes that function collaboratively to produce and distribute essential goods and services (Rinaldi et al., 2001) which are heavily relied upon by society for daily function (Dunn et al., 2013). The critical infrastructure discussed here includes electrical supply networks, water and wastewater networks, terrestrial transportation networks and communications. We also consider buildings, heating, ventilation and air conditioning (HVAC) systems and electronic equipment common to all infrastructure sectors. There has been a lack of systematic, quantitative collection and reporting of impacts to critical infrastructure, which has hindered quantitative risk assessment.

In this review we build an evidence base of disruption and direct damage to critical infrastructure sectors from tephra falls, PDCs, lava flows and lahars, and distil common impact trends to contribute to improved quantitative volcanic risk assessment. Section 2 of this paper places this review in the context of natural hazard risk assessment and summarises physical vulnerability assessments in volcanology and other natural hazards whilst also highlighting some of the challenges faced with adoption of robust quantitative volcanic vulnerability assessment. Section 3 summarises the current knowledge of physical impacts to critical infrastructure from volcanic hazards highlighting vulnerable infrastructure components and impact mechanisms from a range of international case studies. In Section 4 we discuss general trends in impact severity and at which hazard intensities disruption and damage may be likely to occur for each hazard. We also provide an approach to estimate vulnerability with impact states and fragility functions. We conclude in Section 5 with a discussion of future directions for continued development of quantitative physical vulnerability assessment with the goal to improve volcanic risk assessment. Definitions of terms used throughout this review are in Table 2.

2. Natural hazard risk assessment

Natural hazard risk assessments combine hazard, exposure, and vulnerability assessments (Fig. 1) in order to determine the risk posed to a site, area or region from a single- or multi-hazard source. Risk assessment informs the development of mitigation strategies and effective risk management, reducing loss and increasing resilience (Papathoma-Köhle et al., 2011). We provide a brief description of these assessments and refer the reader to Rougier et al. (2013) and Smith (2013) for in-depth reviews of natural hazard and risk assessments.

Hazard assessment procedures are similar for all natural hazards and concern determining hazard occurrence frequency, the spatial extent (hazard footprint) and hazard intensities (e.g., tephra thickness) within the hazard footprint (Smith, 2013). Deterministic (scenario-based) or probabilistic (range of scenarios) hazard models are used, the choice of which is determined by data availability and the type of assessment required (Panza et al., 2011). Hazard assessment outputs are commonly in the form of hazard maps which show hazard intensity as a function of spatial extent or hazard curves which show exceedance probability of certain hazard intensities at a given location. Exposure assessments identify the number, typology and location of elements (e.g., buildings, infrastructure and people) which have the potential to be impacted by the hazard(s) of interest. Exposure assessments can be at any scale, from site specific to regional, although an inverse relationship generally exists between level of detail and spatial scale. These assessments commonly make use of existing asset inventory data sets (e.g., asset databases held by local and regional authorities: Schmidt et al., 2011), although project specific data sets may be obtained through field investigation or remote sensing (e.g., Foulser-Piggott et al., 2014; Jenkins et al., 2014a). Vulnerability assessments are concerned with the consequences of natural hazard impacts on exposed elements and may be undertaken in physical, economic and/or social contexts (Fuchs et al., 2012) (see Section 2.1 for a detailed discussion).

Risk assessments are the combination of hazard, exposure and vulnerability assessments (Fig. 1) and determine the nature and extent of risk to a site, area or region of interest. Assessments can be qualitative (descriptive data) or quantitative (measurable data) or a combination of both, depending on the nature of available data and the purpose of the assessment (Jelínek et al., 2012). If possible, quantitative assessments are preferred because they can facilitate a more precise comparison between risks, although results can be expressed using qualitative descriptions such as 'high', 'medium' or 'low' risk (Jelínek et al., 2012) to facilitate effective communication (Uzielli et al., 2008). There is an increasing use of multi-hazard risk assessment (e.g., Schneider and Schauer, 2006; Schmidt et al., 2011; Marzocchi et al., 2012; UNISDR, 2013) for particular sites or regions that may be impacted by more than one natural hazard as the combined effect of all hazards influences risk (Zuccaro et al., 2008). Hazard, exposure and vulnerability assessments for each hazard are combined to create a multi-hazard risk index or ranking for a particular area (Marzocchi et al., 2012).

Whilst in theory both hazard and vulnerability aspects of risk assessment should be advanced to the same level of detail, there is often discrepancy between the two, notably for volcanic hazards (Sparks et al., 2013). Quantitative assessments of various volcanic hazards and their processes are well advanced (e.g., Bonadonna, 2006; Wadge, 2009; Jenkins et al., 2012), with fieldwork, laboratory studies and numerical models providing qualitative outputs for the spatial and temporal extent and intensities of hazards, whilst taking into account uncertainties. Vulnerability assessments are less advanced. For tephra fall and PDC there has been steady progress in qualitative understanding of vulnerability for structures, agriculture and some critical infrastructure, however quantitative assessment of vulnerability over a range of hazard intensities is more sparse. This lack of comprehensive understanding can preclude robust quantitative volcanic risk assessment (Wilson et al., 2012b; Jenkins et al., 2014a).

2.1. Natural hazard vulnerability assessments

There are different types of vulnerability (e.g., physical, social, economic; see Fuchs et al., 2012); in this paper we restrict our focus to physical vulnerability, that is, the susceptibility of an infrastructure system or component to impact from a natural hazard. There are three main approaches for physical vulnerability assessment: the use of vulnerability indicators, damage matrices, and fragility or vulnerability functions (Kappes et al., 2012). Fig. 2 briefly summarises these approaches and provides examples of when they may be used in volcanic vulnerability assessment.

Data for deriving physical vulnerability assessments come from empirical, analytical, expert judgement, and hybrid sources (Rossetto and Elnashai, 2003). Table 3 presents some of the advantages and disadvantages of each approach. The most common data source for all natural hazards, including volcanic eruptions, is observational (empirical) data collected during or immediately after a hazardous event. These data are generally scarce due to the danger and limited access in impacted zones, the expense of collecting such data and the infrequent nature of some hazards (Jenkins et al., 2014a), although some remote sensing techniques allow data collection in hazardous areas (e.g., Sanyal and Lu, 2005; Mas et al., 2012; Dong and Shan, 2013; Jenkins et al., 2014a). The advantage of empirical data is that a range of hazard intensities and exposed element properties are taken into account, which are

Table 2
Definitions of terms used throughout this review.

Term	Definition	Reference
Natural hazard	A dangerous natural phenomenon that may cause loss of life, property damage and disruption.	UNISDR (2009)
Exposure	People, property, systems and other elements present in the hazard zone that are subject to potential loss.	UNISDR (2009)
Vulnerability	The characteristic of an element that makes it susceptible to the effects of a hazard.	UNISDR (2009)
Risk	The combination of the probability of an event and its negative consequences.	UNISDR (2009)
Risk assessment	A methodology to determine the nature and extent of risk.	UNISDR (2009)
Risk management	The systematic approach of managing uncertainty and minimising potential loss through the implementation of mitigation strategies.	UNISDR (2009)
Resilience	The ability of a system to absorb and recovery from the effects of a hazard.	UNISDR (2009)
Critical infrastructure	A network of man-made systems and processes that function collaboratively to produce and distribute essential goods and services.	
	Sectors include: electrical supply networks, water and wastewater networks, transportation routes, communications, electronics and air conditioning.	Rinaldi et al. (2001)
Impact	Function of the hazard and vulnerability on the exposed asset.	Jenkins et al. (2014b)
Impact mechanism	The different methods by which a natural hazard can impact infrastructure.	–
Impact severity	The relative level of damage to elements.	–
Disruption	Impact caused to infrastructure prior to the onset of physical damage.	–
Physical damage	General term to describe damage to infrastructure causing complete loss of function until repair or replacement is undertaken.	–
Hazard intensity	The magnitude of a hazard at a particular site. We use the terms “low” and “high” to describe the end members of hazard intensity.	–
Hazard intensity metric (HIM)	Different hazard properties which can impact infrastructure. These properties can be measured and are related to the level of impact.	–
Fragility function	Equations which express the probability of differing levels of damage sustained for different infrastructure as a function of hazard intensity.	Rossetto et al. (2013)
Mitigation	The lessening of the adverse impacts of hazards through policy or structural strategies.	UNISDR (2009)

often difficult to include in models. Empirical data can also be used to confirm and calibrate other data sources and assessments (e.g., Turner et al., 2013), although this is unfortunately rare (Rossetto and Elnashai, 2003). In the absence of empirical data, other forms of data such as analytical (experimental), expert judgement or hybrid combinations can be sought (Table 3).

A quick note on risk assessment in other natural hazard fields is warranted to place volcanic risk assessment in context. Earthquake risk

Vulnerability approach example	Description

Population exposure index	Volcanic hazard level		
	1 (low)	2	3 (high)
0-0.5	1	1	1
1	1	2	2
1.5	1	2	3
2	2	2	3
2.5-3	2	3	3

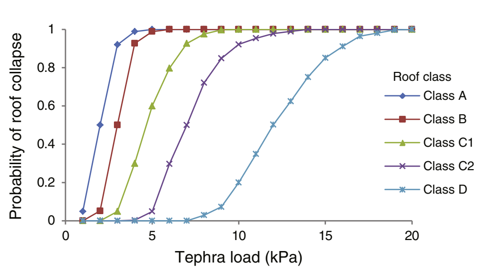
Vulnerability indicator
- Vulnerability indicators or indices represent a property of a system and provide information regarding its susceptibility to natural hazard(s) impacts (Birkmann, 2006; Kappes et al., 2012).
- Widely used in social sciences, but less common in physical vulnerability assessment due to difficulties in applicability of indicators to characterise a large spectrum of hazards (Kappes et al., 2012).

Example:
Vulnerability indices (coloured squares) for developing countries based upon volcanic hazard level and population exposure. From Aspinall et al. (2011).

Damage level	PDC intensity			
	4 kPa	6 kPa	8 kPa	10 kPa
D0	0.0	0.00.1	0.0	0.0
D1	0.1	0.2	0.0	0.0
D2	0.19	0.13	0.0	0.0
D3	0.28	0.31	0.0	0.0
D4	0.3	0.31	0.1	0.0
D5	0.15	0.54	0.9	1.0

Damage matrix
- Define the probability of a specific damage level being reached for a infrastructure element at a specific hazard intensity level (Menoni, 2006; Kappes et al., 2012; Rossetto et al., 2013).
- Matrices may only provide data for specific regions where elements fit defined vulnerability classes, limiting their wide applicability.
- Used when infrastructure damage can be easily assigned to a damage level and specific hazard intensity.

Example:
Probability of European building class A being at a specific damage level for a specific PDC intensity. D0-no damage, D5-complete damage. From Zuccaro et al. (2008).



Fragility function
- Quantitatively estimates the probability of a damage state being exceedance as a function of hazard intensity.
- Used when there is sufficient hazard intensity data for all damage states.
- Requires large statistically valid data sets.

Example:
Probability of reaching partial or total roof collapse (damage state D5) as a function of tephra load for European roofs (reprinted from Zuccaro et al. (2008) with permission from Elsevier).

Fig. 2. Graphical representation and descriptions of the three most common approaches to assess natural hazard vulnerability: vulnerability indicators (Aspinall et al., 2011); damage matrices and fragility functions.
Zuccaro et al. (2008).

Table 3
Advantages and disadvantages of the different methodological approaches used to develop fragility and vulnerability functions in natural hazard vulnerability assessment. Modified from Schultz et al. (2010).

Approach	Data	Advantages	Disadvantages
Empirical	• Controlled experiments • Post-event damage assessment	• Repeatable experiments • Range of hazard and infrastructure characteristics taken into account	• Difficulties in replicating natural hazards in laboratory • Site, region, structure specific • Scarce data of variable quality
Judgement-based	• Expert elicitation	• Assess wide range of impacts, some of which have not been previously observed • Not limited by impact data or models • Can be used to refine other functions	• Quality depends on expert's expertise and subjectivity • Can be difficult to validate • Differing and contradictory opinions
Analytical	• Numerical modelling	• Increased reliability and repeatability and reduced bias • Can be extrapolated to new situations	• Substantial computation • Based on simplifications and assumptions
Hybrid	• Combination of different approaches	• Reduce limitations by combining different approaches • Reduce uncertainties in fragility functions	• Limitations are the same as individual approaches

assessment has well established quantitative vulnerability assessments that estimate damage, disruption and casualty impacts (Reitherman, 2012), which have informed the establishment of robust seismic building codes; pioneering work began in the 1980s focusing on seismic safety of nuclear power plants (e.g., Kennedy et al., 1980; Kennedy and Ravindra, 1984). The field has well-established methods for post-earthquake building assessments (Rossetto et al., 2010) and for deriving fragility functions to probabilistically estimate structural damage (Porter et al., 2007). Other natural hazard fields employ similar empirical approaches to earthquake vulnerability assessment but are less well defined. Analytical modelling approaches are also used to develop fragility functions (e.g., Vaidogas and Juocevičius, 2008; Koshimura et al., 2009; Quan Luna et al., 2011). As a field, volcanology trails behind earthquake risk assessments but is on par with landslide and tsunami risk assessment.

2.2. Volcanic perspective on vulnerability assessments

Volcanic risk assessment has typically focused on loss of life and therefore physical vulnerability assessments have primarily targeted building damage and occupant exposure with limited analysis of other physical societally-relevant assets such as critical infrastructure.

2.2.1. Data sources

Observational data is the key data set for modern volcano risk assessment, and began in earnest with observations in the aftermath of the 1980 eruption of Mt. St. Helens, USA which affected critical infrastructure, health and economic activities across Washington (Lipman and Mullineaux, 1981). A formative review of the effects of volcanic eruptions is presented by Blong (1984), who documents a wide range of volcanic hazard impacts on buildings, infrastructure, agriculture, economy and people. The Blong (1984) review is a significant contribution to the field and is the basis for the current understanding of impacts to the built environment and still relied upon heavily today. Since the eruption of Mt. St. Helens, field observations following eruptions from Mt. Pinatubo in 1991 (e.g., tephra induced building damage: Spence et al., 1996), Rabaul in 1994 (e.g., tephra induced building damage: Blong, 2003a), Montserrat in 1997 (e.g., PDC induced building damage: Baxter et al., 2005), Merapi in 2010 (e.g., PDC induced building and infrastructure damage: Jenkins et al., 2013) and other case studies (e.g., Wilson et al., 2012b; Jenkins et al., 2014a) have strengthened the knowledge regarding volcanic impacts to society, particularly around building damage and occupant safety. In order to continue collecting high quality empirical data Jenkins et al. (2014a) proposes a standardised physical vulnerability survey methodology detailing minimum data requirements to ensure quantifiable data collection.

Where observational data are lacking, experimental assessment (e.g., Spence et al., 2004a; Zuccaro et al., 2008; Wardman et al., 2012c) has been used to estimate vulnerability. Experimental data are sparse due to difficulties in accurately replicating some volcanic hazard properties in the laboratory (Jenkins et al., 2014a). Theoretical calculations (e.g., Petrazzuoli and Zuccaro, 2004; Jenkins et al., 2013) and expert elicitation (e.g., Coppersmith et al., 2009; Aspinall and Crooke, 2013) can also be used to produce both qualitative and quantitative vulnerability assessments that can be applied to a range of element typology and hazard properties.

2.2.2. Quantifying vulnerability

Quantifying vulnerability of buildings is more common within the literature as volcanic risk assessment is primarily concerned with loss of life. Jenkins et al. (2014b) suggest that vulnerability assessments of buildings can also be undertaken to: (1) identify buildings that may benefit from mitigation measures; (2) quantify potential damage and loss of buildings following successful evacuation; and (3) support development of improved construction guidelines for new buildings. As such, numerous studies (Spence et al., 2005, 2007; Marti et al., 2008; Zuccaro et al., 2008) and field observations (Spence et al., 1996; Baxter et al., 2005; Jenkins et al., 2013) have quantitatively estimated building vulnerability for volcanic hazards, particularly tephra falls and PDCs. The outputs of these studies are similar to those of earthquake risk assessment and describe building damage as a function of hazard intensity using hazard intensity thresholds, damage matrices and fragility and vulnerability functions. See Supplementary material 1 for a brief review of fragility and vulnerability functions derived for volcanic hazards. The majority of these studies have assessed vulnerability to European

Table 4
Existing critical infrastructure fragility and vulnerability functions developed for different volcanic hazards. We found no published peer-reviewed fragility functions for water supply, communication networks or lava flows. See Supplementary material 1 for a review of these functions.

	Tephra fall	PDC	Lahar
Electrical supply	[a]		
Wastewater networks	[b]		
Transportation networks	[b]		
Buildings	[b,c,d]	[d,e,f]	[e]
Critical components	[g]		

[a] Wardman et al. (2012c).
[b] Kaye (2007).
[c] Spence et al. (2005).
[d] Zuccaro et al. (2008).
[e] Zuccaro and De Gregorio (2013).
[f] Spence et al. (2007).
[g] Wilson et al. (2012a).

buildings with a large focus on buildings in Naples, Italy and those surrounding Mt. Vesuvius. The primary reason for the focus on these buildings is because there is a large population living close to or on the flanks of one of the most dangerous volcanoes in the world (Baxter et al., 2008). As such, these assessments apply only to European building typologies would need to be re-evaluated and refined for other areas of interest.

In contrast, vulnerability assessment for critical infrastructure systems and components is not well established, with the majority of assessments qualitative in nature. However, damage or disruption to critical infrastructure is likely to have a higher magnitude impact on society than building damage (Jenkins et al., 2014a) due to the interconnectedness of these infrastructure (Wilson et al., 2012b). The New Zealand Volcanic Impacts Study Group (NZ VISG) has over the past 15–20 years systematically assessed tephra fall impacts to critical infrastructure through post eruption impact assessment and semi-structure interviews with critical infrastructure managers (Wilson et al., 2012b, 2014). These studies (e.g., Wilson et al., 2012b) provide a large amount of qualitative data describing the likely impacts and points of vulnerability for each critical infrastructure sector as a result of tephra fall. Some studies have attempted to quantitatively relate infrastructure disruption and damage to hazard intensity using intensity thresholds (e.g., Jenkins et al., 2014b) and fragility functions (Table 4 and Supplementary material 1). However, these quantitative relationships have been based on few empirical data and therefore are associated with sizeable uncertainty. There is a need to refine infrastructure vulnerability estimates for tephra fall and volcanic flow hazards in order to have robust volcanic risk assessments, hence the need for this review and continued and standardised research in this field.

2.2.3. Challenges in assessing physical vulnerability

There are a number of aspects when assessing physical vulnerability in regards to volcanic hazards which make fully-quantitative approaches difficult to achieve. Douglas (2007) attributed this to a number of challenges, including:

(1) Volcanic eruptions are multi-hazard events and therefore critical infrastructure sites can by impacted by multiple sequential or

Table 5

Summary table of documented volcanic impacts to critical infrastructure grouped by decade indicating the prevalence and occurrence of impacts over time.

Sector	Damage	Tephra falls	PDCs	Lava flows	Lahars
Electrical supply					
	Flashover	# * § +			
	Abrasion – dry	# +			
	Abrasion – wet	*			*
	Corrosion	+			
	Gravel contamination	+			
	Physical damage to lines	§	§	× §	§
Water supply network					
	Pump, motor abrasion	# * +			
	Pipe, channel blockage	× # * +			× *
	Pipe ruptures		* §	× §	§
	Intake & filter blockages	× * +			×
	Water quality decrease	× # § +		§	
	Water shortages	× *			
Wastewater network					
	Pump, motor abrasion	× #			
	Pipe blockage	× # §			
	Infill of tanks	§ +			
	Filter blockage	§			
	Treatment disruption	# §			
Transportation					
	Road damage		# §	× # §	# * +
	Road burial/closure	* § +	§	# §	+
	Vehicle damage	# * § +	# *	#	× #
	Traction/visibility reduction	# * § +		#	
	Airport closure or damage	× # * +	*	§	§
	Aircraft damage	× # * +			
	Railway closure or damage	× # +		× #	× #
	Port closure or damage	× +		×	
	Ship damage	§	×		
Communications					
	Physical damage	# §	*		
	Signal interference	# * § +			
Buildings					
	Lateral impact damage		× # * § +	× # * §	# * § +
	Roof damage/ collapse	* § +	#		
	Fire		× * +	# §	
	Corrosion	*			
	Gutter damage	* §			
	Burial	× §	# §	× # §	# *
Critical components					
	Computer damage	# §			+
	HVAC damage	*			

Table 6
Summary of the main vulnerabilities for critical infrastructure sectors for impacts from tephra falls, PDCs, lava flows and lahars and whether impacts can be mitigated by site exclusion (avoidance), physical design of infrastructure or response and operational planning.

Infrastructure sector	Hazard			
	Tephra fall	PDC	Lava flow	Lahar
Electrical supply	• *Vulnerability*: Flashover of insulators, abrasion of HEP turbines, line breakage, tephra ingress into critical equipment. • *Site exclusion*[a]: No • *Design*[b]: Increase insulation and use of anti-pollution strategies to minimise flashover. Strengthen structures or use tephra shedding designs to minimise tephra loading. Increase system redundancy. • *Contingency planning*[c]: Tephra clean-up operations and methods. Use of backup generators.	• *Vulnerability*: Breakage of towers, poles and lines, damage to other structures, abrasion of HEP turbines. • *Site exclusion*: Yes — where possible all equipment should be located away from valleys and known flow paths. • *Design*: Strengthen some structures if possible. Locating services underground. • *Contingency planning*: Clean-up operations and methods.	• *Vulnerability*: Breakage of towers, poles and lines, damage and inundation to other structures. • *Site exclusion*: Yes — where possible all equipment should be located away from known flow paths. • *Design*: Locating services underground. Construction of embankments around critical components. • *Contingency planning*: –	• *Vulnerability*: Breakage of towers, poles and lines, damage to other structures, sedimentation in HEP storage reservoirs, abrasion of HEP turbines. • *Site exclusion*: Yes — where possible all equipment should be located away from valleys and known flow paths. • *Design*: Locating services underground. Construction of embankments around critical components. Use of hardened materials to limit abrasion. • *Contingency planning*: Use of early warning systems, rain gauges and flow sensors. Clean-up operations and methods.
Water supply network	• *Vulnerability*: Increased turbidity, decreased water quality, increased water demand, clogging of filters, abrasion of moving parts in motors and pumps, corrosion of metals. • *Site exclusion*: No • *Design*: Strengthen structures to minimise tephra load damage. Cover open filter beds, clarifiers and pumps. Consider the use of groundwater sources to increase resilience. • *Contingency planning*: Tephra clean-up operations using dry methods (brooms, shovels). Anticipate increased water demand and possible contamination. Increase maintenance frequency. Close water intakes until turbidity decreases.	• *Vulnerability*: Lateral loading damage to tanks, well heads and pipes. • *Site exclusion*: Yes — where possible all equipment should be located away from valleys and known flow paths. • *Design*: Strengthen all structures at treatment facility. Strengthen pipes crossing flow paths or locate them deep underground. • *Contingency planning*: Clean-up operations and methods. Anticipate possible water contamination.	• *Vulnerability*: Burial of underground access points, rupturing of pipes. • *Site exclusion*: Yes — where possible all equipment should be located away from known flow paths. • *Design*: Construction of embankments around critical components. • *Contingency planning*: –	• *Vulnerability*: Lateral loading damage to tanks, well heads and pipes, erosive damage to underground pipes, abrasion damage to river intake structures. • *Site exclusion*: Yes — where possible all equipment should be located away from valleys and known flow paths. • *Design*: Use of abrasion resistant materials for intake structures in rivers. • *Contingency planning*: Clean-up operations and methods. Anticipate possible water contamination. Close water intakes until turbidity decreases. Use of early warning systems.
Wastewater network	• *Vulnerability*: Abrasion damage to components with moving parts, blockage of filters and screens, ingress into pipe network and treatment facility. • *Site exclusion*: No • *Design*: Strengthen structures to minimise tephra load damage. Cover exposed equipment, tanks and pumps. Limit tephra ingress by utilising separate stormwater system. • *Contingency planning*: Tephra clean-up operations and methods. Increase maintenance frequency. Consider bypassing pumping stations and treatment facilities to protect against further equipment damage.	• *Vulnerability*: Lateral loading damage to structures and equipment, ingress into pipe network. • *Site exclusion*: Yes — where possible all equipment should be located away from valleys and known flow paths. • *Design*: Strengthen all structures at treatment facility. Strengthen pipes crossing flow paths or locate them deep underground. • *Contingency planning*: Clean-up operations and methods.	• *Vulnerability*: Lateral loading damage to structures and equipment. Burial of underground access points. • *Site exclusion*: Yes — where possible all equipment should be located away from known flow paths. • *Design*: Construction of embankments around critical components. • *Contingency planning*: –	• *Vulnerability*: Lateral loading damage to structures and equipment, ingress into pipe network. • *Site exclusion*: Yes — where possible all equipment should be located away from valleys and known flow paths. • *Design*: Construction of bunds around oxidation ponds to prevent lahar ingress. • *Contingency planning*: Clean-up operations and methods. Use of early warning systems.
Transportation networks	• *Vulnerability*: Reduced visibility and traction, covering of road and runway markings, abrasion and corrosion damage to vehicles, jamming of rail switches, and disruption to airspace. • *Site exclusion*: No	• *Vulnerability*: Burial of roads, rail networks and airport runways, increased sedimentation into harbours, erosive damage and destruction of bridges, extensive damage to vehicles. • *Site exclusion*: Yes — where possible all routes	• *Vulnerability*: Burial of roads, rail networks and airport runways. • *Site exclusion*: Yes — where possible all routes should be located away from known flow paths. • *Design*: Construction of embankments around	• *Vulnerability*: Burial of roads, rail networks and airport runways, increased sedimentation into harbours, erosive damage and destruction of bridges, extensive damage to vehicles. • *Site exclusion*: Yes — where possible all routes

	• *Design*: Strengthen buildings (airports, train stations) and increase roof pitch to minimise tephra load damage. • *Contingency planning*: Tephra clean-up operations and methods. Road, rail and airport closure protocols. Established tephra avoidance guidelines for aircraft.	should be located away from valleys and known flow paths. • *Design*: Raise bridge decks over valleys and strengthen piers and abutments. • *Contingency planning*: Identify alternate routes if primary routes are damaged. Anticipate the need for temporary bridges. Clean-up operations and methods.	critical parts of the network. • *Contingency planning*: –	should be located away from valleys and known flow paths. • *Design*: Automated barriers to close road and rail routes when lahars occur. Raise bridge decks over valleys and strengthen piers and abutments. • *Contingency planning*: Use of early warning systems. Identify alternate routes if primary routes are damaged. Anticipate the need for temporary bridges.
Communications	• *Vulnerability*: Signal interference and attenuation, corrosion of metal surfaces. • *Site exclusion*: No • *Design*: Strengthen structures or use tephra shedding designs to minimise tephra loading. Sealing of equipment to prevent tephra ingress. • *Contingency planning*: Tephra clean-up operations and methods. Use of different redundant and backup communication systems. Increase maintenance frequency.	• *Vulnerability*: Signal interference and attenuation, damage of towers, poles and masts, burial of equipment. • *Site exclusion*: Yes — where possible all equipment should be located away from valleys and known flow paths. • *Design*: Locate services underground or inside strengthened buildings. Strengthen all equipment, especially those crossing flow paths. • *Contingency planning*: Clean-up operations. Increase maintenance frequency.	• *Vulnerability*: Damage of towers, poles and masts, burial of equipment. • *Site exclusion*: Yes — where possible all equipment should be located away from known flow paths. • *Design*: Construction of embankments around critical parts of the network. Locate equipment inside strengthened buildings. • *Contingency planning*: –	• *Vulnerability*: Damage of towers, poles and masts, burial of equipment. • *Site exclusion*: Yes — where possible all equipment should be located away from valleys and known flow paths. • *Design*: Locate services underground or inside strengthened buildings. Strengthen all equipment, especially those crossing flow paths. • *Contingency planning*: Clean-up operations. Increase maintenance frequency. Use of early warning systems.
Critical components	• *Vulnerability*: Clogging of air filters, overheating, short circuits, abrasion of moving parts, and corrosion of metal surfaces. • *Site exclusion*: No • *Design*: Seal equipment and locate equipment inside sealed buildings to prevent tephra ingress. Install air filters designed for fine particles. Install hoods over HVAC air intakes. • *Contingency planning*: Tephra clean-up operations and methods. Increase maintenance frequency.	• *Vulnerability*: Destruction and transportation of equipment. • *Site exclusion*: Yes — where possible all equipment should be located away from valleys and known flow paths. • *Design*: Relocation of equipment into strengthened buildings. • *Contingency planning*: Clean-up operations and methods. Increase maintenance frequency.	• *Vulnerability*: Destruction and burial of equipment. • *Site exclusion*: Yes — where possible all equipment should be located away from known flow paths. • *Design*: Relocation of equipment into strengthened buildings. • *Contingency planning*: –	• *Vulnerability*: Destruction and transportation of equipment. • *Site exclusion*: Yes — where possible all equipment should be located away from valleys and known flow paths. • *Design*: Relocation of equipment into strengthened buildings. • *Contingency planning*: Use of early warning systems. Clean-up operations and methods. Increase maintenance frequency.
Buildings	• *Vulnerability*: Blocked and/or damaged gutters, tephra ingress, corrosion of metal surfaces, and structural damage to roof. • *Site exclusion*: No • *Design*: Strengthen roofs, increasing roof pitch to reduce static load. • *Contingency planning*: Sealing of building to prevent tephra ingress. Removing tephra from roof to prevent collapse.	• *Vulnerability*: Damage to windows and doors, structural damage to whole building, inundation and burial, ignition of fires. • *Site exclusion*: Yes — where possible all buildings should be located away from valleys and known flow paths. • *Design*: Strengthen walls and avoid having them perpendicular to flow path to reduce dynamic load. Use of shutters on openings to prevent ingress. • *Contingency planning*: Evacuation planning and implementation.	• *Vulnerability*: Structural damage to whole building, burial, ignition of fires. • *Site exclusion*: Yes — where possible all buildings should be located away from known flow paths. • *Design*: Strengthen building walls. Use of non-flammable materials. • *Contingency planning*: –	• *Vulnerability*: Inundation and burial, structural damage to walls, float building off foundations. • *Site exclusion*: Yes — where possible all buildings should be located away from valleys and known flow paths. • *Design*: Strengthen walls and avoid having them perpendicular to flow path to reduce dynamic load. Fix buildings to foundations. • *Contingency planning*: Use of early warning systems. Evacuation planning and implementation.

[a] A 'yes' for site exclusion indicates that infrastructure development should be avoided at a particular site as damage from a hazard cannot be mitigated.
[b] Design considerations include altering the design of components and infrastructure sectors to lower their vulnerability to disruption and damage from volcanic hazards (e.g., strengthen building roof) and the design of site protection measures for flow hazards (e.g., construction of diversion barriers).
[c] Contingency planning involves making decisions and plans in advance about the management and response to volcanic eruptions to minimise impact severity and decrease recovery time (e.g., evacuation plans, clean-up plans and availability of resources).

simultaneous hazards. This can lead to a range of different impact mechanisms to be considered, again adding complexity.

(2) Individual volcanic hazards can cause different types of damage to the same asset depending on the hazard properties. For example, tephra fall can damage a metal roof by increasing the static load causing it to collapse, in addition to damaging it through corrosion and abrasion.
(3) There are no widely adopted volcanic building codes or building performance guidelines which regulate infrastructure design in volcanic hazard zones and prompt vulnerability assessment and fragility function development.
(4) There is a diverse range of infrastructure system design, configuration and components which make it difficult to assign generic vulnerability assessments for all infrastructure sectors.
(5) Time scales leading up to volcanic eruptions can be long compared to earthquakes (discrete events). Long eruption lead times can allow pre-event warnings, resulting in evacuations which remove the danger to life. Given the focus on loss of life vulnerabilities, the mitigative measure of mandatory, encouraged, or self-evacuations reduces social pressure to evaluate building fragility.
(6) Volcanic episodes with multiple hazardous events can take place over a long time, adding complexity to vulnerability assessments.
(7) Difficulties in accurately measuring hazard intensity (e.g., bulk densities of lahars, dynamic pressures of PDCs, tephra thickness). Often PDC and lahar parameters are inferred from deposits due to personal safety concerns and destruction of measuring instruments during flow emplacement. Deposits, especially tephra fall, may be reworked by erosional processes and thus incorrectly measured (Engwell et al., 2013).
(8) Volcanic eruptions are infrequent events, resulting in a lack of quantitative observational impact data. Volcanic post event assessments are primarily focused on the hazard itself and not the impacts.

3. Historically observed impacts to critical infrastructure

In order to estimate vulnerability to critical infrastructure during future eruptions, insights can be gained from analysing past impacts. In this section we review the literature to provide a semi-qualitative overview of disruption and damage to critical infrastructure by volcanic hazards. We consider impacts from tephra falls, PDCs, lava flows and lahars (see Table 1 for hazard descriptions) to electrical supply networks, water supply and wastewater networks, terrestrial transportation networks, communications, computers and air conditioning. As buildings and critical components (HVAC and electronic equipment) are widely used as key components in each infrastructure sector we finish with a dedicated section for critical components and building impacts (Sections 3.6 and 3.7, respectively). Table 5 tabulates documented impact occurrence per decade for the past century for each infrastructure sector indicating the prevalence and occurrence of impacts over time. Table 6 summarises the main vulnerabilities for each infrastructure sector and summarises mitigation actions based on site exclusion, infrastructure design and operation and response planning.

3.1. Electrical supply networks

Electricity is essential for a functioning modern society and the continued operation of other critical infrastructure. Electrical equipment and apparatus used in power generation, transmission and distribution is typically located above ground, comprising of a series of nodes (power stations, substations) connected by extensive corridors (transmission and distribution lines) which can stretch thousands of kilometres (Fig. 3A). The ubiquitous scope of the electrical supply network increases its level of exposure making the network particularly vulnerable to volcanic hazards (Wardman et al., 2012c). Volcanic hazards affect the electric supply network in a number of ways (Fig. 4), the most common being temporary outages caused by insulator flashover as a result of tephra accumulation (Wardman et al., 2012c). Many of the impacts discussed below can occur at any location within the network as similar equipment is located throughout the network (Fig. 3A). See Wardman et al. (2012c) for a review of tephra fall impacts and mitigation strategies for the electrical supply network.

3.1.1. Insulator flashover

The most common tephra fall impact on the electrical supply network is insulator flashover (Wardman et al., 2012c). A flashover is an unintended electrical discharge (short circuit) around the insulator and typically leads to a line fault. Dry tephra has high resistivity but in the presence of moisture resistivity becomes very low (Wardman et al., 2012b). So when tephra is deposited on insulators, in the presence of moisture, a flashover may result. It may only take one insulator to suffer flashover for an entire line of potentially hundreds of kilometres to be disrupted. Tephra, in this case, can result from direct falls, PDCs or from wind remobilisation of unconsolidated tephra deposits. Flashover has been observed worldwide after volcanic eruptions where tephra accumulations exceed ~3 mm (Fig. 4). However tephra moisture content is the critical factor controlling flashover occurrence, as dry tephra has very low electrical conductivity (Wardman et al., 2012b). Insulator and system design also influence flashover susceptibility. Wardman et al. (2012c) found that tephra accumulations on the underside of insulators are equally important as accumulations on the topside in assessing vulnerability. Electrical supply providers can minimise tephra induced flashover by increasing insulation, using anti-pollution designs and cleaning strategies (Wardman et al., 2012c).

Tolerance to flashover faults and continued operation of electrical networks have been documented in some cases (Fig. 4), although Wardman et al. (2012c) suggest that they may be under-reported as it is more common to document failures. Tolerance is observed over a wide range of tephra fall thicknesses ranging from 2 to 300 mm. Differences in tolerance values are due to different component designs, tephra properties and environmental conditions, as these parameters influence how tephra affects insulators.

3.1.2. Damage to electrical lines

Volcanic flows have snapped poles and damaged electrical lines, resulting in supply disruption, during volcanic eruptions of: Heimaey, Iceland in 1973 (lava flows: Morgan, 2000); Mauna Loa, Hawaii in 1984 (lava flows: Associated Press, 1984; Hawaiian Volcano Observatory, 1998a); Nyiragongo, Democratic Republic of the Congo (DRC) in 2002 (lava flows: Baxter and Ancia, 2002); Chaitén, Chile in 2008 (lahars: Wilson et al., 2009); and Merapi in 2006 (PDCs: Wilson et al., 2007). Fig. 5 shows that these impacts tend to occur at low hazard intensities although the scarce evidence suggests that any presence of volcanic flows is likely to cause disruption to electrical infrastructure. Tephra accumulations on lines may cause them to break such as those that occurred in the 2008 eruption of Chaitén, although here snow added to the load on the lines (Wilson et al., 2012b). Flow deposits, especially solidified lava flows, will restrict access to buried services (e.g., underground cables) limiting future serviceability.

3.1.3. Damage at generation sites

Hydroelectric power (HEP) turbines at generation sites are particularly vulnerable to abrasion after tephra material (either from direct fall or PDCs and lahars) is deposited into storage reservoirs. Tephra suspended in reservoirs may pass through turbines causing abrasion to them and other auxiliary components over time (Fig. 6A). Abrasion reduces the performance and life span of turbines leading to turbine replacement (e.g., Meredith, 2007). For example, four turbines at the Agoyan HEP station, Ecuador have been replaced over the last 21 years as a result of abrasion damage from ongoing tephra fall from Volcán Tungurahua being deposited in the Pastaza catchment (Sword-Daniels et al., 2011). Tephra properties (e.g., particle hardness and morphology) and exposure time are the primary controls on abrasion occurrence with longer exposure times leading to increased abrasion severity although turbine design, materials, protective coatings and maintenance will also influence abrasion damage. Wind turbines and blades are also at risk of abrasion by tephra particles and may result in damage and reduced performance similar to that caused by sand particles (e.g., Khalfallah and Koliub, 2007; Dalili et al., 2009).

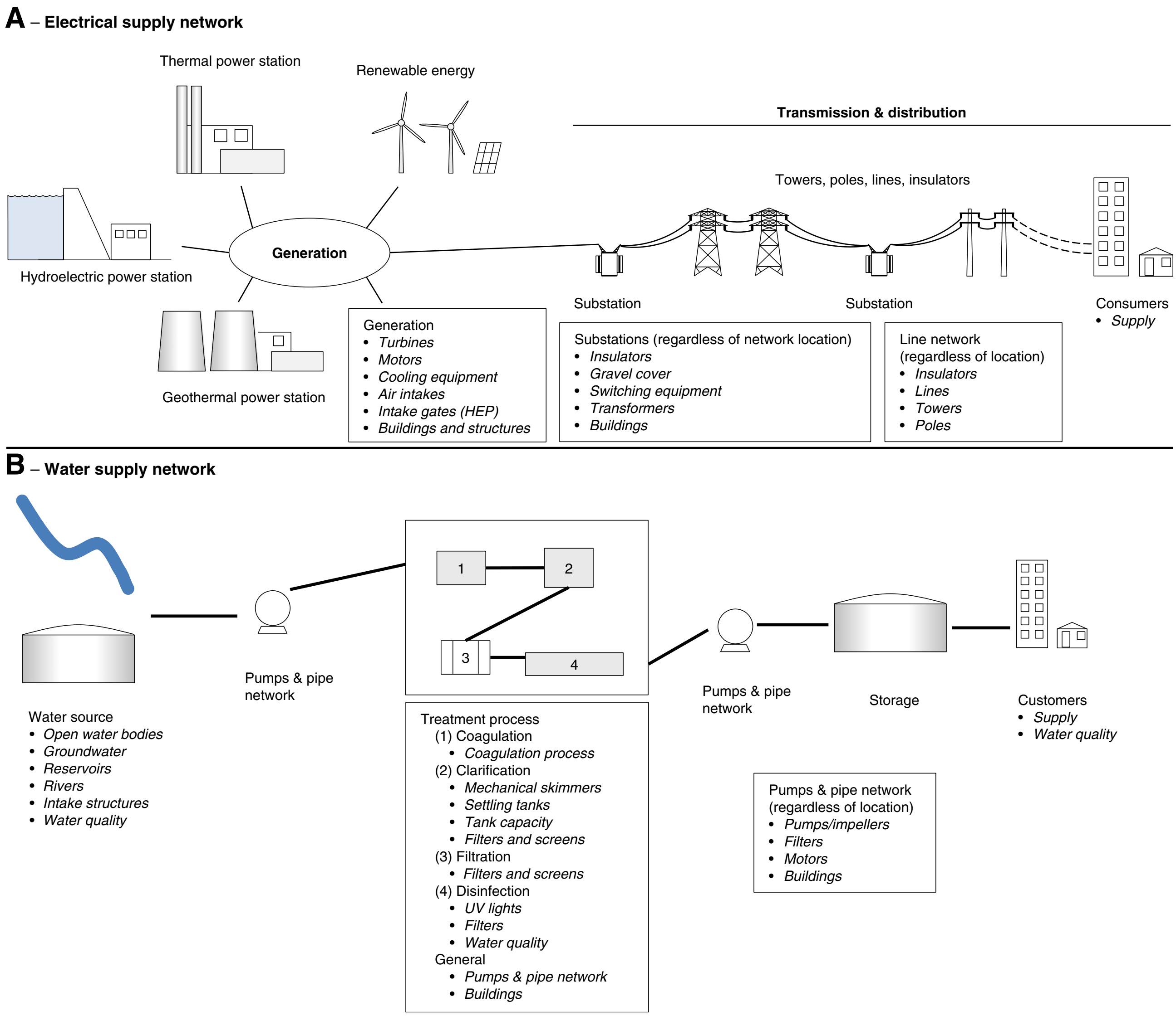


Fig. 3. Schematic of (A) an electrical supply network showing generation at different power stations and then transmission and distribution to consumers (modified from Wardman et al., 2012c) and (B) a water supply network from water source, water treatment through to distribution to consumers. Components vulnerable to volcanic hazards are indicated in italics.

The only known example of a geothermal power generation site being impacted by tephra fall is the Amatitlán plant located 3 km north of Volcán Pacaya, Guatemala. During the 2010 eruption of Pacaya, the plant received 20 cm of coarse tephra and bombs up to 250 mm in diameter. The upward facing uncovered steam condenser fans suffered abrasion damage and denting from falling blocks, rendering them non-operational (Wardman et al., 2012a). Minor denting of intake and outlet pipe cladding also occurred. The plant was shut down for three weeks whilst cleaning was undertaken (Wardman et al., 2012a).

Lahars have been documented impacting river water intake systems used for generation site cooling. After the 1980 Mt. St. Helens eruption, lahars filled the Columbia River with sediment, the same river where the now decommissioned Trojan Nuclear Power Plant had a water intake system. Fortunately the water intake was located in an area with less sedimentation and the plant was off-line at the time of the eruption for fuel replacement (Schuster, 1981).

New renewable energy technologies such as photovoltaic (PV) panels may be impacted by volcanic hazards as they are open to the atmosphere; however there is limited empirical observation of this occurring. One instance occurred during the 2011 eruption of Shinmoedake, Japan, when tephra accumulated (<2 mm) on PV panels at the University of Miyazaki, 50 km east of the vent. PV panel performance was reduced by ~60% (Ota et al., 2012) but recovered after rainfall removed the tephra a few days later.

3.1.4. Clean-up disruption

Deposition of unconsolidated tephra deposits either from direct falls or flows (PDCs and lahars) at electrical supply sites may require removal to restore function. Tephra clean-up operations have been conducted by electrical supply operators worldwide to minimise ongoing flashover faults and prevent future tephra induced impacts (e.g., corrosion, abrasion) to their components and network (Fig. 4). Documented thicknesses of when cleaning occurs are varied; ranging from 1 mm after eruptions at Tungurahua (1999–2010) to >100 mm after the eruption of Pacaya in 2010 (Fig. 4). This range in thickness can be attributed to infrastructure design, tephra properties and the operational practices of the particular electrical supply providers. In some instances cleaning can be undertaken whilst components are energised, reducing the need to shut down and limiting disruption (Wardman et al., 2012c), however, controlled shutdowns may be necessary in order to protect equipment and personnel (Sword-Daniels et al., 2011) (Fig. 4). Controlled shutdowns will cause supply disruptions unless there are redundant networks capable of supplying electricity whilst cleaning is being undertaken.

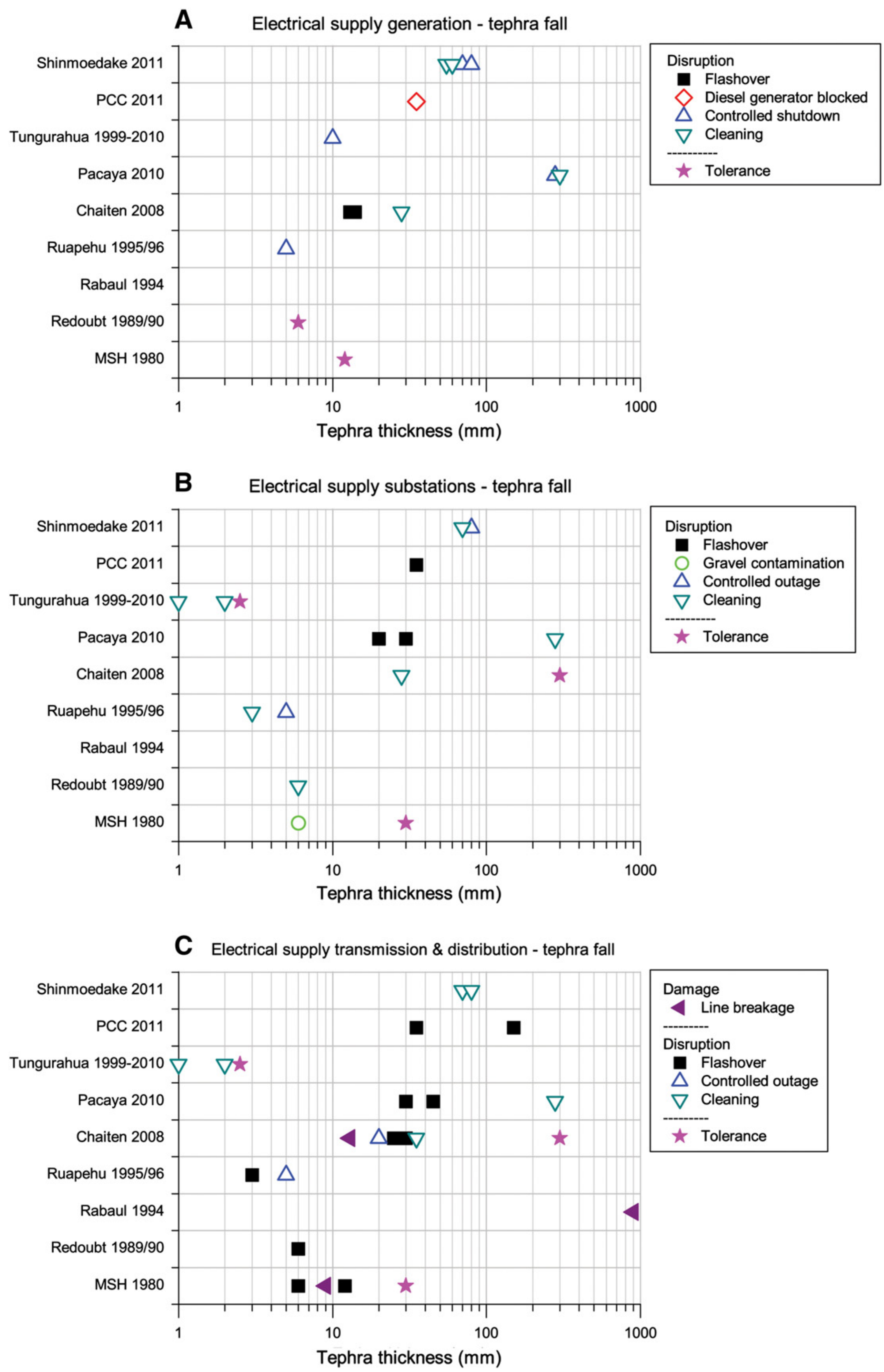


Fig. 4. Summary of documented tephra fall impacts and disruption to the electrical network as a function of tephra thickness for (A) generation, (B) substations and (C) transmission and distribution (modified from Wardman et al., 2012c). Note: only data where tephra thickness is known or derived are plotted.

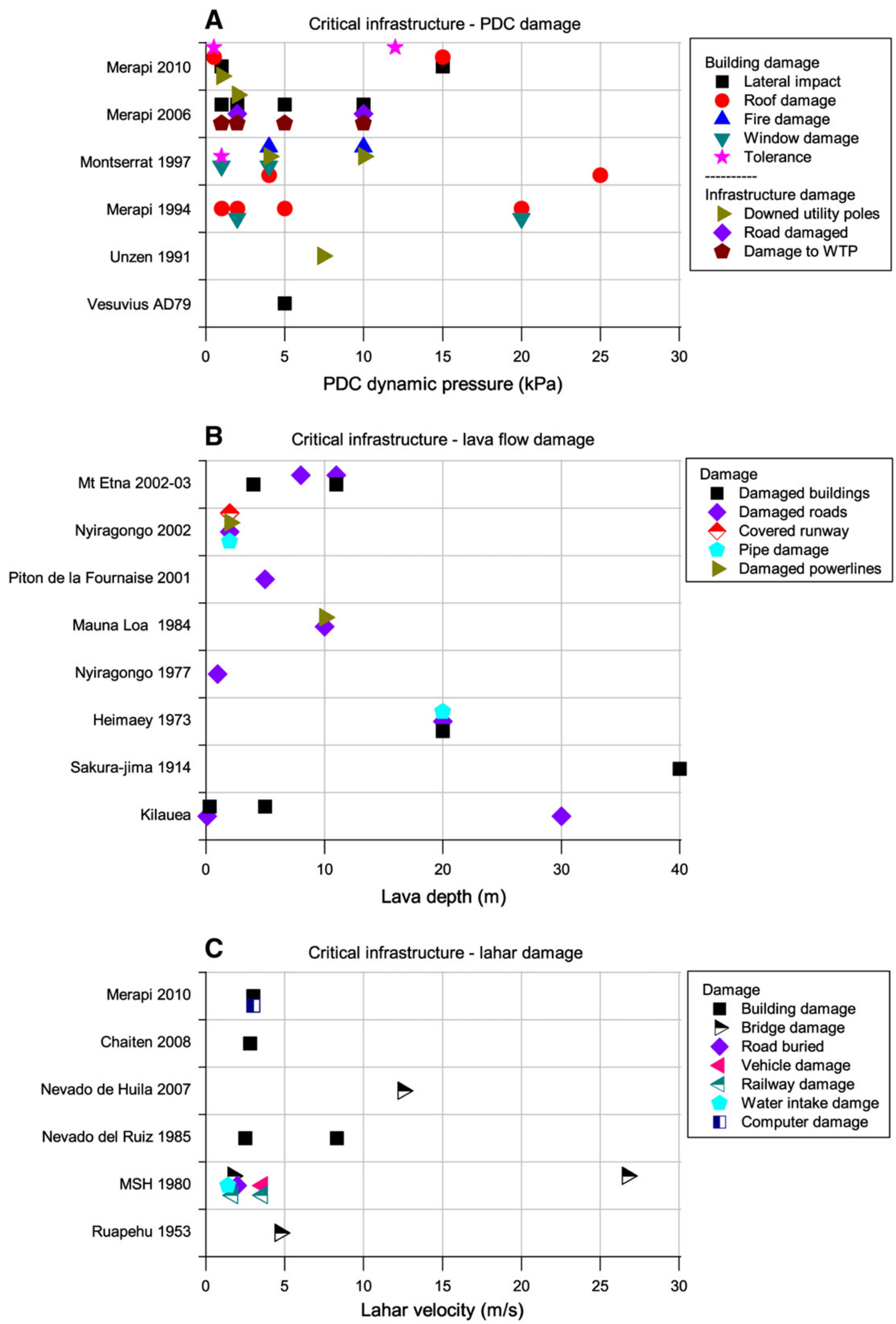


Fig. 5. Summary of documented critical infrastructure impacts from (A) PDCs, (B) lava flows and (C) lahars as a function of hazard intensity. Note: only data where tephra thickness is known or derived are plotted.

3.2. Water supply networks

Water supply networks are comprised of water source, water treatment and storage sites as well as a vast distribution network of mostly underground pipes. There are numerous vulnerable components throughout the network that can be impacted by volcanic hazards (Fig. 3B). The majority of documented impacts to water supply are due to tephra falls causing disruption and minor damage (Fig. 7A). The less frequent volcanic flow impacts tend to cause physical damage (Fig. 5). Stewart et al. (2009b) group impacts to water networks into

Fig. 6. (A) Abrasion damage to a turbine removed from the Agoyan hydro electric power station, Ecuador as a result of exposure to tephra laden water derived from the 1999–2010 eruptions of Volcán Tungurahua (photo: Johnny Wardman). (B) Houses covered with a thin layer of tephra after the eruption of Mt. Kelud on February 14, 2014 (photo: Dwi Oblo). (C) personnel cleaning tephra from the Bariloche, Argentina water treatment plant after the June 4, 2011 eruption of PCCVC (photo: Carol Stewart). (D) Laboratory experiments to determine the settling rate of tephra in water. Each beaker contains a different tephra and shows the turbidity after 1 h of settling (photo: J White).

three categories: (1) direct physical damage; (2) changes in water quality; and (3) water demand issues which are very much controlled by system design. We follow this structure here.

3.2.1. Physical damage

Physical damage to water supply networks tends to be caused by volcanic flows, heavy tephra falls and prolonged exposure to tephra. Volcanic flows have caused complete destruction of water supply infrastructure as a result of increased lateral loading (Fig. 5). Groundwater well heads, springs, reservoirs and pipes were damaged around Montserrat by PDCs (Howe, 2003) and lahars (CDERA, 2006) during the 1995 eruption of Soufrière Hills volcano. Water pipes have been damaged and buried by lahars around Mayon volcano, Philippines (Nasol, 2001; Smithsonian Institution, 2002) and by lava flows in Goma, DRC after the 2002 eruption of Nyiragongo (Smithsonian Institution, 2001; Baxter and Ancia, 2002). These examples show that water supply infrastructure located above ground in or near flow paths (i.e., river valleys) are vulnerable to damage from volcanic flows at low hazard intensities (Fig. 5).

Direct tephra falls or exposure to tephra–water slurries (such as those in pipes) can cause minor physical damage in the form of abrasion of moving parts (e.g., pumps, motors) and corrosion of metals. Damage of this nature is documented after numerous eruptions (Stewart et al., 2006; Wilson et al., 2012b) and is attributed to tephra thicknesses exceeding 30 mm (Fig. 7A), however duration of exposure is the primary control on this type of damage, which is difficult to establish in these cases. Tephra-induced damage reduces pumping efficiency which leads to reduction in production and distribution capacity and increased maintenance and/or repair of pumps and pipes.

3.2.2. Disruption to water treatment

Disruption and increased maintenance from tephra falls are more common than physical damage (Wilson et al., 2012b). Treatment disruption occurs when there is partial to complete blockage of water intakes, filters and pipes, as these have to be cleaned before normal operation can resume (Fig. 6C). These impacts can occur at tephra thicknesses >1 mm (Fig. 7A). This can be illustrated from a case study from the 2011 eruption of the Puyehue–Cordón Caulle volcanic complex (PCCVC), Chile. During this eruption the town of Bariloche, 100 km from the vent, received 30–45 mm of tephra and the town of Jacobacci, 240 km from the vent, received 50 mm of tephra (Wilson et al., 2013). The Bariloche plant was designed for low levels of suspended solids and raw water passed directly through the sand filters. During the eruption, tephra laden water blocked the filter pore spaces requiring additional daily cleaning to return filter functionality and water treatment capacity (Wilson et al., 2013). In contrast, in Jacobacci water supplies were resilient to disruption as all pumphouses were enclosed and water is sourced from groundwater wells (Wilson et al., 2013). This example illustrates that system design will affect impact occurrence and severity (Stewart et al., 2009b).

3.2.3. Water quality impacts

Raw and treated water within water supply networks can also be impacted by volcanic hazards and requires consideration in vulnerability assessments. We refer the reader to Stewart et al. (2006, 2009a, 2009b) and Wilson et al. (2012b) for in-depth reviews.

Water quality impacts occur when tephra, from either tephra falls or PDCs, enters water source areas or treatment facilities (Fig. 3B). Tephra

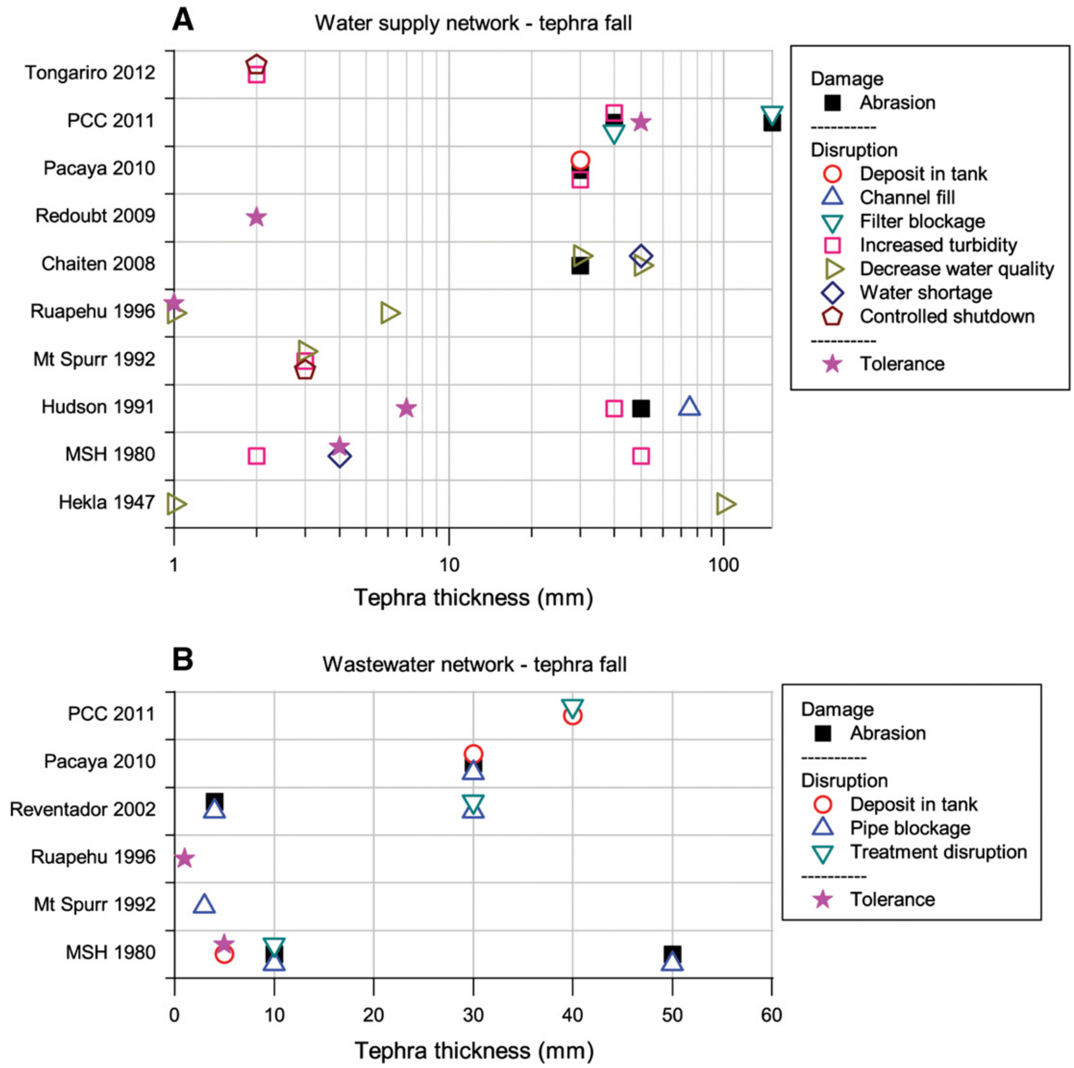


Fig. 7. (A) Summary of documented tephra fall impacts and disruption to (A) the water supply network and (B) the wastewater network as a function of tephra thickness. Note: only data where tephra thickness is known or derived are plotted.

will cause an increase in turbidity (cloudiness of water caused by suspended particles) at tephra thicknesses >2 mm (Figs. 6D and 7A) (Stewart et al., 2006). Chemical contamination of water occurs as soluble surface coatings on fresh tephra particles dissolve readily upon contact with water, releasing a range of ions (Witham et al., 2005; Delmelle et al., 2007). Increased ion concentration may breach drinking water standards, however this is usually only for short time periods (Stewart et al., 2009a). Chemical contamination of water supplies from tephra fall is difficult to predict prior to an eruption due to variability in soluble salt and water chemistry, however it can occur at tephra thicknesses >1 mm (Fig. 7). Turbidity and chemical contamination are commonly controlled though management practices (Stewart et al., 2009b), however if turbidity becomes too high to treat effectively, the treatment plant may have to be shut down. This occurred at the Ship Creek treatment facility in Anchorage which received 3 mm of tephra and was shut down for 30 h as a precaution following the 1992 eruption of Mt. Spurr, Alaska (Wilson et al., 2012b).

3.2.4. Water shortages

After tephra falls, clean-up is commonly undertaken by washing away unconsolidated deposits placing large demands on water resources (Wilson et al., 2012b). In 1992 Anchorage, Alaska was covered with 3 mm of tephra from the eruption of Mt. Spurr. After residents began cleaning tephra deposits, there were severe water shortages and loss of pressure in some parts of the city (Stewart et al., 2009b). In contrast, successful management of water supply occurred in Esquel, Argentina during the eruption of Volcán Chaitén in 2008. During residential clean-up supply exhaustion was avoided as authorities advised residents to use alternative ‘dry’ clean-up methods such as use of brooms and shovels (Stewart et al., 2009b).

3.3. Wastewater treatment networks

Wastewater networks comprise an underground network of pipes and pumps and above ground treatment facilities (Fig. 8A). Wastewater networks may be combined with stormwater systems or the two may be completely separate. Combined wastewater and stormwater systems are more vulnerable to impacts than separate systems because unconsolidated tephra can easily enter the network through stormwater drains (Barnard, 2009).

3.3.1. Physical damage

There is limited documented evidence of volcanic flows directly impacting wastewater treatment facilities, except in the case of Plymouth, Monserrat in which the entire town was destroyed by pyroclastic flows from Soufrière Hills volcano in 1997 (Rozdilsky, 2001). Abrasion

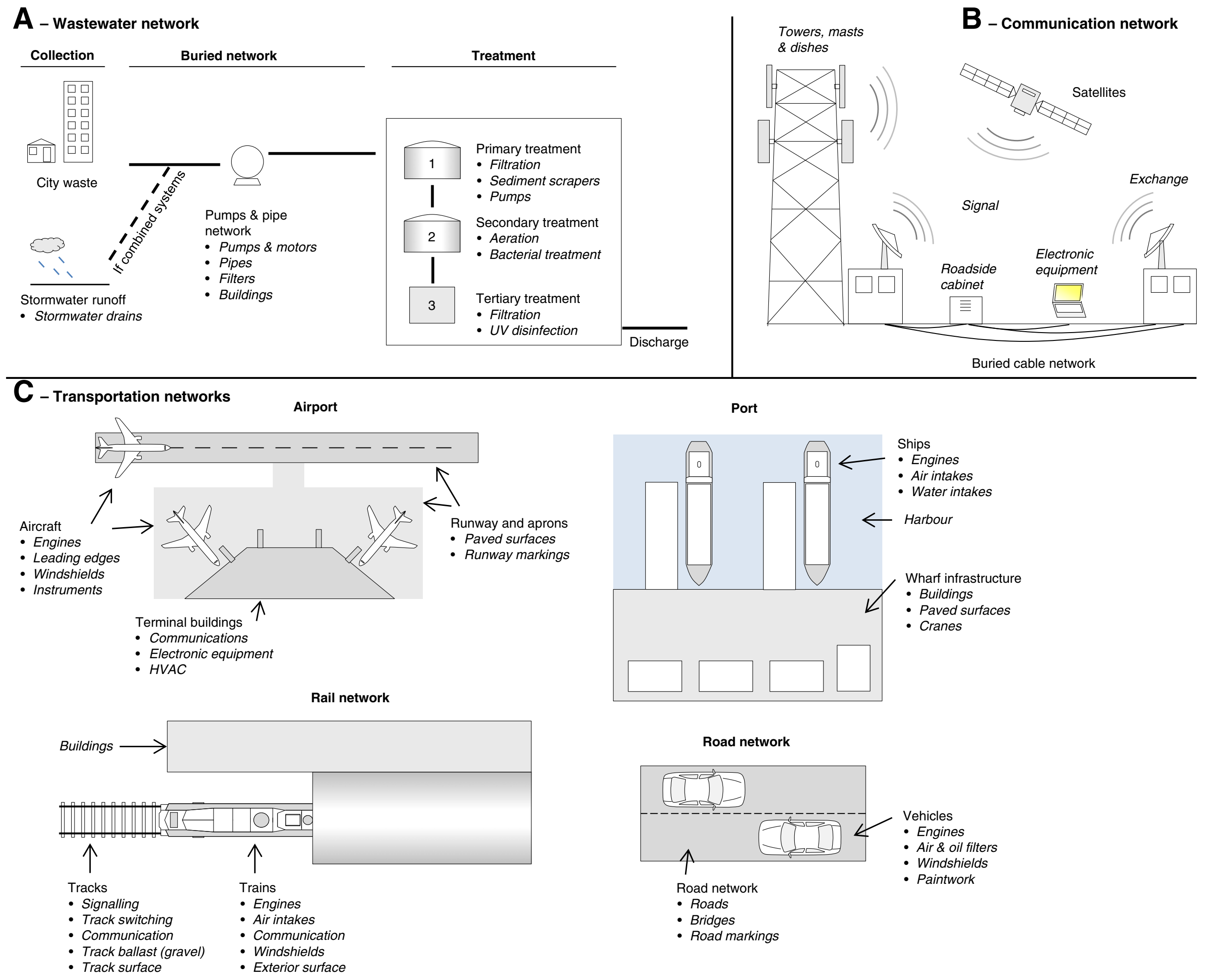


Fig. 8. Schematic of (A) wastewater and stormwater collection and treatment network, (B) typical components used within communication networks and (C) air, rail, sea and road transportation networks and vehicles. Components vulnerable to volcanic hazards are indicated in italics.

damage to pumps, pipes, sediment scrapers, filtration components and debris screens may occur as tephra laden slurries pass through these components (Blong, 1984; Johnston, 1997; Barnard, 2009) again occurring over extended periods of time. Eruptions from Mt. St. Helens (1980), El Reventador, Ecuador (2002) and Pacaya (2010) show abrasion damage occurring over tephra thicknesses ranging from 4–50 mm Fig. 7B.

3.3.2. Treatment disruption

Wastewater treatment can be disrupted if tephra is deposited directly onto treatment facilities as the capacities of open ponds, reactors and clarifiers will be reduced (Fig. 7B) (Wilson et al., 2012b). For example, disruption occurred during the 2010 eruption of Pacaya volcano when a combined sludge and sedimentation tank in Guatemala City was filled with 4–5 m of tephra and had to be cleaned before continued operation (Wilson et al., 2012b). Tephra can form large hardened and unpumpable masses within the pipe network which require manual removal (Wilson et al., 2012b). Fig. 7B suggests that pipe blockage occurs with tephra thicknesses >3 mm however accumulations larger than this may occur in pipes. Blockages are likely to occur at distinct points and not throughout the entire network.

If treatment disruption and/or damage become excessive, wastewater might have to bypass the system and be discharged into the environment as untreated waste. This decision was made at the Yakima waste treatment facility, USA after it received 10 mm of tephra from the 1980 Mt. St. Helens eruption (Blong, 1984). Tephra caused damage to most of the treatment facility including the biofilters and a decision was made four days after the eruption to bypass treatment and discharge waste, after chlorination, into the Yakima River (Barnard, 2009). The decision was made because continued operation of the plant would have caused greater damage and more periods of discharge would have occurred in the future.

3.4. Transportation networks

Transportation networks can be vast and cover large expanses of the landscape, increasing their exposure to volcanic hazards similar to electrical networks (Fig. 8C). Volcanic hazards have been documented adversely affecting all transportation systems (e.g., road networks, vehicles, rail tracks, trains, ports, ships, airports; Figs. 5 and 9A). Additionally, a number of cascading impacts may occur, not discussed here, affecting other sectors which rely on transportation, as well as possible evacuation and emergency response during a volcanic crisis.

3.4.1. Road networks and vehicles

3.4.1.1. Physical damage. Volcanic flows can cause physical damage to road networks (Fig. 5). Perhaps the best known example of this was

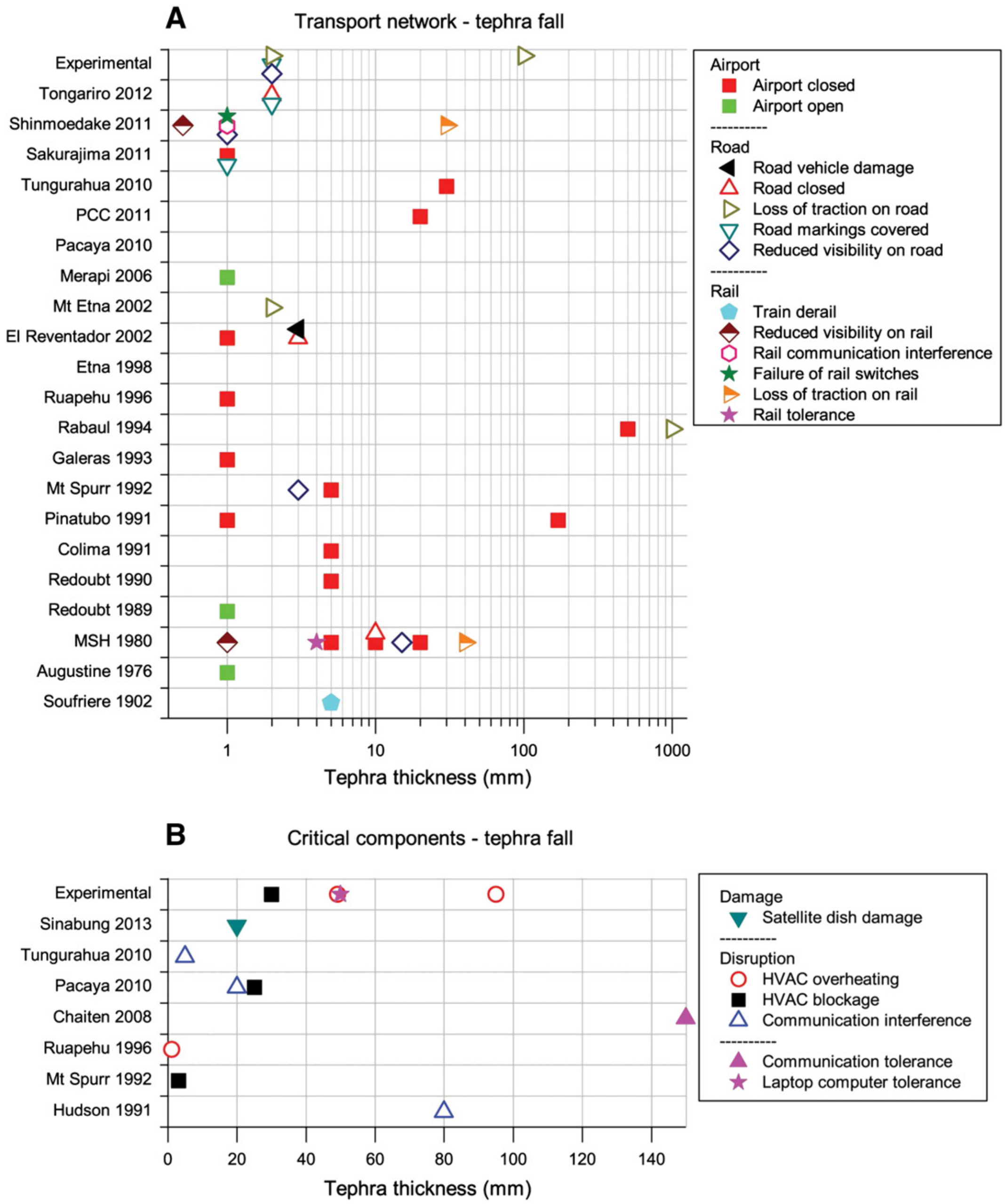


Fig. 9. Summary of documented tephra fall impacts and disruption to (A) the transportation network and (B) critical components and communication equipment as a function of tephra thickness. Note: only data where tephra thickness is known or derived are plotted.

after the 1980 eruption of Mt. St. Helens where lahars and PDCs caused extensive damage or destruction to 300 km of road and 48 bridges in the valleys draining the volcano (Blong, 1984). Bridges are particularly vulnerable as they generally cross flow paths and can be damaged by scouring around abutments and piers and lateral loading (Nairn, 2002). Roadways located on flow channel banks are vulnerable to undercutting by lahars. For example, three months after the 2010 eruption of Merapi volcano, Indonesia, a lahar eroded a 60 m section of a major highway causing its closure (Smithsonian Institution, 2011).

Lava flows, regardless of depth, cause irreparable damage to roads around the world by simply crossing them (Fig. 5B). Since the early 1900s, numerous roads in Hawaii have been covered by lava from eruptions of Mauna Loa and Kilauea (Blong, 1984; Hawaiian Volcano Observatory, 1998b, 2000). Thin (<1 m) flows buried a main road in Goma during the 1977 Nyiragongo eruption, DRC (Blong, 1984) and again during the 2002 eruption (Baxter et al., 2003). Sections of roads along the western and southern flanks of Mt. Etna, Italy have been buried numerous times by lava flows (Smithsonian Institution, 1999; Andronico et al., 2005). These examples indicate that lava flows conform to a binary impact model based on the presence or absence of lava.

PDCs can move, overturn, burn and/or impact vehicles located in flow paths. For example, vehicles within 15 km of Mt. St. Helens were totally destroyed by the 1980 eruption (Blong, 1984). During the September 1991 Unzen, Japan eruption, a vehicle sustained extensive panel damage, was burnt and transported 120 m by PDCs (Fujii and Nakada, 1999). Lahars are also likely to completely damage vehicles as they are carried downstream whilst being impacted by debris (Blong, 1984); however reports are limited. Tephra particles can damage vehicles by abrading moving parts and blocking air and oil filters (Wilson et al., 2012b). Windshields and paintwork are highly susceptible to abrasion from tephra, which can be made worse by attempting to clean these surfaces. Despite possible damage, resilience has also been

Fig. 10. A sequence of photos, from left to right, showing the remobilisation of tephra and decrease in visibility from a passing car as the car travels towards the observer near Volcán Chaitén after the 2008 eruption.
Photos: G Leonard.

documented. For example, in Yakima, USA, after the 1980 Mt. St. Helens eruption, 30 police cars which were used during tephra falls suffered no long term damage, other than increased oil change frequency (Blong, 1984).

3.4.1.2. Disruption. Decreased road drivability in the form of traction loss, covered road markings and poor visibility (Fig. 10) can result from tephra fall or remobilised unconsolidated tephra deposits (Nairn, 2002; Leonard et al., 2005; Wilson et al., 2012b). These impacts start to occur at thin (~2–3 mm) tephra thicknesses (Fig. 9A). Disruption may increase as authorities close roads, limit the number of circulating vehicles or lower the speed limit to decrease the likelihood of traffic accidents and limit tephra remobilisation. Clean-up operation following tephra fall will restore road drivability although it may be possible to drive on thick tephra deposits as they become compacted over time.

3.4.2. Rail network and trains

3.4.2.1. Physical damage. Rail bridges are vulnerable to lahar damage as they are likely to cross lahar paths. In 1953, a lahar travelled down

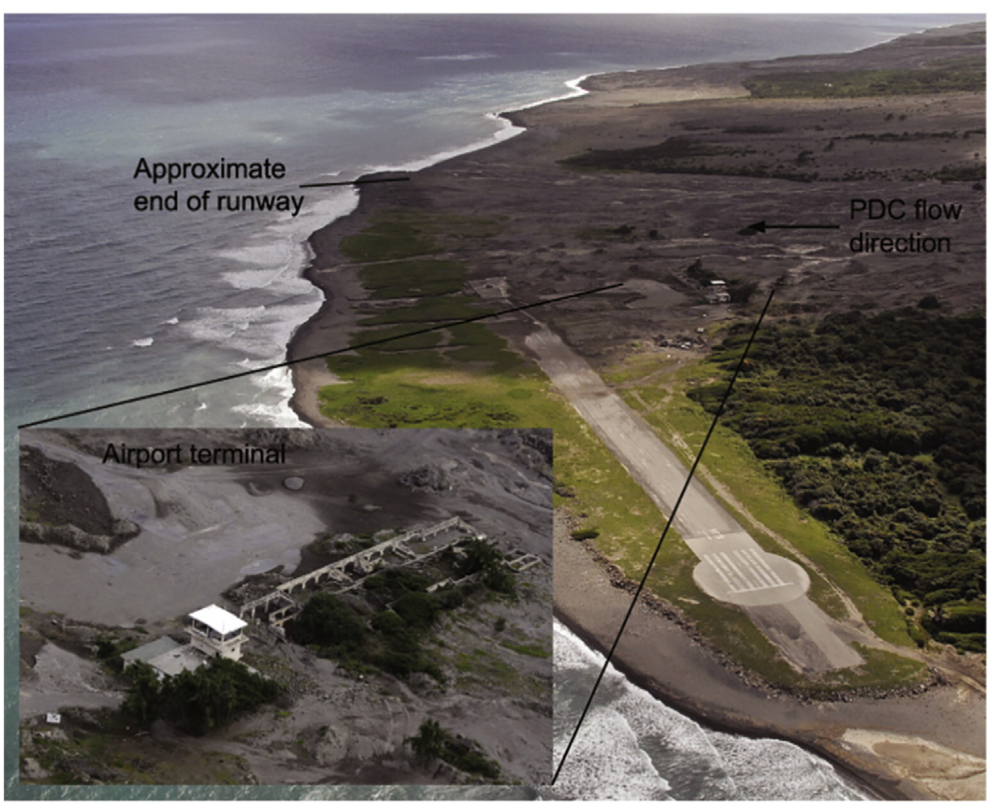


Fig. 11. Burial and destruction of the runway and terminal building at the W. H. Bramble Airport, Montserrat by a PDC during the 1997 eruption of Soufrière Hills. The runway has since been completely buried and abandoned.
Photos: Brian Digital.

the Whangaehu River on the slopes of Mt. Ruapehu, New Zealand and collapsed part of the Tangiwai rail bridge minutes before a passenger train arrived (Scott, 2013). The train derailed and plunged into the river; 151 people were killed. Valentine (1998) studied damage from nuclear weapon blasts and inferred that PDC damage to trains and rail tracks will occur at dynamic pressures >10 kPa. Lava flows have blocked, covered and damaged railway lines numerous times in the 1900s around Mt. Etna and Mt. Vesuvius, Italy rendering them unusable (Blong, 1984). It is likely that railways lines covered by lava flows of any depth will result in complete localised damage.

3.4.2.2. Disruption. Disruption to the rail network is most likely from tephra fall. The best documented example of tephra fall impacting rail networks is the 2011 Shinmoedake eruption in Japan. Here 168 km of track and 48 stations were impacted by tephra, causing delays and cancellations (Smithsonian Institution, 2010; Magill et al., 2013). The main issues were the mechanical failure of track switches and loss of electrical contact between the track and train (Fig. 9A), which in this rail network is how communications are sent to the train operator. Problems did not begin at a particular critical threshold, and therefore a zero tolerance policy was adopted with services cancelled until tephra was removed (Magill et al., 2013). Track ballast (crushed gravel used to support tracks) was infiltrated by tephra, reducing its cushioning properties and required frequent replacement. Tephra also infiltrated train carriages, requiring additional cleaning. Damage was minimised by suspending services in ashy conditions (Magill et al., 2013).

3.4.3. Ports and ships

Lahars and PDCs can affect harbours or water bodies due to increased sedimentation. The most notable example occurred in the Columbia Shipping Canal, USA after the 1980 Mt. St. Helens eruption. Lahar deposits filled it and reduced its capacity by 85%, rendering the canal effectively unusable (Blong, 1984), affecting the economy in the Pacific Northwest. Lava flows have also affected ports, the best known event is the 1973 Eldfell eruption in Heimaey, Iceland. Lava threatened to block the harbour entrance, however, an extensive lava cooling operation successfully prevented this from occurring (Williams and Moore, 2008).

Ships may sustain damage, such as abrasion of moving parts and clogging of air filters and water intakes during tephra falls (Wilson et al., 2012b). Vesiculated tephra (pumice and scoria) can float on water creating a pumice raft, which may be ingested into ship water intakes (Wilson et al., 2012b) and/or disrupt shipping routes. There are

Fig. 12. (A, B) Extensive damage to a school in Chaitén town, Chile from a lahar after the 2008 eruption of Volcán Chaitén. Two exterior walls have been completely removed and the ground around the foundations has been scoured. (C) Burial of a building, up to window level, in Chaitén town from a lahar after the 2008 eruption of Volcán Chaitén. A power pole is also damaged. (D) A building in Chaitén town, inundated by a lahar after the 2008 eruption of Volcán Chaitén.
Photos: G Leonard.

instances of resilience, for example, during the 2008 eruption of Okmok Volcano, Alaska several boats received minor tephra fall with no impacts other than damage to one air filter (Neal et al., 2011).

3.4.4. Airports

3.4.4.1. Physical damage to airports. Volcanic flows can completely destroy airports if they are located near river valleys or flood plains. During the 1997 eruption of Soufrière Hills volcano, Montserrat, the W. H. Bramble Airport was overrun and completely destroyed by PDCs (Guffanti et al., 2009) (Fig. 11). Likewise, after the 2008 eruption of Chaitén volcano, lahars completely buried the Chaitén airport runway and inundated many associated buildings; the airport subsequently closed (Pallister et al., 2010). A temporary airport runway was established on a widened road to restore flights to the area. The runway at Goma International Airport, DRC was inundated by lava during the 2002 Nyiragongo eruption, reducing the runway's length by 1 km, however it is still usable for smaller sized aircraft (Baxter and Ancia, 2002).

Damage to aircraft in flight is well documented and includes: loss of engine thrust as a result of tephra ingestion and adherence to turbine blades; and abrasion of turbine blades, windshields, leading edges, protruding probes and sensors. We refer the reader to Casadevall (1994), the International Civil Aviation Organization (2007), Guffanti et al. (2010), Dunn (2012) and Drexler et al. (2011) for comprehensive reviews of tephra related damage to aircraft.

3.4.4.2. Disruption to aviation. Trace (~1 mm) quantities of tephra deposited on runways, taxiways and aprons can reduce visibility, cause loss of traction, interrupt ground services and damage parked aircraft (Guffanti et al., 2009) (Fig. 9A). When these impacts occur, airports typically close due to flying safety regulations leading to widespread disruption. Because such thin tephra deposits can close airports, airports located in distal areas may also be affected resulting in widespread airport closure and travel disruption. In addition, the presence of tephra in the atmosphere can force the closure of airspace or the re-routing of travel routes. For example, during the 2010 eruption of Eyjafjallajökull volcano, Iceland, European and North Atlantic airspace was closed for six days in April 2010 to prevent potential aircraft damage and limit risk to life (Sammonds et al., 2010).

3.5. Communication networks

Communication networks are typically expansive and comprise a wide range of components in many different network configurations (Fig. 8B).

3.5.1. Physical damage to communication equipment

Volcanic flows are likely to cause considerable damage to communication infrastructure (e.g., tower, poles, lines) if they are situated in flow paths or in areas close to the volcano, however evidence is scarce. During the 1991 Unzen eruption, numerous utility poles were broken at their bases after being impacted by PDCs (Clarke and Voight, 2000).

3.5.2. Disruption to communication equipment

Theoretically tephra particles may cause communication signal attenuation and interference as it is known that dust storms cause this type of disruption (e.g., Saleh and Abuhdima, 2011). A review by Wilson et al. (2009) suggest that tephra induced signal attenuation may preferentially affect low frequency (30–300 kHz) services. Signal interference has been reported during tephra falls from Pacaya volcano, Guatemala (Wardman et al., 2012a), Tungurahua volcano, Ecuador (Sword-Daniels et al., 2011), Mt. Hudson, Chile (Wilson et al., 2011) and Merapi volcano, Indonesia (Wilson et al., 2007) (Fig. 9B), however these occurrences are poorly documented. In contrast, cellular and ultra high frequency networks and telemetered sites operated without interruption in Futaleufú, Chile, which received >150 mm of tephra during the 2008 Chaitén eruption (Wilson et al., 2012b).

3.6. Critical components

We define critical components as those that are integral to most critical infrastructure sectors such as heating, ventilation and air conditioning (HVAC) systems and electronic equipment. HVAC systems are used in most critical infrastructure sectors for internal environmental control,

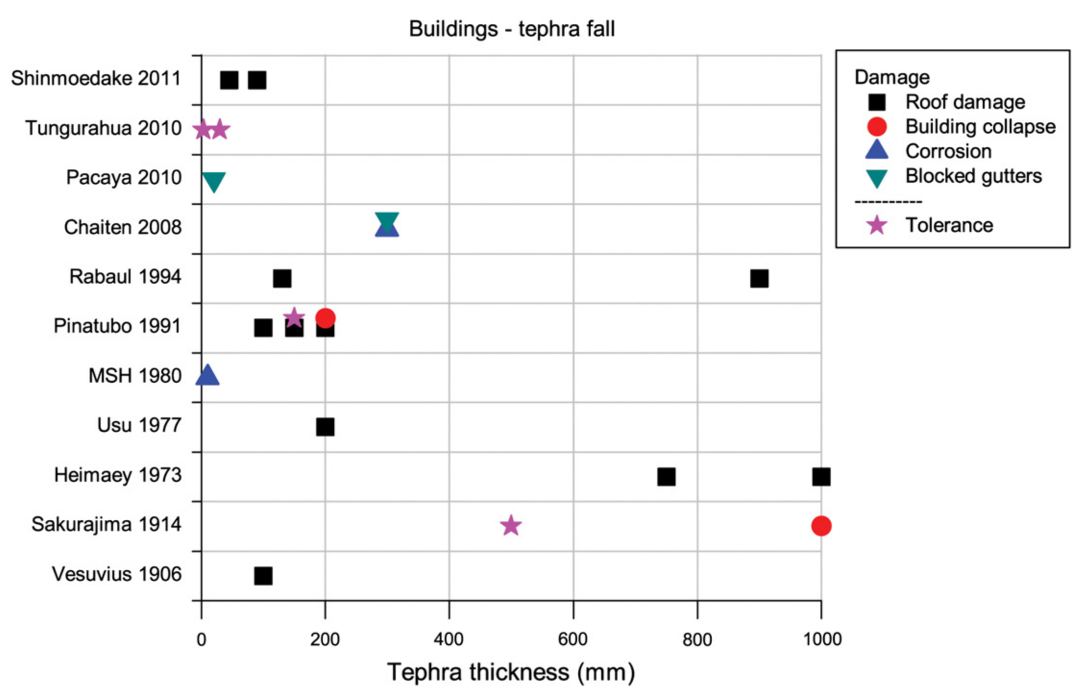


Fig. 13. Summary of documented tephra fall impacts to buildings as a function of tephra thickness. Note: only data where tephra thickness is known or derived are plotted.

and to also keep equipment within normal operating temperatures (Wilson et al., 2012b).

3.6.1. Physical damage to critical components

The majority of HVAC and computing systems are physically small and therefore very likely to be completely destroyed and carried away by volcanic flows. In addition, the high temperatures of PDCs and lava flows will likely melt plastics and the wet nature of lahars will cause electrical short circuits. The only documented case that specifically mentions volcanic flow impacts to electronics is de Bélizal et al. (2013) who describe a lahar from Merapi volcano destroying a house in which all electronic equipment was lost and/or destroyed. Tephra particles can cause abrasive damage to moving components such as cooling fans, potentially resulting in fan failure. Abrasion is more likely to occur with fine tephra particles that can penetrate fan bearings and will occur over a long period of time (Barnard, 2009; Wilson et al., 2012a).

3.6.2. Disruption to critical components

Filters and fans are particularly vulnerable to blockage from tephra fall as these components are in direct contact with the atmosphere (Wilson et al., 2012a) (Fig. 9B). These impacts may result in

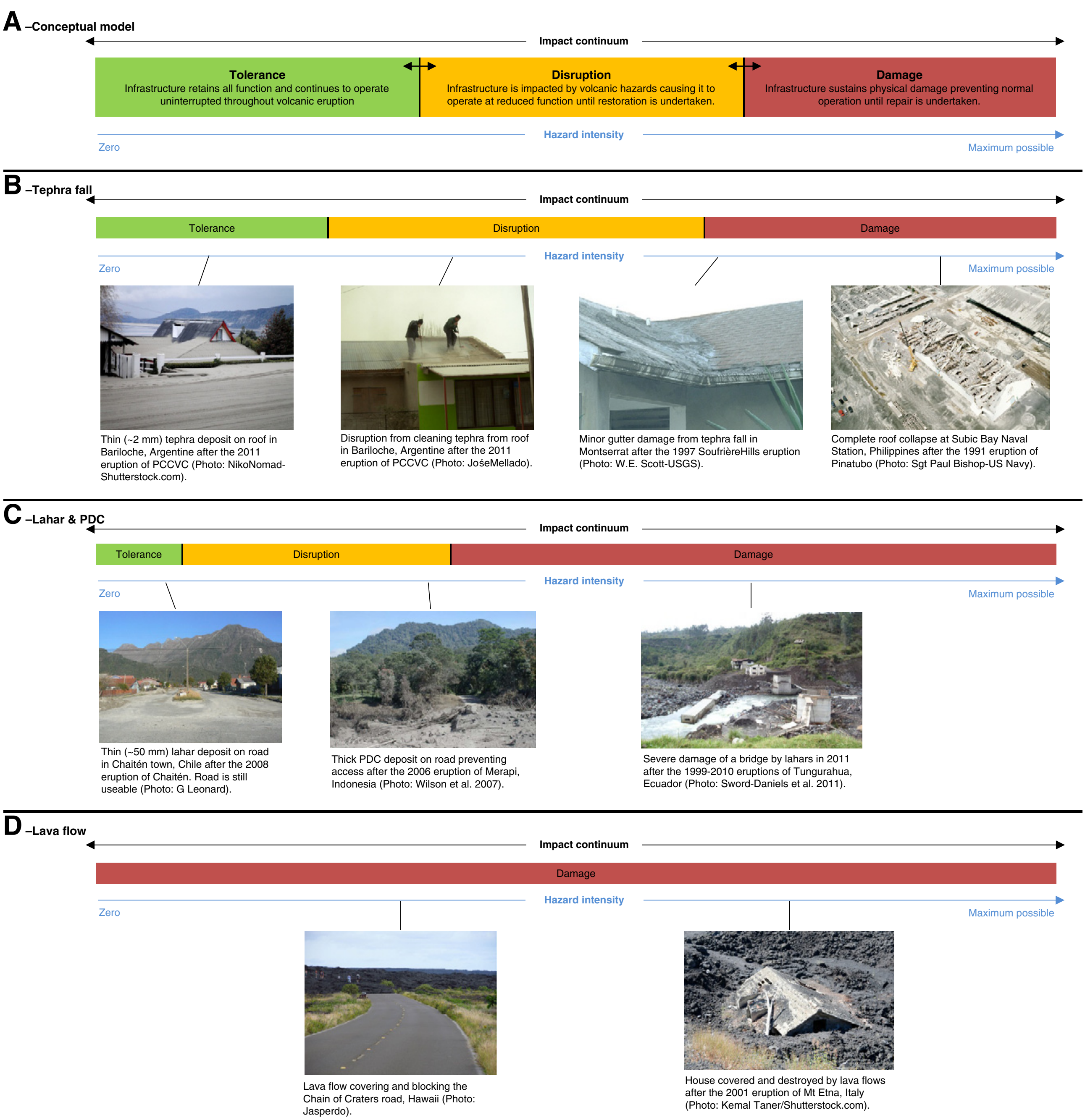


Fig. 14. (A) Conceptual model of the continuum of impacts to critical infrastructure observed as a function of hazard intensity. Boundaries between impact severities (tolerance, disruption and damage) will occur at different hazard intensities for different volcanic hazards and for different critical infrastructure components and system designs. Generalised examples of the range of each impact severity (tolerance, disruption and damage) as a function of hazard intensity for (B) tephra falls, (C) lahars and PDCs, and (D) lava flows assuming generic infrastructure design.

overheating and shutdown of HVAC and electronic equipment, causing disruption to services. During the 1992 Mt. Spurr, Alaska eruption, tephra fall (3 mm) blocked a number of HVAC system filters. Fortunately no electronic equipment overheated due to the cool ambient temperatures in Anchorage at the time (Wilson et al., 2012b). Computers may also suffer from jamming of mechanical components and keyboards and overheating under a thick covering of tephra (Gordon et al., 2005; Wilson et al., 2012a). Generally disruption appears to be temporary as once tephra has been removed from the components, functionality is restored (Wilson et al., 2012a).

3.7. Buildings

Buildings and other similar structures can be impacted by all volcanic hazards considered here. Buildings may experience no or light physical damage through to complete destruction. We review structural damage from increased lateral and static loads, fire, abrasion and corrosion. We refer the reader to Baxter et al. (2005) and Jenkins et al. (2014a) for a detailed review of building impacts for tephra fall and PDC hazards.

3.7.1. Physical damage from lateral loads

Volcanic flows cause extensive damage to buildings located in and near flow paths (e.g., de Bélizal et al., 2013) (Fig. 5). Historic eruptions at Mt. Vesuvius (79 AD) and Mt. Pelée, Martinique (1902) and the recent eruptions at Mt. St. Helens (1980), Unzen volcano (1991) and Merapi volcano (1994, 2006, 2010) demonstrate that PDCs cause substantial damage to buildings and structures (Fig. 5A). Lahars generated during and after the eruptions of Mt. Pinatubo (1991) and Chaitén (2008) flowed into populated areas, causing considerable destruction and burial of buildings (Janda et al., 1996; Pierson et al., 2013) (Fig. 12) and large economic losses (Mercado et al., 1996). The principal damaging mechanism of these flows is increased lateral loads. If lateral loads are greater than the strength of a building's walls and roof (depending on the flow height) structural damage will result and in the worst case the building will collapse. Windows and doors are the most vulnerable components in a building as they have low resistance to lateral loads and are easily damaged by entrained debris impacts (Baxter et al., 2005; Spence et al., 2007). Shielding of buildings by topography and other buildings can affect damage distribution (Zuccaro and Ianniello, 2004).

Lava flows are less energetic than PDCs and lahars and cause damage to buildings due to their considerable mass and ‘bulldozing’ action (i.e., lava flows can push buildings over) (Fig. 5B). Weaker buildings and those located in lava flow paths or on the flanks of the volcano are most vulnerable and sustain the highest degree of damage. Numerous volcanoes have produced lava flows that have caused damage to buildings, including Mt. Vesuvius, Mt. Etna, Nyiragongo volcano, Kilauea, Sakura-jima and Heimaey (Blong, 1984). Attempts have been made to lessen the impacts of lava flows through water cooling of flows (e.g., Heimaey, 1973: Williams, 1997) and by diverting flows with barriers (e.g., Mt. Etna, 2001: Barberi et al., 2003) with varying levels of success.

3.7.2. Physical damage from static loads

Tephra falls can cause damage to buildings by increased static load as a result of tephra accumulation (Fig. 13). High intensity tephra falls (>100 mm) can increase the static load on a building's roof and if it exceeds the load carrying capacity, damage or collapse may occur (Spence et al., 1996) (Fig. 13). Damage and indeed tolerance to damage is dependent on building typology and maintenance, tephra density, thickness and moisture content, as water will increase bulk density and therefore tephra load (Johnston, 1997). During the 1973 Heimaey eruption numerous houses with flat roofs suffered collapse following accumulation of ~1 m of dry tephra (Blong, 1984). In contrast, during the 1991 Mt. Pinatubo eruption, ~200 mm of wet tephra was sufficient to cause severe roof damage to ~50% of the building stock in the town of Castillejos, whilst the remaining 50% of buildings sustained no or minor damage (Spence et al., 1996). Tephra removal may exacerbate roof damage due to increased static load from people on the roof (Jenkins et al., 2014a). Buildings in close proximity to the volcano are most vulnerable to structure damage as this is commonly where high intensity tephra accumulations occur.

Non-structural components such as gutters and roof overhangs are vulnerable to increased static loads. Because these elements were not designed to withstand large loads, they will sustain damage first during low intensity tephra fall.

3.7.3. Other impact mechanisms

Fire can also cause damage to buildings following PDCs, lava flows and hot tephra particles. PDCs comprise of hot gases and particles and if these infiltrate a building fires can be ignited. In addition, lava flows have temperatures above the ignition point of common construction materials and therefore can ignite fires causing damage to many buildings. In most cases if buildings are not destroyed by lava flow impact, they will be destroyed by fire (Blong, 1984). Flow deposits may also bury buildings causing further damage and preventing access (Fig. 12).

Abrasion of exterior elements such as windows and cladding may occur as a result of tephra falls, PDCs or lahars however damage is likely to be aesthetic. In addition, prolonged tephra exposure, in the presence of water, may cause corrosion damage to metal roofs and gutters (Oze et al., 2013).

4. Characteristics of impacts to critical infrastructure

Empirical data of impacts to critical infrastructure presented above (Section 3) suggests that primary impacts occur on a continuum from causing disruption to complete damage (Fig. 14). The hazard intensity window over which disruption and damage occurs is dependent on hazard type and characteristics, infrastructure design and any preparedness and response actions (Fig. 14). However, disruption resulting from tephra fall, PDC and lahar hazards tends to occur at low hazard intensities where there is insufficient intensity to cause damage. Physical damage results at higher hazard intensities. In contrast, lava flows rarely cause disruption to critical infrastructure systems and tend to cause damage at all intensities (Fig. 5). Secondary disruption will also result from physical damage to infrastructure components. A semi-quantitative analysis of infrastructure impacts (Fig. 15), which draws upon impact data from Figs. 4, 5, 7, 9, and 13 shows that tephra falls tend to cause disruption type impacts and less damage, whilst volcanic flows cause high levels of both damage and associated secondary disruption. The solid line in

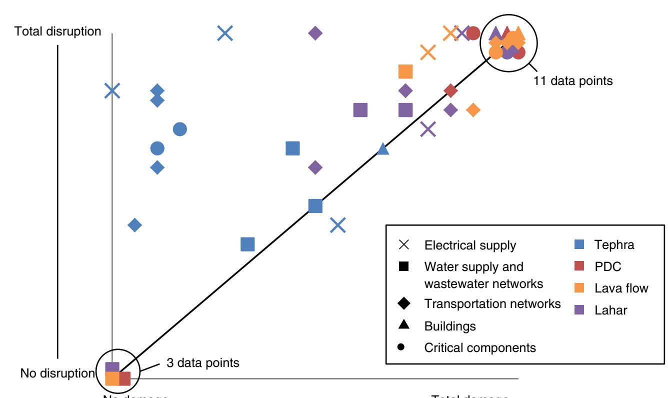


Fig. 15. Relationship between critical infrastructure disruption and damage for investigated eruptions (1973–2011) as a result of tephra fall (blue), PDC (red), lava flow (orange) and lahar (purple). Black line shows an idealised 1:1 relationship between disruption and damage, where disruption are impacts that occur prior to the onset of physical damage and damage are impacts that occur as a result of direct physical damage (Section 3).

Table 7
Relevant tephra fall hazard intensity metrics for each infrastructure sector.

Critical infrastructure sector	Tephra fall hazard intensity metrics							
	Thickness	Static load	Particle density	Surface chemistry	Grainsize	Moisture content	Hardness (abrasiveness)	Atmospheric concentration
Electrical supply								
Generation	E			E	e	e	E	
Transmission & distribution	E	e		E	e	E		*t*
Water supply network								
Source	E		*T*	E	e		*T*	
Treatment	E	*T*	E	E	E		E	
Buried network	*t*		*t*		*t*		E	
Wastewater network								
Treatment	E	*T*	E	e	E		E	
Buried network	*t*		*T*		*t*		E	
Transportation network								
Road	E	*t*		e	e		e	e
Air	E	*t*		*t*	e		E	E
Rail	E	*t*		*t*	e		*T*	e
Sea	e	*t*	E	*t*	e		e	*T*
Buildings	E	E		e	*T*	e	*T*	
Communication systems	e	*T*						e
Critical components								
HVAC	E			*T*	E	e	e	*T*
Electronics	E			e	E	E	e	*T*

Abbreviations are: E — strong empirical bases (numerous post-eruption and analytical data); e — weak empirical bases (few post-eruption data); *T* — strong theoretical bases (likely to be relevant but no post-eruption data); and *t* — weak theoretical bases (may be relevant). Refer to Table 1 for definitions of hazard intensity metrics.

Fig. 15 shows the 1:1 relationship between disruption and damage, with those infrastructure that plot above or below this line showing their tendency to preferentially cause one impact type over the other. A limitation of Fig. 15 is that it assumes generic infrastructure design. There are numerous different components, designs and network configurations for such infrastructure systems which may vary within and between cities, regions and countries. Each different infrastructure design can influence vulnerability as each design will be tolerant to different hazard intensities.

In the following subsections we discuss the characterisation of impacts as causing disruption (Section 4.1) or damage (Section 4.2) based upon hazard types and intensities and infrastructure design. We explore how clean-up, exclusion zones, infrastructure design and different hazard properties influence impact type and severity. We finish by developing impact scales, based on hazard intensity thresholds, to estimate vulnerability (Section 4.3.2).

4.1. Disruption impacts to critical infrastructure

Disruption to critical infrastructure can occur as a result of direct interaction with volcanic hazards (Section 4.1.1), as a result of hazard clean-up operations (Section 4.1.2) and from restricted access with the implementation of emergency management exclusion zones (Section 4.1.3).

4.1.1. Critical infrastructure disruption from direct hazard impacts

Examining observed impacts (Section 3) and hazard intensity relationships (Figs. 4, 5, 7, 9, 13) it is evident that most infrastructure sectors can be disrupted by the direct impact of tephra fall, PDCs and lahars. As Fig. 14 shows, disruption tends to occur at low hazard intensities.

During low intensity tephra falls, there appears to be insufficient accumulated tephra mass to induce any increased static loading damage on these infrastructure components and tephra will simply accumulate on exposed components (Fig. 6B). Likewise, for low intensity regions of PDCs and lahars (i.e., flow peripheries) there is insufficient dynamic pressure to cause physical damage to critical infrastructure (Baxter et al., 2005) and deposition will occur. The deposition of unconsolidated tephra in or on components will cause disruption and reduce function by causing blockages (e.g., air and water filters) or limiting access and preventing use of certain infrastructure such as buildings and transportation networks.

In addition, the presence of tephra particles in the atmosphere can cause significant and prolonged disruption for some infrastructure, particularly transportation networks as suspended tephra will reduce visibility and cause abrasion damage, for example, the 2010 eruption of Eyjafjallajökull, Iceland and subsequent closure of European and North American airpace for six days to prevent aircraft damage (Sammonds et al., 2010).

Table 8
Relevant PDC hazard intensity metrics for each infrastructure sector.

Critical infrastructure sector	PDC hazard intensity metrics			
	Dynamic pressure	Velocity	Temperature	Thickness of deposit
Electrical supply				
Generation	*T*	*T*		*T*
Transmission & distribution	E	E	*t*	*t*
Water supply network				
Source	E	E		*T*
Treatment	*T*	*T*		*t*
Buried network	e		*t*	
Wastewater network				
Treatment	*T*	*T*		*t*
Buried network				
Transportation network				
Road	E		*T*	e
Air	E		*T*	*t*
Rail	*T*			*t*
Sea	*t*			*t*
Buildings	E	E	E	e
Communication systems	E	E		*t*
Critical components				
HVAC	*T*	*T*		*T*
Electronics	*t*	*T*	*T*	*T*

Abbreviations are: E — strong empirical bases (numerous post-eruption and analytical data); e — weak empirical bases (few post-eruption data); *T* — strong theoretical bases (likely to be relevant but no post-eruption data); and *t* — weak theoretical bases (may be relevant). Refer to Table 1 for definitions of hazard intensity metrics.

Table 9
Relevant lava flow hazard intensity metrics for each infrastructure sector.

Critical infrastructure	Lava flow hazard intensity metrics					
	Presence of lava	Depth of flow	Dynamic pressure	Velocity	Temperature	Cooling duration
Electrical supply						
Generation	*T*	*T*	*T*	*T*		
Transmission & distribution	e	e	*T*	*T*		
Water supply network						
Source	*T*	*t*	*t*	*t*		
Treatment	*T*	*t*	*t*	*t*		
Buried network	e	E				
Wastewater network						
Treatment		*T*	*T*	*T*		
Buried network	*t*					
Transportation network						
Road	E	E				*T*
Air	E	E				*T*
Rail		E				
Sea	E	E				
Buildings	E	E	E	E	E	
Communication systems	*T*	*T*	*T*	*T*		
Critical components						
HVAC	*T*	*T*	*t*	*t*		
Electronics	*T*	*T*		*t*		

Abbreviations are: E — strong empirical bases (numerous post-eruption and analytical data); e — weak empirical bases (few post-eruption data); *T* — strong theoretical bases (likely to be relevant but no post-eruption data); and *t* — weak theoretical bases (may be relevant). Refer to Table 1 for definitions of hazard intensity metrics.

Infrastructure component and system design will also influence disruption. Components with no or few moving parts are unlikely to be damaged at low hazard intensities as tephra particles will not be lodged between moving parts; a primary cause of abrasion damage. However, these components will become covered in tephra limiting access and causing disruption. Systems with electrical components (e.g., insulators and electronic devices) may sustain short circuit faults in the presence of wet tephra (Wardman et al., 2012c), disrupting their operation. In addition, some infrastructure systems and components, such as road transportation and electrical insulators, are resilient to damage at all tephra hazard intensities and are likely to be disrupted at high hazard intensities (Figs. 4 and 8A).

Some disruption may only affect the infrastructure operators. For example, after the 2011 PCCVC eruption, sand filters at the Bariloche water treatment plant required increased maintenance time for cleaning however during this time there were no water outages and services continued as normal (Wilson et al., 2013). In these instances, increased maintenance requirements will incur additional costs and may prevent operators from undertaking other tasks.

4.1.2. Critical infrastructure disruption during clean-up operations

Tephra falls, PDCs and lahars produce unconsolidated deposits that require removal and clean-up to avoid ongoing and prolonged disruption or to reinstate critical infrastructure services (Wilson et al., 2012b). Proper clean-up will reduce tephra remobilisation, and minimise the potential for future damage (e.g., abrasion and corrosion) and human health effects which can result from inhalation of tephra particles (Horwell and Baxter, 2006). Whilst it is possible for some infrastructure sectors to clean deposits from their equipment and sites without causing disruption (e.g., live cleaning of electrical networks), many sectors will have to partially or completely shutdown (a controlled shutdown) to undertake cleaning. Performing controlled shutdowns of all or parts of an infrastructure network will cause further disruption and prevent society from using these services. In many cases however, this is unavoidable as continued operation may result in physical damage of components leading to further disruption. Controlled shutdowns for cleaning purposes have been documented for electrical supplies to prevent continual flashover (Fig. 4), water supplies to prevent water shortages and plant damage (Fig. 7A) and at airport runways to prevent aircraft damage and tephra remobilisation (Fig. 9A). Ultimately the decision to clean up unconsolidated deposits and/or initiate controlled shutdowns will be dependent on hazard intensity but also on the operational practices of the particular infrastructure operators.

4.1.3. Critical infrastructure disruption in exclusion zones

Disruption to critical infrastructure can occur without the presence of any volcanic hazards through the implementation and enforcement of evacuation and exclusion zones by emergency management authorities. Generally these zones will be developed for flow hazards, as these are more dangerous than tephra fall. Zones may be implemented prior to the onset of an eruption or during an eruption to prevent loss of life in dangerous areas. If infrastructure networks or sites are located

Table 10
Relevant lahar hazard intensity metrics for each infrastructure sector.

Critical infrastructure sector	Lahar hazard intensity metrics			
	Dynamic pressure	Velocity	Thickness of deposit	Depth of flow
Electrical supply				
Generation	*T*	*T*	*T*	
Transmission & distribution	E	E	*t*	e
Water supply network				
Source	*T*	*T*	*T*	
Treatment	*T*	*T*	*t*	*t*
Buried network	e	e		
Wastewater network				
Treatment	*T*	*T*	*t*	*t*
Buried network	*t*	*t*		
Transportation network				
Road	E	E	E	
Air	*T*	*T*	E	
Rail	E	E	*T*	
Sea	*t*	*t*	e	
Buildings	E		E	E
Communication systems	*T*	*T*	*t*	*t*
Critical components				
HVAC	*T*	*T*	*T*	
Electronics	e	e	e	

Abbreviations are: E — strong empirical bases (numerous post-eruption and analytical data); e — weak empirical bases (few post-eruption data); *T* — strong theoretical bases (likely to be relevant but no post-eruption data); and *t* — weak theoretical bases (may be relevant). Refer to Table 1 for definitions of hazard intensity metrics.

within these zones, services are likely to be disrupted as personnel will not be able to access these areas. For example, during the eruption of Montserrat (1995–ongoing) and the subsequent destruction of Plymouth, the water utility had to move some of the springs and wells which were located inside the exclusion zone (Sword-Daniels et al., 2014). If infrastructure within an exclusion zone is damaged it is unlikely that personnel will be able to enter to perform repairs unless an agreement is made with emergency management officials.

4.2. Physical damage to critical infrastructure

All volcanic hazards considered here can cause physical damage to critical infrastructure sectors and components. Physical damage has been observed occurring at all intensity levels for PDCs, lahars and lava flows (Fig. 5) and at high intensity tephra falls (Figs. 4, 5, 7, 9, 13).

Abrasion damage can occur to any exposed element as a result of contamination with tephra particles or from passing PDCs and lahars. Components with moving parts such as water and wastewater pumps, electrical switches, and cooling fans are more vulnerable as tephra particles may become lodged between moving surfaces. Abrasion damage to pumps has been documented for water supply and wastewater networks at tephra thicknesses of >30 mm and >4 mm, respectively (Fig. 7). Whilst these reports document the tephra thickness at which damage occurred, hazard exposure time, which is a primary control for abrasion severity, is not documented. Likewise, corrosion of metal surfaces, particularly building roofs (Fig. 13), also occurs over time. In addition, increasing tephra thickness will increase corrosion severity as more acidic tephra leachates will be delivered to the roof surface (Oze et al., 2013).

At higher tephra fall intensities structural damage can occur due to increased static loading. Most observed tephra-induced structural damage has occurred to buildings (residential and commercial) and their roofs (Fig. 13), as research has tended to focus on occupant safety. However, tephra accumulations on other exposed infrastructure components (e.g., electrical substation gantries, water storage and treatment tanks) are likely to cause structural damage if the load exceeds the structure's strength. Damage severity is influenced by tephra density and moisture content as these parameters increase so does the static load on the structure (Macedonio and Costa, 2012; Jenkins et al., 2014a). Damage to non-structural elements is likely to occur first as they are inherently weaker than engineered structural components.

PDCs, lahars and lava flows cause physical damage at all hazard intensities (Fig. 5). The primary damage mechanism is increased dynamic pressures which overcome structural design causing structures to fail. PDCs and lahars become rapidly less energetic with increasing distance from vent and flow axis (Spence et al., 2004b; Jenkins et al., 2013) and higher damage severity is expected in flow paths and river valleys and in proximal areas (Baxter et al., 2005). However, damage assessments of Baxter et al. (2005) and Jenkins et al. (2013) suggest that dynamic pressures can vary between ~1 and 5 kPa within tens of metres, resulting in non-uniform building damage. For most infrastructure sectors there is a lack of data (Fig. 5) regarding gradations in damage severity and therefore as a first order approximation, we assume a binary impact model, where damage is predicated on the presence of a volcanic flow(s). However for building damage there is sufficient impact data (e.g., Spence et al., 2004a; Baxter et al., 2005; Jenkins et al., 2013) to assess gradational damage.

Lava flows and sufficiently hot PDCs will cause fire damage to combustible structures and materials. Once a structure is ignited it will generally be completely destroyed by fire; for most structures, the benefit of extinguishing the fire is far outweighed by life safety concerns that would be encountered in an attempt. Buildings, structures and infrastructure (e.g., transportation routes) will become inundated and covered by volcanic flows, resulting in disruption or permanent damage, especially for lava which will solidify once cooled.

4.3. Estimating critical infrastructure vulnerability

Estimating vulnerability of critical infrastructure to volcanic eruptions can be difficult due to the number of facets that influence vulnerability and resilience. By reviewing empirical data (Figs. 4, 5, 7, 9, 13) relationships between disruption and/or damage and hazard intensity (Section 4.3.1) can be estimated and presented using impact scales (Section 4.3.2). When assessing vulnerability, consideration must also be given to the interactions between multiple volcanic hazards (Section 4.3.3).

4.3.1. Hazard intensity metrics

Volcanic hazards have a number of different hazard properties which can cause disruption and damage. This is in contrast to other natural hazards where there are generally few hazard properties which contribute to disruption and damage. For example, the principal damaging property of earthquakes is ground shaking, commonly assessed by peak ground acceleration, whereas PDCs can cause damage through lateral loading (dynamic pressure) and fire (temperature). We define these properties collectively as hazard intensity metrics (HIMs). When assessing vulnerability a single HIM may not accurately capture all of the impactful attributes that a hazard has to a particular infrastructure sector. To this end, Tables 7–10 present the relative relevance of different HIMs for each volcanic hazard and infrastructure sector and provide an indication on whether these are strong empirical or theoretical relationships. Selection of a HIM for vulnerability and risk assessment should consider: (1) the HIMs' appropriateness to accurately describe a range of impact severity; (2) the ease of HIM measurement in the field or laboratory; and (3) the applicability of the HIM to hazard model outputs. The most appropriate and commonly used HIM candidates are thickness or mass loading (tephra fall), dynamic pressure (PDC), flow height (lava flow) and flow velocity (lahar), however different HIMs can be used depending on the impact(s) and infrastructure sector(s) of interest.

4.3.2. Disruption and damage states

To classify and categorise impacts to critical infrastructure a common impact scale can be used (Blong, 2003b) which includes disruption and damage states. In volcanology, impact scales are available for building damage from tephra fall (e.g., Spence et al., 1996; Blong, 2003a) and PDC impacts (e.g., Spence et al., 2004b; Baxter et al., 2005). Here we expand impact scale coverage to include critical infrastructure sectors examined in Section 3 for tephra fall, PDC, lava flow and lahar hazards (Tables 11–14). We define four common impact levels: Level 0, no damage; Level 1, cleaning required; Level 2, repair required; and Level 3, replacement or financially expensive repair. Four levels were chosen because empirical impact data across a range of impact levels was lacking for most infrastructure and therefore further subdivision was not justified. Separate descriptions for disruption and physical damage are provided to reflect impact dichotomy presented in Sections 4.1 and 4.2. For each impact scale (Tables 11–14) the most diagnostic HIM, based on its relationship with empirically observed impacts, was used, these are: thickness (tephra fall); dynamic pressure (PDC); flow depth (lava flow); and flow velocity (lahar) (Tables 7–10). Intensity thresholds were derived by categorising empirical impact data in Figs. 4, 5, 7, 9, and 13 and Section 3 and by using expert judgement to indicate anticipated impacts where data was lacking, primarily at high hazard intensities.

For tephra fall (Table 11), different intensity thresholds were derived for each critical infrastructure sector because each sector responds differently given a specific hazard intensity. For example, ~1 mm of tephra will close an airport whilst this tephra thickness will not cause any damage to a building. Differences in how infrastructures respond to tephra fall precluded the use of generic tephra fall thresholds which would be applicable to all infrastructure sectors. In contrast, for PDCs and lahars (Tables 12 and 14) we consider impacts to be binary for all

Table 11
Proposed disruption and damage levels for expected impacts to critical infrastructure as a function of tephra fall thickness (mm).

	Level	Level 0	Level 1	Level 2	Level 3
	Description	No damage	Cleaning required	Repair required	Replacement or financially expensive repair
Electrical supply	Threshold (mm)	<3	3–10	10–*100*	>*100*
	Damage	No damage	Possible abrasion to some moving parts, infiltration of tephra into substation gravel.	Damage to exposed equipment especially those with moving parts, possible electrical line breakage.	Structural damage to some equipment at generation and transmission/distribution sites, irreparable damage to moving parts (e.g., hydro power turbines).
	Disruption	No disruption	Temporary disruption to service caused by insulator flashover, cleaning and repair.		Widespread disruption to electrical supply with possible permanent disruption.
Water supply network	Threshold (mm)	<1	1–20	20–*100*	>*100*
	Damage	No damage	Possible clogging of filters and some abrasion to moving components.	Damage to pumping equipment, other moving parts and infilling of tanks.	Collapse of reservoir roofs and infilling of open reservoirs and tanks.
	Disruption	No disruption	Normal operation with increased frequency of filter cleaning and increased turbidity.	Contamination of water and increased treatment required. Possible water use restrictions.	Severe contamination of water supply and exhaustion of supply due to damage and/or increased demand.
Wastewater network	Threshold (mm)	<3	3–*10*	*10–50*	>*50*
	Damage	No damage	Possible minor abrasion to pumps, clogging of filters and possible interference with chemical treatment process.	Large amounts of sedimentation in network some causing blockages, some damage to treatment plant components and possible infilling of open tanks.	Widespread sedimentation throughout entire network causing some blockages, irreparable damage to pumps and extensive structural damage to treatment plant components.
	Disruption	No disruption	Reduced capacity, operation with increased cleaning of filters.	Temporary disruption to service to unblock network and clean tanks possibly resulting in discharge of untreated sewage.	Long term to possible permanent disruption to service. Unable to treat wastewater, discharge of untreated sewage.
Airport	Threshold (mm)	<1	1–*30*	*30–150*	>*150*
	Damage	No damage	Possible abrasion of runway and apron markings and possible abrasion of paved surfaces.	Moderate abrasion of paved surfaces and landing lights.	Complete burial.
	Disruption	Airport open	Airport closure, reduced visibility.		Possible permanent closure.
Road	Threshold (mm)	<2	2–*50*	*50–150*	>*150*
	Damage	No damage	Possible abrasion of road markings and possible abrasion of paved surfaces.	Moderate abrasion of paved surfaces, weak bridges may experience structural damage.	Complete burial, structural damage to some bridges.
	Disruption	No disruption	Reduced visibility, loss of traction, covering of markings and possible road closure.	Roads impassable for 2WD vehicles. Dangerous driving conditions.	Roads impassable if tephra is unconsolidated, compacted tephra may be driven on by 4WD vehicles. Widespread road closures.

Rail	Threshold (mm)	<1	1–*30*	*30–150*	>*150*
		No damage	Possible abrasion and/or corrosion of railway tracks and signals, jamming of mechanical signals and contamination of track ballast.		Complete burial
		No disruption	Reduced visibility, signals and communications disrupted.	Loss of traction and possible derailing.	Impassable.
Marine	Threshold (mm)	<1	1–*30*	*30–150*	>*150*
		No damage	Possible abrasion of paved surfaces.	Moderate abrasion of paved surfaces, pumice rafts covering the water surface.	Complete burial of paved surfaces.
		No disruption	Reduced visibility on land and sea.	Ship movements obstructed by pumice rafts.	Inoperable.
Vehicles	Threshold (mm)	<3	3–*30*	*30–100*	>*100*
	Damage	No damage	Possible abrasion and/or corrosion to windshields, paintwork, aircraft leading edges, moving parts and clogging of air filters.	Extensive abrasion of moving parts and possible seizing of engines.	Extensive damage that is uneconomical to repair.
	Disruption	No disruption	Infiltration of tephra into personal compartments.	Frequent fluid and filter replacement and possible cleaning and reconditioning of engines.	Completely inoperable.
Communications	Threshold (mm)	<5	5–*30*	*30–100*	>*100*
	Damage	No damage	No damage	Blockage and shutdown of cooling systems and damage to exposed components (e.g., dishes, towers, lines).	Structural damage to communication components (e.g., dishes, towers, lines).
	Disruption	No disruption	Overloading of communication network from high demand and possible signal attenuation and interference.	Temporary disruption to service due to shutdowns and cleaning.	Permanent disruption.
Buildings	Threshold (mm)	<10	10–100	100–*500*	>*500*
	Damage	No damage	Light roof damage and gutter damage and possible abrasion to windows and cladding.	Severe roof damage, damage to vertical structure, possible partial collapse.	Complete roof collapse and severe damage to rest of building.
	Disruption	Occupied	Infiltration of tephra into building and able to be occupied.	Large volumes of tephra inside building as well as parts of the structure, uninhabitable.	Beyond economic repair and uninhabitable.
Critical components	Threshold (mm)	<1	1–10	10–*50*	>*50*
	Damage	No damage	No damage	Abrasion of moving parts and blockage of filters.	Extensive damage to most components.
	Disruption	No disruption	Reduced function until cleaned.	Reduced function and temporary shutdowns until cleaned.	Uneconomic to repair, disruption to service until replaced.

Disruption and damage descriptions and threshold values are subject to uncertainty and assume generic infrastructure design. Italicised threshold values indicate where expert judgement was used to derive theoretical estimates of when disruption and damage would occur. Disruption and damage at higher intensities (Level 3) include those at lower intensities (Level 1).

Table 12
Proposed disruption and damage levels for expected impacts to critical infrastructure as a function of PDC dynamic pressure (kPa).

	Level	Level 0	Level 1	Level 2	Level 3
	Description	No damage	Cleaning required	Repair required	Replacement or financially expensive repair
Electrical supply	Threshold (kPa)	<0	–	–	>0
	Damage	No damage	–	–	Destruction of transmission and distribution lines, poles, towers and substations and damage to generation sites.
	Disruption	No disruption	–	–	Permanent disruption to service.
Water supply network	Threshold (kPa)	<0	–	–	>0
	Damage	No damage	–	–	Damage to treatment facilities and above-ground pipes and infilling of un-covered water sources.
	Disruption	No disruption	–	–	Permanent disruption to service.
Wastewater network	Threshold (kPa)	<0	–	–	>0
	Damage	No damage	–	–	Damage to treatment facilities and above-ground pipes, infilling of ponds and blockage of drains.
	Disruption	No disruption	–	–	Permanent disruption to service.
Transport	Threshold (kPa)	<0	–	–	>0
	Damage	No damage	–	–	Complete burial and heat damage of paved surfaces and railways. Destruction of some bridges. Infilling of harbours.
	Disruption	No disruption	–	–	Roads and rail impassable and widespread closures.
Vehicles	Threshold (kPa)	<0	–	–	>0
	Damage	No damage	–	–	Vehicles buried, extensively damaged by pressure and heat and swept away.
	Disruption	No disruption	–	–	Completely inoperable.
Communications	Threshold (kPa)	<0	–	–	>0
	Damage		–	–	Destruction of ground level components (e.g., lines, cabinets, exchanges).
	Disruption	No disruption	–	–	Permanent disruption and signal interference caused by pyroclastic surges.
Buildings	Threshold (kPa)	<1	1–10	*10–25*	*>25*
	Damage	No damage	Openings damaged, possible internal fire damage, external fire damage, sandblasting of walls and some damage to weak masonry.	All opening damaged, missile impacts evident and partial collapse of walls and/or roof, extensive internal fire damage.	Complete damage to building with few structural elements remaining.
	Disruption	Occupied	Infiltration of tephra, missiles and building material into building and fire damage making it uninhabitable.	Beyond economic repair and uninhabitable.	
Critical components	Threshold (kPa)	<0	–	–	>0
	Damage	No damage	–	–	Complete destruction of exposed electronic equipment with most being swept away and/or buried and melting of plastic components.
	Disruption	No disruption	–	–	No functionality and uneconomic to repair.

Disruption and damage descriptions and threshold values are subject to uncertainty and assume generic infrastructure design. Impacts to most infrastructure are considered binary (see Section 4.2) thus there are no descriptions for Level 1 or Level 2 except for buildings where there is additional empirical data. Italicised threshold values indicate where expert judgement was used to derive theoretical estimates of when disruption and damage would occur.

infrastructure sectors except buildings. Whilst there may be gradational infrastructure impacts from PDCs and lahars at flow margins (see Section 4.2) we found insufficient empirical evidence to derive hazard thresholds for intermediary impact states. Intermediary impact states for building damage are included and are drawn from the existing scales of Baxter et al. (2005) and Spence et al. (2004b). For lava flow hazards we consider impacts to be binary for all infrastructure sectors (Table 13) based on the destructiveness of lava flows.

Caution is urged when using our impact scales (Tables 11–14) as a number of assumptions have been made, such as: generic infrastructure design and typology, one discrete hazard occurrence and no mitigation actions taken by infrastructure operators. These scales should only be used either as guides or at regional scale vulnerability and risk assessment. Whenever possible, local vulnerability studies which account for each system's vulnerability characteristics should be undertaken first.

4.3.3. Interactions between volcanic hazards

During a volcanic eruption multiple hazardous phenomena often occur simultaneously or in short succession. This is caused by changes in eruption style (from effusive to explosive or from explosive to effusive), during explosive eruptions or as a result of multiple vents erupting simultaneously. The interaction and impact of multiple volcanic hazards on critical infrastructure may lead to different vulnerability outcomes compared to single hazard impacts. However, multiple volcanic hazard impacts are rarely studied because of the increased complexity of hazard and infrastructure interactions.

One study that addresses multi-volcanic hazard impacts is Zuccaro et al. (2008). They investigate impacts on residential buildings from tephra fall with simultaneous earthquakes or PDCs for a simulated Mt. Vesuvius eruption. For the combination of tephra fall and earthquake a decrease in the seismic response of the building was observed, i.e., the building is more susceptible to earthquake damage if tephra is deposited on the roof. For the scenario of tephra fall followed by a

Table 13
Proposed disruption and damage levels for expected impacts to critical infrastructure as a function of lava flow depth (m).

	Level	Level 0	Level 1	Level 2	Level 3
	Description	No damage	Cleaning required	Repair required	Replacement or financially expensive repair
Electrical supply	Threshold (m)	<0	–	–	>0
	Damage	No damage	–	–	Destruction of transmission and distribution lines, poles, towers and damage a burial of substations and generation sites.
	Disruption	No disruption	–	–	Permanent disruption to service.
Water supply network	Threshold (m)	<0	–	–	>0
	Damage	No damage	–	–	Damage to treatment facilities and above-ground pipes and infilling of uncovered water sources.
	Disruption	No disruption	–	–	Permanent disruption to service.
Wastewater network	Threshold (m)	<0	–	–	>0
	Damage	No damage	–	–	Damage to treatment facilities and above-ground pipes, infilling of ponds and burial of drains.
	Disruption	No disruption	–	–	Permanent disruption to service.
Transport	Threshold (m)	<0	–	–	>0
	Damage	No damage	–	–	Complete burial heat damage to paved surfaces and railways.
	Disruption	No disruption	–	–	Transportation routes impassable resulting in permanent closure.
Vehicles	Threshold (m)	<0	–	–	>0
	Damage	No damage	–	–	Vehicles buried and burnt.
	Disruption	No disruption	–	–	Completely inoperable.
Communications	Threshold (m)	<0	–	–	>0
	Damage	No damage	–	–	Destruction and burial of ground level components (e.g., lines, cabinets, exchanges).
	Disruption	No disruption	–	–	Permanent disruption.
Buildings	Threshold (m)	<0	–	–	>0
	Damage	No damage	–	–	Complete fire damage to building and burial.
	Disruption	Occupied	–	–	Beyond economic repair and uninhabitable.
Critical components	Threshold (m)	<0	–	–	>0
	Damage	No damage	–	–	Complete destruction and burial of exposed electronic equipment and melting of plastic components.
	Disruption	No disruption	–	–	No functionality and uneconomic to repair.

Disruption and damage descriptions and threshold values are subject to uncertainty and assume generic infrastructure design. Impacts to all infrastructure are considered binary (see Section 4.2) thus there are no descriptions for Level 1 or Level 2.

Table 14
Proposed disruption and damage levels for expected impacts to critical infrastructure as a function of lahar velocity (m/s).

	Level	Level 0	Level 1	Level 2	Level 3
	Description	No damage	Cleaning required	Repair required	Replacement or financially expensive repair
Electrical supply	Threshold (m/s)	<0	–	–	>0
	Damage	No damage	–	–	Destruction of transmission and distribution lines, poles, towers and substations and damage to generation sites (e.g., abrasion to hydro power turbines).
	Disruption	No disruption	–	–	Permanent disruption to service.
Water supply network	Threshold (m/s)	<0	–	–	>0
	Damage	No damage	–	–	Damage to treatment facilities, above-ground pipes and water intake structures and infilling of uncovered water sources.
	Disruption	No disruption	–	–	Permanent disruption to service due to damage and severe contamination.
Wastewater network	Threshold (m/s)	<0	–	–	>0
	Damage	No damage	–	–	Damage to treatment facilities and above-ground pipes, infilling of ponds and blockage of drains.
	Disruption	No disruption	–	–	Permanent disruption to service.
Transport	Threshold (m/s)	<0	–	–	>0
	Damage	No damage	–	–	Complete burial and erosion damage to paved surfaces and railways. Destruction of some bridges and scour of embankments. Infilling of harbour.
	Disruption	No disruption	–	–	Transportation routes impassable resulting in permanent closure.
Vehicles	Threshold (m/s)	<0	–	–	>0
	Damage	No damage	–	–	Vehicles buried, extensively damaged by pressure and swept away.
	Disruption	No disruption	–	–	Completely inoperable.
Communications	Threshold (m/s)	<0	–	–	>0
	Damage	No damage	–	–	Destruction of ground level components (e.g., lines, cabinets, exchanges).
	Disruption	No disruption	–	–	Permanent disruption.
Buildings	Threshold (m/s)	<1	*1–3*	*3–5*	*>5*
	Damage	No damage	Damage to openings and non-structural elements and infilling of building interior with debris.	Moderate structural damage to walls, some partially collapse.	Complete damage to building with few structural elements remaining and/or swept off foundations.
	Disruption	Occupied	Infiltration of debris and building material into building making it uninhabitable.		Beyond economic repair and uninhabitable.
Critical components	Threshold (m/s)	<0	–	–	>0
	Damage	No damage	–	–	Complete destruction of exposed electronic equipment with most being swept away and/or buried.
	Disruption	No disruption	–	–	No functionality and uneconomic to repair.

Disruption and damage descriptions and threshold values are subject to uncertainty and assume generic infrastructure design. Impacts to most infrastructure are considered binary (see Section 4.2) thus there are no descriptions for Level 1 or Level 2 except for buildings where there is additional empirical data. Italicised threshold values indicate where expert judgement was used to derive theoretical estimates of when disruption and damage would occur.

PDC, Zuccaro et al. (2008) found that the vertical load exerted on the roof from tephra fall provided a stabilising effect when the building was impacted by a PDC. Whilst this approach estimated building vulnerability it could also be applied to critical infrastructure. Multi-volcanic hazard research should be advanced to develop vulnerability assessments for volcanic eruptions and/or scenarios rather than just specific individual volcanic hazards.

5. Future direction

5.1. Implications for volcanic risk assessment

Over the past few decades there has been an emphasis on understanding, quantifying and modelling volcanic hazards. This has produced a number of high quality empirical, physical and probabilistic models which evaluate occurrence probabilities and spatial extents of various volcanic hazards (e.g., Schilling, 1998; Bonadonna, 2006; Charbonnier and Gertisser, 2009; Wadge, 2009; Marzocchi et al., 2010; Jenkins et al., 2012). These models have contributed to a detailed understanding of volcanic hazards and have greatly improved the contribution of volcanology science to disaster risk reduction and management.

At present, volcanic vulnerability and comprehensive risk assessments are less advanced than hazard assessments (Section 2), however the contributions of Blong (1984), Spence et al. (1996), Blong (2003a), Baxter et al. (2005), Wardman et al. (2012c), Wilson et al. (2012b) and Jenkins et al. (2014a) have progressively increased and broadened the knowledge of volcanic impact occurrence, damage mechanisms, mitigation strategies and emergency management response. Whilst these studies go a long way towards improved vulnerability assessment, collectively they have not progressed to the point of developing robust quantitative vulnerability models to inform land-use planning and infrastructure design codes (perhaps with the exception of residential buildings). Additionally, lack of awareness of volcanic impacts in critical infrastructure mitigation strategies, such as citing, design and contingency planning rarely, if ever, consider volcanic hazards. Whilst land-use planning and engineering design might not be appropriate in all situations it is appropriate for sensitive and/or high value infrastructure, such as nuclear power stations. For example, the International Atomic Energy Agency initiative (IAEA, 2013) has considered volcanic hazards in site evaluation at nuclear power installations. The NZ VISG science/industry collaboration is also an example of critical infrastructure organisations supporting and using volcanic resiliency research to reduce risk (Wilson et al., 2014). And global awareness is increasing with the inclusion of volcanic hazards for the first time in the Global Assessment Report on Disasters Risk Reduction 2015 (Jenkins et al., 2014b). Engineering design, often implemented at little extra cost, and effective contingency planning is likely to offer substantial societal benefits through reduced infrastructure service downtime and restoration costs. A cost–benefit analysis would be the next step to investigate the value of such mitigation strategies.

5.2. Goals for the next 10 to 25 years

Reducing the impacts of volcanic eruptions on society is the ultimate goal of volcanic risk management. Population growth, land-use pressure and society's increasing expectation of infrastructure performance during and after disasters will make this a challenge for critical infrastructure operators.

To progress towards increased critical infrastructure resilience, a crucial first step is for infrastructure operators to include volcanic hazards as a risk routinely managed. A value proposition is required where scientists and operators identify and establish the risk context and demonstrate the value of risk mitigation. The scientific community must support this collaboration through producing the best possible quality hazard, vulnerability and risk information to support risk mitigation and management. Broad and in-depth understanding of direct and indirect impacts from all credible volcanic hazards and hazard intensities is required. By first understanding the intensity at which impacts occur for different critical infrastructure components and the resulting impact severity enables decisions to be made about the most appropriate mitigation strategy for the particular situation; whether it be land-use planning, infrastructure design or contingency planning (Table 6). To improve volcanic vulnerability assessments, the volcanology community in partnership with engineers, infrastructure operators, risk and continuity managers, and the communities which rely on critical services, need to identify safe and acceptable levels of critical infrastructure performance during volcanic crises by robustly analysing existing impact data and seeking additional quantitative empirical and theoretical data. Continued investment in research to identify and refine vulnerability (or conversely resilience) of critical infrastructure requires continued field observations, laboratory experiments and numerical modelling to inform mitigation strategies and resilience design. We acknowledge that this can be resource intensive and in some cases impractical due to hazard and infrastructure complexity, but if the benefit of mitigation strategies is well defined and recognised then such investments become justified. Mitigation for volcanic hazards is also likely to reduce risk for other non-volcanic hazards.

Future research priorities to reduce risk and increase resilience for critical infrastructure sectors that we believe should be addressed within the next 10 to 25 years are:

(1) Focus on quantitative vulnerability estimation for critical infrastructure impacted by volcanic hazards. This should include open source standardised methodologies and databases for collection of quantitative impact data from post-eruption field assessments, laboratory experiments and numerical modelling and the derivation of fragility and vulnerability functions. Developing such approaches for critical infrastructure will be challenging due to the wide variability in system and component design, operational requirements and the interdependency between different infrastructure sectors. However, a standardised approach allows repeatable quantitative vulnerability estimates to be made and facilitates direct comparisons with other critical infrastructure and natural hazards.
(2) Laboratory analysis of infrastructure systems and components under controlled conditions to more robustly inform vulnerability estimates; particularly for high-value infrastructure components from which society requires high levels of reliable performance.
(3) Increasing the awareness of volcanic hazards, their impacts and the value of volcanic risk management for critical infrastructure operators. This may be achieved through partnerships between volcanic scientists, infrastructure operators and engineers to encourage the inclusion of volcanic hazards in infrastructure site evaluation/assessment criteria, design and contingency planning aimed at increasing resilience.
(4) Demonstrate the value of volcanic risk management for critical infrastructure by the provision of useful and understandable vulnerability and mitigation information, backed by cost–benefit analysis, to critical infrastructure operators so informed decision making regarding infrastructure operation and resilience can take place.

6. Summary

This paper reviews disruption and physical damage impacts to critical infrastructure sectors from tephra falls, pyroclastic density currents (PDC), lava flows and lahars. Data are primarily from post-eruption impact assessments and are generally qualitative, although several quantitative assessments are available. Impacts to critical infrastructure can be classified on a continuum from disruption to complete damage. Impact severity is primarily controlled by the type of hazard, its intensity and the specific type of infrastructure and its design. In general, disruption occurs at low hazard intensities for tephra falls, PDCs and lahars, whilst physical damage occurs at higher intensities for all hazards. Lava flows are the exception and tend to cause physical damage at all intensities.

Quantitative volcanic hazard assessment is at an advanced state, however, quantitative vulnerability assessments are lacking. The lack of these assessments can be attributed to: (1) difficulties in determining which hazard characteristic is the primary cause of damage to infrastructure and its accurate measurement; (2) ongoing eruptions, clean-up and mitigative strategies can alter infrastructure impacts and are challenging to account for in assessments; and (3) lack of volcanic construction or design codes, or performance guidelines which could prompt and facilitate detailed vulnerability assessment. Despite this, several studies have assessed the vulnerability of buildings and critical infrastructure sectors impacted by tephra fall, PDCs and lahars. To facilitate continued development of vulnerability assessments in volcanology, impacts to critical infrastructure from volcanic hazards should be quantified in a more robust, systematic and standardised manner. We have highlighted a number of aspects to consider when estimating vulnerability and developing fragility and vulnerability functions, such as hazard intensity measures, hazard interactions, infrastructure interdependencies, limitations and uncertainties.

We challenge the volcanology community to create a consistent methodology for the development and refinement of physical vulnerability assessment for all volcanic hazards and critical infrastructure. The final goal is to provide robust quantified vulnerability estimates for volcanic risk managers, decision makers and policy experts in order to minimise disruption, reduce economic losses and loss of life during volcanic eruptions.

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