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Volcanic ash impacts on critical infrastructure

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ABSTRACT

Volcanic eruptions can produce a wide range of hazards. Although phenomena such as pyroclastic flows and surges, sector collapses, lahars and ballistic blocks are the most destructive and dangerous, volcanic ash is by far the most widely distributed eruption product. Although ash falls rarely endanger human life directly, threats to public health and disruption to critical infrastructure services, aviation and primary production can lead to significant societal impacts. Even relatively small eruptions can cause widespread disruption, damage and economic loss.

Volcanic eruptions are, in general, infrequent and somewhat exotic occurrences, and consequently in many parts of the world, the management of critical infrastructure during volcanic crises can be improved with greater knowledge of the likely impacts. This article presents an overview of volcanic ash impacts on critical infrastructure, other than aviation and fuel supply, illustrated by findings from impact assessment reconnaissance trips carried out to a wide range of locations worldwide by our international research group and local collaborators. ‘Critical infrastructure’ includes those assets, frequently taken for granted, which are essential for the functioning of a society and economy.

Electricity networks are very vulnerable to disruption from volcanic ash falls. This is particularly the case when fine ash is erupted because it has a greater tendency to adhere to line and substation insulators, where it can cause flashover (unintended electrical discharge) which can in turn cause widespread and disruptive outages. Weather conditions are a major determinant of flashover risk. Dry ash is not conductive, and heavy rain will wash ash from insulators, but light rain/mist will mobilise readily-soluble salts on the surface of the ash grains and lower the ash layer’s resistivity. Wet ash is also heavier than dry ash, increasing the risk of line breakage or tower/pole collapse. Particular issues for water supply managers include: monitoring turbidity levels in raw water intakes, and if necessary increasing chlorination to compensate for higher turbidity; managing water demand; and communicating monitoring results with the public to allay fears of contamination. Ash can cause major damage to wastewater disposal systems. Ash deposited onto impervious surfaces such as roads and car parks is very easily washed into storm drains, where it can form intractable masses and lead to long-term flooding problems. It can also enter wastewater treatment plants (WWTPs), both through sewer lines and by direct fallout. Damage to modern WWTPs can run into millions of dollars. Ash falls reduce visibility creating hazards for ground transportation. Dry ash is also readily remobilised by vehicle traffic and wind, and dry and wet ash deposits will reduce traction on paved surfaces, including airport runways. Ash cleanup from road and airports is commonly necessary, but the large volumes make it logistically challenging. Vehicles are vulnerable to ash; it will clog filters and brake systems and abrade moving parts within engines. Lastly, modern telecommunications networks appear to be relatively resilient to volcanic ash fall. Signal attenuation and interference during ash falls has not been reported in eruptions over the past 20 years, with the exception of interference from ash plume-generated lightning. However, some telecommunications equipment is vulnerable to airborne ash, in particular heating, ventilation and air-conditioning (HVAC) systems which may become blocked from ash ingestion leading to overheating.

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This summary of volcanic ash impacts on critical infrastructure provides insight into the relative vulnerability of infrastructure under a range of different ashfall scenarios. Identifying and quantifying these impacts is an essential step in building resilience within these critical systems. We have attempted to consider interdependencies between sectors in a holistic way using systems thinking. As modern society becomes increasingly complex and interdependent this approach is likely to become increasingly necessary.

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1. Introduction

It has been estimated that nine percent of the world's population lives within 100 km of a historically active volcano (Horwell and Baxter, 2006). This proportion is likely to continue to increase due to higher-than-average rates of population growth in many regions and countries such as Central America, equatorial Africa, Colombia, Ecuador and the Philippines that are highly volcanically active. Eruption frequencies for a range of volcanically-active countries are shown in Table 1.

Volcanic eruptions can produce a wide range of hazards. Although phenomena such as pyroclastic flows and surges, sector collapses, lahars and ballistic blocks are most destructive and dangerous (Hansell et al., 2006), volcanic ash fall is by far the most widely distributed eruption product. Volcanic ash can affect many people because of the large areas that can be covered by ash fall. Although ash falls rarely endanger human life directly, threats to public health, disruption to critical infrastructure services (e.g. electricity and water supplies, transport routes, waste water and communications), aviation, buildings and primary production, can lead to significant societal impacts (Horwell and Baxter, 2006; Stewart et al., 2006). Even relatively small eruptions can cause widespread disruption, damage and economic loss. For example, the 1995/1996 eruptions of Ruapehu volcano in the central North Island of New Zealand were very small by geological standards (VEI 3, refer to Table 1 for definition) but still covered over 20,000 km^2 of agricultural land with ash fall and caused significant disruption and damage to aviation, communication networks, a hydro-electric power scheme, electricity transmission lines, water supply networks, wastewater treatment plants, agriculture and the tourism industry (Cronin et al., 1998; Johnston et al., 2000). The total cost of the eruption was estimated to be, in 1995/1996 value, in excess of $NZ 130 million ($US 104 million).

However, volcanic eruptions which produce abundant ash are, in general, infrequent and somewhat exotic occurrences, and consequently in many parts of the world, infrastructure managers may not have devoted serious consideration to management of a volcanic crisis.

1.1. Research context and methods

Over the past 15 years our international research group has aimed to undertake a sustained and systematic approach to volcanic impact assessment in the following areas:

- Critical infrastructure: including electricity, water supplies, wastewater, land and air transport, telecommunications.
- Ash cleanup and disposal.
- Primary industries, including agriculture.
- Emergency management.

Our group has utilised a research model of undertaking reconnaissance trips to areas impacted by volcanic eruptions worldwide, in conjunction with empirical, laboratory-based testing of critical infrastructure components. Trips have been undertaken to investigate the impact of the following eruptions: Ruapehu, New Zealand (1945, 1995/1996); Mt St Helens, USA (1980 eruption); Sakurajima, Japan (1980s to present); Pinatubo, Philippines (1991); Hudson, Chile (1991); Mt Spurr, Alaska (1992); Reventador, Ecuador (2002); Etna, Italy (2004); Tungurahua, Ecuador (1999–2000 and 2010); Merapi, Indonesia (2006); Chaitén, Chile (2008); Redoubt, Alaska (2009), Soufrière Hills Volcano, Montserrat (2010) and Pacaya, Guatemala (2010) (Johnston, 1997; Johnston et al., 2000; Durand et al., 2001; Wilson et al., 2010a,b,c; Leonard et al., 2005; Barnard, 2004; Wilson et al., 2007; Stewart et al., 2009a; Sword-Daniels, 2010; Sword-Daniels et al., in press; Wardman et al., in press).

Research methods for the fieldwork included: field observation, field testing, meetings, and semi-structured interviews. International fieldtrips were carried out in partnership with local or

Table 1
Eruption frequencies for selected countries (after Jenkins et al. (in press) and Wilson et al. (2010a)).

Selected countries	Population (2008)[a] (million)	Number of eruptions		Average eruption frequency	
		VEI[b] 0–3	VEI 4–7	VEI 0–3	VEI 4–7
Indonesia	239.9	1170	28	6 months	15 years
Iceland	0.3	147	26	6 years 10 months	43 years
Japan	127.7	892	71	7 months	44 years
Guatemala	13.7	105	8	4 years 9 months	53 years
Phillippines	90.5	133	11	1 year 4 months	59 Years
Papua New Guinea	6.5	191	23	8 months	81 years
Alaska, Kamchatka, Kuril Islands	1.1	713	115	5 months	100 years
Ecuador	13.8	188	31	2 years 5 months	102 years
Canada, Lower 48 states USA	335.8	147	18	1 year 6 months	143 years
Italy	59.9	242	21	5 years	215 years
Colombia	44.4	5134	15	6 years 6 months	304 years
Mexico	107.7	114	25	7 years 6 months	375 years
New Zealand	4.3	189	17	11 months	394 years
Chile	16.8	339	17	1 year 4 months	554 years
Nicaragua	5.7	130	10	1 year 2 months	806 years
Peru	27.9	39	4	14 years 2 months	832 years

[a] 2008 World Population Data Sheet, Population Reference Bureau.
[b] The Volcanic Explosivity Index (VEI) is a classification scheme for volcanic eruptions, ranging from VEI 0–8, with VEI 0 the least explosive (Newhall and Self, 1982).

national in-country bodies in volcanic monitoring and emergency management. Meetings and interviews were carried out with infrastructure managers and operations and maintenance staff at affected facilities. The interviews followed several prompt questions which were used to steer the conversation, and touched upon the main topics of interest for research including: the general impacts of volcanic ash fall on the sector; actions taken in response to ash fall; ash clean-up operations; emergency management plans; and interrelated power, water and access impacts on the sectors. Interviews were semi-structured in nature to allow for freer exploration and discussion around the various topics that were touched upon in conversation.

Trips have been undertaken at varying intervals post-eruption to capture immediate impacts as well as impacts which have manifested over time. The focus has been on both understanding ash fall impacts on individual system components and overall system functionality. We are also working towards developing predictive capacity by relating characteristics of ash fall events (fall thickness, grain size distributions, engineering properties such as density and abrasiveness, and chemical characteristics of the ash,

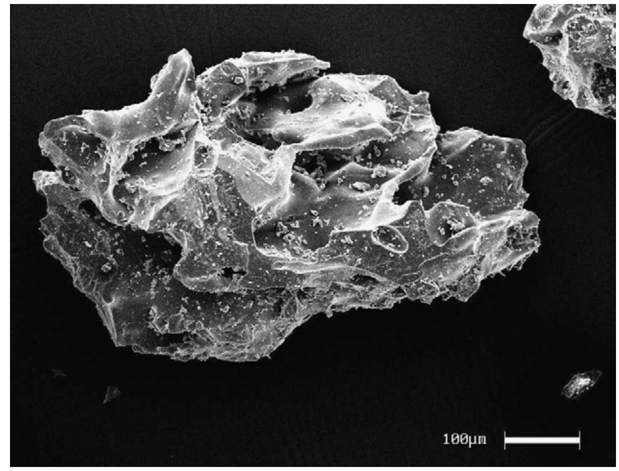

Fig. 1. Volcanic ash particle. Note the cavities are the broken walls of vesicles.

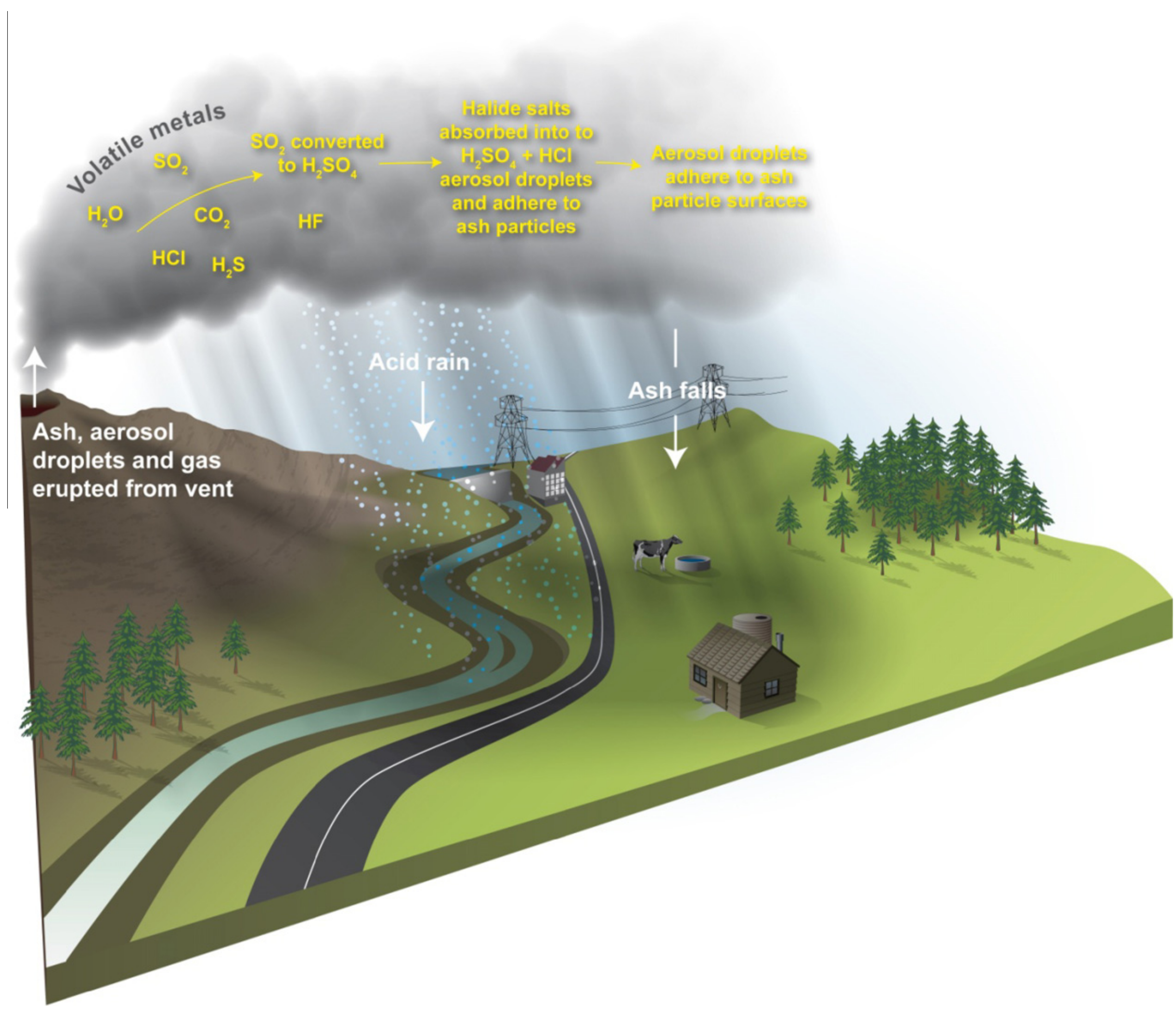

Fig. 2. Processes occurring within volcanic plumes. Volcanic ash particles are thought to have a very thin surface coating comprised of readily soluble sulphate and chloride salts, and more sparingly-soluble fluoride compounds. These are thought to be formed following the condensation of acidic aerosols (H_2SO_4, HCl and HF) onto ash particles, followed by the dissolution of cations such as Ca^{2+} and Na^{+} from the mineral surface. Consequently, freshly-fallen ash can release soluble components into surface waters, and is both corrosive and conductive. Figure used with permission of GNS Science.

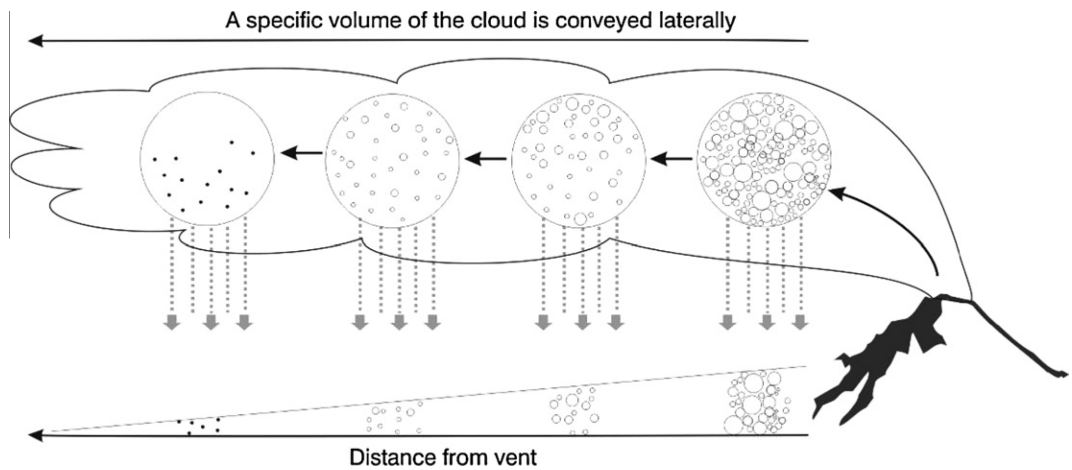

Fig. 3. Schematic illustration of the fall-out of particles from an umbrella eruption cloud showing decreasing thickness and grain-size with distance from source.

in combination with environmental conditions) to the type and severity of impacts.

The purpose of this article is to present an overview of volcanic ash impacts on critical infrastructure, illustrated by recent data obtained by our group. We define 'critical infrastructure' (sometimes also referred to as 'lifelines') as assets that are essential for the functioning of a society and economy. In a broad sense it includes the following (Platt, 1991):

- electricity generation, transmission and distribution;
- gas and oil production, transport and distribution;
- telecommunications;
- water supply (drinking water, waste water/sewage disposal, stormwater and drainage networks);
- food production and distribution;
- heating (e.g. natural gas, fuel oil, district heating);
- transportation systems (road and rail networks, airports, ports, inland shipping).

1.2. Scope of the paper

In this paper we focus on the following critical infrastructure: electricity generation, transmission and distribution; water supply; waste water; telecommunications; and transportation systems (excluding aviation which is covered by Casadevall (1994) and Guffanti et al. (2010)). Impacts on other critical infrastructure, including food production and fuel production, will be the focus of future analysis. The topics of building damage caused by ash, and health hazards of ash have been recently and comprehensively addressed by others (Spence et al., 2005; Horwell and Baxter, 2006) and are not considered in this paper. Similarly, social consequences of volcanic ash falls are beyond the scope of this paper.

The systems and networks that make up the infrastructure of society are often taken for granted, yet a disruption to any one of those systems can have consequences across other sectors. Hence, this article also addresses interdependence of critical infrastructure from a 'systems thinking' perspective.

1.3. Properties of volcanic ash

Volcanic ash is the material produced by explosive volcanic eruptions that is <2 mm in diameter. Fine ash is <0.063 mm; coarse ash is between 0.063 and 2 mm. Due to their violent and rapid formation, volcanic ash particles are made up of various proportions of vitric (glassy, non-crystalline), crystalline or lithic (non-magmatic) particles. The density of individual particles may vary roughly between 700–1200 kg/m^3 for pumice, 2350–2450 kg/m^3 for glass shards, 2700–3300 kg/m^3 for crystals, and 2600–3200 kg/m^3 for lithic particles. Since coarser and denser particles are deposited close to source, fine glass and pumice shards are relatively enriched in ash fall deposits at distal locations (Shipley and Sarna-Wojcicki, 1982). The abrasiveness of volcanic ash is a function of the hardness of the material forming the particles and their shape, with a high degree of angularity leading to greater abrasiveness.

Vitric particles typically contain small voids, known as vesicles (Fig. 1), formed by expansion of magmatic gas before the enclosing magma solidified. Ash particles can have varying degrees of vesicularity. Vesicular particles can have extremely high surface area to volume ratios (Heiken and Wohletz, 1985). Exsolved magmatic gases condense onto ash particle surfaces while they are in the conduit and ash plume (Fig. 2). Surface coatings on fresh ash can be highly acidic, due to the presence of strong mineral acids H_2SO_4 (formed from the oxidation of SO_2), HCl and HF. Over 55 soluble components have been measured in volcanic ash leachates. Freshly deposited volcanic ash is therefore potentially corrosive and electrically conductive (Witham et al., 2005; Stewart et al., 2006; Wilson and Stewart, in press).

1.4. Distribution

Volcanic ash is the most widely distributed product of explosive volcanic eruptions. Ash particles ejected from an eruption vent are typically incorporated into an eruption column that may buoyantly rise tens of kilometres (and up to 50 km) into the atmosphere. Eruption plumes are dispersed by prevailing winds and the ash can be deposited hundreds to thousands of kilometres from the volcano, depending on wind strength, ash grain size, ash density and eruption magnitude. Additionally, the aggregation of ash, as observed in deposits (e.g., Brown et al., 2011), directly settling from an eruption plume (Taddeucci et al., in press) or during laboratory experiments (e.g., Kueppers et al., 2011), influence the characteristics of a fall deposit. Ash deposit thicknesses and grain size generally decrease exponentially with distance from a volcano (Fig. 3; Pyle, 1989). Unconsolidated ash deposits may be subject to remobilisation by fluvial or wind processes.

2. Impacts on electricity networks

Modern society has a critical dependence on the reliable supply of electricity. Outages can have significant cascading impacts for other critical infrastructure sectors and for society as a whole.

Volcanic ash can cause a range of impacts on electrical generation, transmission and distribution networks (Fig. 4). The main impacts are: (1) supply outages from insulator flashover caused by

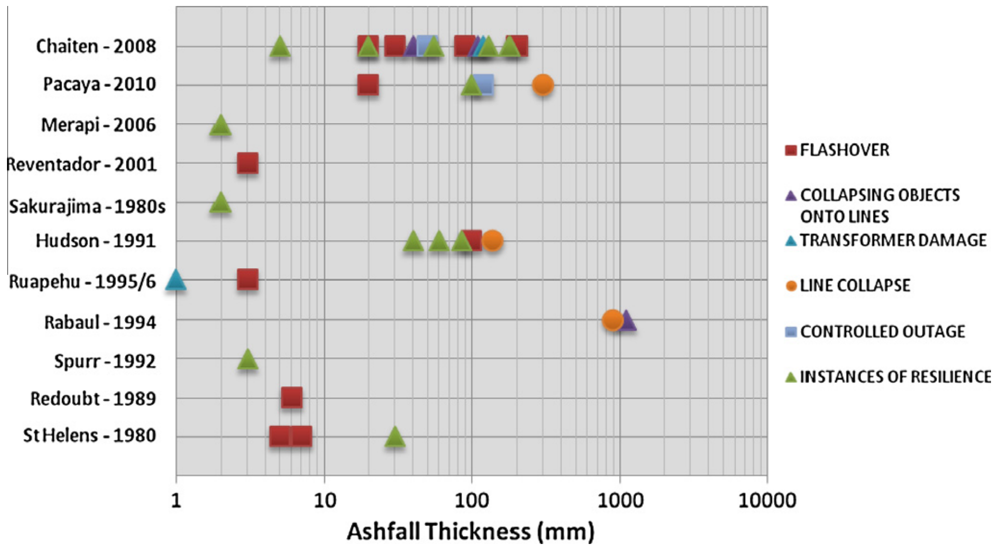

Fig. 4. Summary of volcanic ash impacts to electrical systems following different volcanic eruptions since 1980.

ash contamination; (2) controlled outages during ash cleaning; (3) line breakage due to ash loading; (4) abrasion and corrosion of exposed equipment; and (5) disruption of generation facilities (Nellis and Hedrix, 1980; Stember and Batiste, 1981; Sarkinen and Wiitala, 1981; Blong, 1984; Heiken et al., 1995; Wilson et al., 2009).

2.1. Insulator flashover and the resistivity of volcanic ash

Insulator flashover is the most common impact on electrical networks from volcanic ash fall, and is a problem across generation, transmission and distribution components. An unintended electrical discharge around or across the surface of an insulating material is known as a 'flashover' (Fig. 5). Flashovers can occur when insulating surfaces are coated with a substance that is conductive, such as volcanic ash. Fresh volcanic ash has a thin surface coating of soluble salts (see Section 1.3 and Fig. 2). When dry, ash typically has a low conductivity (high resistivity) to electrical current, but when wetted, the soluble salts on the surface are mobilised and lower the resistivity. Power outages may occur if the load on the circuit is sufficient to trip the circuit breaker.

Many factors influence flashover potential from volcanic ash contamination, including grain size, soluble salt content, ash fall thickness, shape and composition of exposed components, network configurations and weather conditions before, during and after the event (Fig. 6 and Table 2; Johnston, 1997). Interactions between variables increase the complexity and difficulty of making predictions. Important variables are discussed further below.

The presence of moisture is generally required to initiate flashover. There have been no observations of dry volcanic ash causing flashover to electrical distribution networks. However, heavy rain and/or strong winds will remove ash from lines, insulators and other equipment. Weather conditions of light, misty rain (1–2 mm/h) are considered the most likely to initiate flashover during or after ash fall (Wilson et al., 2009). Moisture may also be derived from the eruption plume itself or if the eruption has occurred through a water source such as a crater lake.

Moisture is also an important factor in ash adherence to exposed surfaces. Dry ash generally tends to rest only on horizontal or gently sloping surfaces whereas wet ash will stick to all exposed surfaces. In experiments on ash from the Mt. St. Helens eruption (Nellis and Hedrix, 1980), heavy rain washed 66% of deposited ash from insulators whereas light rain removed little ash. Winds of 55 km/h removed 95% of dry ash.

Field observations suggest that where ash thicknesses are the same, finer ash will cause greater problems than coarser ash. It

Fig. 5. An example of a flashover (three faults) on a glass string insulator. The insulator has been coated with 3 mm of wet volcanic ash. Flashover occurred at ~40 kV (insulator string design voltage 40 kV).

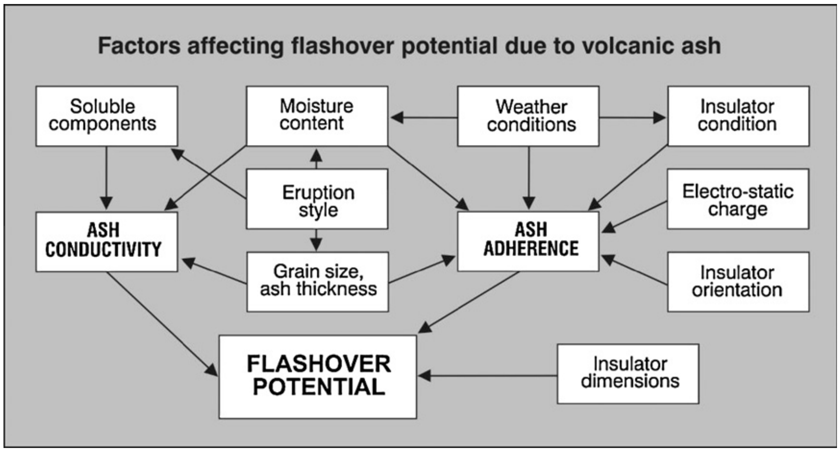

Fig. 6. Factors affecting flashover potential due to volcanic ash (from Johnston, 1997).

Table 2
Risk of line and substation insulator flashover following ash fall (based on Wilson et al. (2009)).

Risk factors		Probability of failure			
Line voltage	Ash moisture content	Ash thickness < 5 mm		Ash thickness > 5 mm	
		Fine ash	Coarse ash	Fine ash	Coarse ash
<33 kV (domestic)	Wet	High	Low	High	Medium
	Dry	Low	Low	Low	Low
>33 kV (regional–national)	Wet	Medium	Low	High	Medium
	Dry	Low	Low	Low	Low

has greater adherence to surfaces, more easily penetrates electrical equipment, and a higher surface area giving a higher soluble salt load and thus electrical conductivity when moist (Wilson et al., 2009).

Insulator size, composition, condition and orientation of insulators also influence ash-induced flashover potential. In general, smaller insulators will be more vulnerable to flashover because of the shorter distance for the current to travel. The risk of flashover increases as the proportion of the surface covered by ash increases; Nellis and Hedrix (1980) demonstrated that insulation that has 30% or more of its creepage distance (the shortest distance on the surface of an insulating material between two conductive elements) either clean or dry has a low probability of initiating insulator flashovers. Composition is also important; newer-style epoxy insulators increase ash adherence compared to porcelain or glass insulators (Heiken et al., 1995). Finally, surfaces that are already contaminated (e.g. by sea spray) are more vulnerable to ash-induced flashover.

2.2. Generation sites

General impacts of volcanic ash fall on generation sites can include flashover in substation yards (see Section 2.3); ash penetration into buildings which may damage sensitive machinery and electronics; damage to heating, venting and HVAC systems (see Section 8); and structure failure such as the collapse of long span roofs in the event of heavy ash fall. Impacts specific to hydroelectric power stations are discussed below. Insufficient information was obtained about the impact to thermal power stations for coverage here.

2.2.1. Hydroelectric power stations

Suspension of ash in storage dams can lead to abrasion of turbines. During the October 1995 Ruapehu eruption, 7.6 million cubic metres of coarse basaltic andesite ash was deposited into the Tongariro river catchment, leading to high levels of suspended sediment. This catchment feeds the Rangipo power station (120 MW), which has an intake to the underground headrace tunnel 20 km from Ruapehu volcano. The ash was composed of varying mixtures of volcanic glass, plagioclase, orthopyroxene and clinopyroxene; there were also minor components of lithic or country rock fragments and spheroids of elemental sulphur (Cronin et al., 1998). Management decided to continue generation throughout the eruptive episode. However, during inspections in April 1996 it was discovered that significant wear had occurred to the two Francis turbines and all auxiliary components that had been in contact with the suspended ash. Over a six month period the components suffered the equivalent of 16 years' abrasion damage (Meredith, 2007).

In contrast, turbine damage did not appear to be a feature of the impacts of the May 2008 eruption of Chaitén volcano, Chile (described in more detail in Section 6.4), on the 448-MW Futaleufú hydro dam, located approximately 90 km SE of the volcano in Chubut province, Argentina. A direct ash fall of between 50 and 100 mm of fine-grained rhyolitic ash was received at the hydro dam, although greater thicknesses were received across the storage lake. Due to the fine grain size and high pumice content of the ash, it remained suspended in the lake for over eight weeks, during which time the dam continued to generate electricity. During our visit in February 2009, engineers reported that there had been no drop in generation efficiency, suggesting that turbines had not been damaged by abrasion. However, no inspection had been made. There were minor concerns about abrasion or corrosion damage to the interior of the penstocks as these were made of softer metal.

The Fuataleufú dam did suffer other problems as a consequence of the ash fall. The heavy ash falls blocked rain gauges in the dam's catchment. This was a major safety concern for the dam as the ash fall occurred during the rainy season when high rainfall events

Table 3
Risk of damage to towers, poles and lines following ash fall (based on Wilson et al., 2009).

	Weather conditions	Ash thickness < 100 mm		Ash thickness > 100 mm	
		Fine ash	Coarse ash	Fine ash	Coarse ash
Towers and poles	Wet	Low–medium	Low	Medium–high	Low
	Dry	Low	Low	Medium	Low
Lines	Wet	Low-medium	Low	High	Low–medium
	Dry	Low	Low	Medium	Low

could lead to rapid lake rises. The management also developed strict building entry/exit protocols to limit ash ingress into buildings, particularly to avoid contamination in the powerhouse and control rooms. This included taping plastic sheeting around windows, doors and HVAC ducts; installing sticky floor mats to collect ash off footwear; and instigating double-door entry.

Cleaning up the dam site was a major task. Over 180 t of ash was removed from the powerhouse roof and substation area (approximately 1500 m^2). There were also difficulties with access to the site due to the poor visibility and traction problems caused by ash falls on roads.

2.3. Substations

An electrical substation is a subsidiary component of an electricity generation, transmission and distribution system where voltage is transformed from high to low or the reverse using transformers. Transmission and/or distribution lines concentrate at a substation, creating a vulnerable network node. Substations generally have an array of switching, protection and control equipment and one or more transformers. Much of this carries live current and so is vulnerable to flashover if sufficient ash accumulates. Experience from the 1980 Mt. St. Helens eruption showed that substation insulators were more susceptible to flashover than line insulators due to their shape and often horizontal orientation (Nellis and Hedrix, 1980). Ash can also abrade and clog equipment such as circuit breakers, cooling fins and HVAC system filters. For these reasons, precautionary cleaning at substations is common after an ash fall.

At Futaleufú dam site, Argentina, during the 2008 Chaitén eruption (discussed in Section 2.2.1) electricity transmission was disrupted by ash accumulating on vertical transformer insulators in the step-up substation which induced a significant flashover fault. The substation connects the dam to the Chubut province power grid, a 240 kV high-voltage transmission system. The fault occurred in early May following light misty rain (approx. 2 mm/h) which wetted the ash, but did not wash it off surfaces. Flashovers also occurred on the 240 kV high-voltage Chubut transmission lines. Following this major fault, the dam, substation and transmission lines were cleaned every 10 days for several months as a precaution, due to ongoing light ash falls and wind-remobilised ash. The ash was difficult to remove even with a high pressure hose, as it had formed a 'cement'. In some cases crews had to chip ash off the insulators with a screwdriver.

The gravel ballast (substrate) in substation and electrical yards is of known resistivity to provide a safe environment for substation workers. The deposition of moistened ash on ballast could potentially reduce resistivity and increase the possibility of an electrocution hazard. However, although this was identified as a potential hazard following the 1980 eruption of Mt. St. Helens, we are unaware of any recorded impacts.

2.4. Transmission and distribution lines

Transmission lines carry bulk electricity at high voltages (110 kV or above) to reduce the energy lost over long distance from generation source to users (e.g. population centres). Power is usually transmitted through overhead power lines using three phase alternating current (AC). Typically transmission lines are supported by large pylons with large strings of insulators (normally ceramic, glass or polymer construction). When close to the users, the voltage is stepped down through a substation transformer, and lower voltage lines distribute electricity to users. These distribution lines are usually mounted on poles with smaller single insulators.

The main impact of volcanic ash fall on transmission and distribution lines is likely to be insulator flashover. Lines may also be damaged by heavy ash falls onto overhanging tree branches, particularly if weather conditions are also snowy (Fig. 4 and Table 3).

Experience from impacts of the 1980 eruption of Mt. St. Helens volcano on electrical networks (Sarkinen and Wiitala, 1981) suggests that transmission networks are generally less vulnerable to ash-induced flashover than distribution networks. Transmission networks (110–500 kV) were able to withstand ash falls of 6–9 mm before serious flashovers occurred. However, on smaller distribution networks (33 kV) and domestic supply voltages (400 V) which received the same thickness of ash, flashovers were a more common problem, leading to sustained power outages of several hours or longer. This was thought to be due to the smaller surface areas of insulators on these systems (Section 2.1).

Problems were also experienced following the May 2008 eruption of Chaitén volcano, Chile. On a 68 km-long 33 kV distribution line feeding the Chilean town of Futaleufú, 10–20% of insulators flashed over following falls of fine rhyolitic ash of at least 50 mm and in some areas over 100 mm, between 2 and 6 May. Failure occurred several days after the ash fall, following light rain during 6–9 May. Subsequent heavy rain washed off most of the ash, but the undersides of insulators remained contaminated because fine ash had adhered to all sides. All insulators along this section of line were replaced as it was considered too laborious to assess each insulator. Impacts were compounded by heavy snowfalls in the region on 18 May, which increased the loading on lines (with 6 mm diameter lines becoming '20 mm tubes' of snow and ash). Ash and snow-laden branches collapsed onto lines, requiring a further 20 km of lines and poles to be replaced.

In other areas that also received ash fall from this eruption, networks were more resilient. In the town of Futaleufú, 75 km southeast of the volcano, there was no failure to domestic supply lines, despite over 100 mm of ash fall during May. In the town of Esquel, 110 km to the east in Argentina, there was no failure to 33 kV, 13.2 kV, 222 V, and three-phase 380 V networks, despite 50 mm of ash falling on the town throughout May 2008. There were several controlled cuts for cleaning ash from transformer insulators.

A key mitigation action following an ash fall is to clean or replace ash-covered insulators. Following the 1995/1996 eruptions of Ruapehu volcano, flashover problems that occurred on 110 kV lines following just 3 mm of ash fall prompted the network owners to experiment with cleaning methods. Methods trialled included water-blasting (1500 psi), fire hosing, dry wiping and using a knapsack sprayer and cloth. The most effective method was found to be water-blasting followed by dry wiping (Powermark, 1995).

3. Impacts on water supplies

There are three main ways in which volcanic ash falls can affect water supplies (Stewart et al., 2009b). Firstly, volcanic ash can physically disrupt or damage water sources and components of water supply, treatment and distribution systems. Secondly, the deposition of ash into surface waters can change its physical and chemical characteristics. And thirdly, following an ash fall, there can be heavy demands placed on water resources for cleanup purposes, and shortages can result if this situation is not managed.

3.1. Physical damage to water supply systems

While proximal hazards (particularly pyroclastic flows, ballistic ejecta and lahars) can be particularly destructive to components of water supply systems, volcanic ash can also cause damage and disruption on a more widespread scale.

Ash can block water intakes. The 1945 eruption of Mt Ruapehu, New Zealand, deposited ash falls of several mm thickness across the North Island, which caused problems for the water supply in the town of Taumaranui. Ash suspended in the Whanganui River, from which the town draws its supply, blocked filters at the supply's intake structure, reducing pumping rates from 90,000 l/h to 31,500 l/h (Johnston, 1997).

Airborne ash can damage components of water distribution systems such as electrically-powered pumps, electrical switchboards, filters and motors. A dome collapse event at Soufrière Hills volcano, Montserrat, in July 2003 caused widespread ash fall over the island. The ash clogged springs and caused corrosion damage to hydrant boxes and valves, and power outages and surges damaged electrical switch gear at a pump station. These problems were compounded by the intermittent power supply from Montserrat's national grid which was commonly affected by volcanic ash induced flashover faults. However the electricity network has recently been upgraded to mitigate damage by using protection circuit boards, so that the system is compartmentalised and the area with the fault can be switched off. Previously whole-island outages would occur, before these were in place (PAHO, 2003; Sword-Daniels, 2010).

A further example comes from the 1991 eruption of Volcán Hudson, Chile (Wilson et al., 2010a, 2010b). This eruption caused widespread and long-lasting impacts on primary production and rural communities in Chile and Santa Cruz province, Argentina (Inbar et al., 1995; Wilson et al., 2010a). Horticulture in the region bordering Lago Buenos Aires/Lago General Carrera is heavily dependent on irrigation, primarily using open channel flood irrigation systems. Channels became clogged with ash, and had to be laboriously excavated by hand. Ongoing ash deposition from windstorms, which remobilised the ash, posed problems for the operation of irrigation systems for two to three years after the eruption. In the arid coastal zone of Santa Cruz province, farm water supplies are sourced from deep (100–120 m) wells. While the water remained uncontaminated by the ash fall, problems were experienced with electric and wind-powered pumps used to extract the groundwater. In the case of windmills, fine ash penetrated the bearings and caused them to seize up. Thus, while groundwater-fed systems are generally less vulnerable to ash fall, well-head pumping equipment can still be a point of vulnerability.

3.2. Water quality impacts

The surface reactivity of volcanic ash is high and a range of ions can be released into surface waters upon contact (Delmelle et al., 2007). Over 55 soluble components have been reported in volcanic ash leachates (Witham et al., 2005), with the anions Cl^-, SO_4^{2-} and F^- and the cations Ca^{2+}, Na^+ and Mg^{2+} generally the most dominant. Stewart et al. (2006) have developed a model to predict ionic concentration increases in waters receiving ash fall (in the absence of environmental buffering). This model can be stated concisely as follows:

$$C_{water} = C_{ash}TDA/V$$

where C_{water} is the predicted concentration increase of a soluble component in the receiving water body in mg/l, C_{ash} is the concentration of that component in the ash in mg/kg dry weight, T is the thickness of the ash fall in metres, D is the density of the ash in kg/l, A is the surface area of the water body receiving ash fall and V is the volume of the receiving water body in cubic metres. The term 'A/V' can be thought of as the vulnerability of a particular water body to aerial contamination as it describes the surface area open to deposition relative to the volume available for dilution.

3.2.1. Fluoride

Witham et al. (2005) has reviewed volcanic ash leachate composition and concluded that while a range of elements of health significance are reported to occur in ash leachates, the principal toxic element adsorbed on volcanic ash is fluoride (F^-). Fluoride concentrations exceeding guideline levels (a level of 1.5 mg/l is set by the World Health Organisation though there are minor variations in levels adopted by different countries) are associated with an increased risk of dental fluorosis, and levels exceeding 10 mg/l can lead to skeletal fluorosis. These are generally long term (chronic) exposure limits and effects. These authors recommend that this element be specifically monitored in volcanic ash from future eruptions, particularly for volcanoes which have a past history of high fluoride levels, such as Hekla volcano in Iceland. However, only a restricted number of volcanic systems worldwide are particularly fluoride-rich, notably in Iceland and Melanesia (Witham et al., 2005).

3.2.2. Acidification

Ash leachates are typically acidic due to the presence in volcanic plumes of the strong mineral acids H_2SO_4 (formed from the oxidation of SO_2), HCl and HF, and consequently may acidify receiving waters, although the majority of surface waters have sufficient alkalinity to buffer against significant pH change. For example, following the May 2008 eruption of Volcan Chaitén in Chile, leachate from ash deposited on the city of Esquel, Argentina, was acidic (pH 4.76 for a 1:25 mixture of fresh ash:distilled water). However, in a surface canal used for the city's water supply, the pH remained at normal levels of 7.8 despite receiving ash fall (Stewart et al., 2009a). Similarly, following the eruption of Mt. Spurr volcano, Alaska in 1992, although deposition of ash into surface waters caused dramatic increases in turbidity levels at the raw water intake of the Ship Creek water treatment facility (Section 3.2.3), the pH of the raw water did not vary from its normal range of 7.5–7.6 over the same time period (Stewart et al., 2009b).

Roof-fed rainwater tanks are particularly vulnerable to changes in acidity as rainwater typically has a very low alkalinity. In Vanuatu, acidification of drinking water supplies (largely rainwater-fed and stored in tanks or cisterns) is a well-characterised problem (Cronin et al., 2003). However, it is attributed primarily to rainout of sulphate aerosol (Cronin et al., 2003) arising from active or passive volcanic degassing rather than ash fall. Even low atmospheric concentrations of SO_2 can strongly acidify water droplets because of the relatively high solubility and dissociation constants for this compound (Stewart et al., 2009b).

3.2.3. Turbidity

Volcanic ash particles suspended in water increase the turbidity (measured in Nephelometric Turbidity Units, or NTU). This is a critically-important parameter in drinking water treatment, and it is

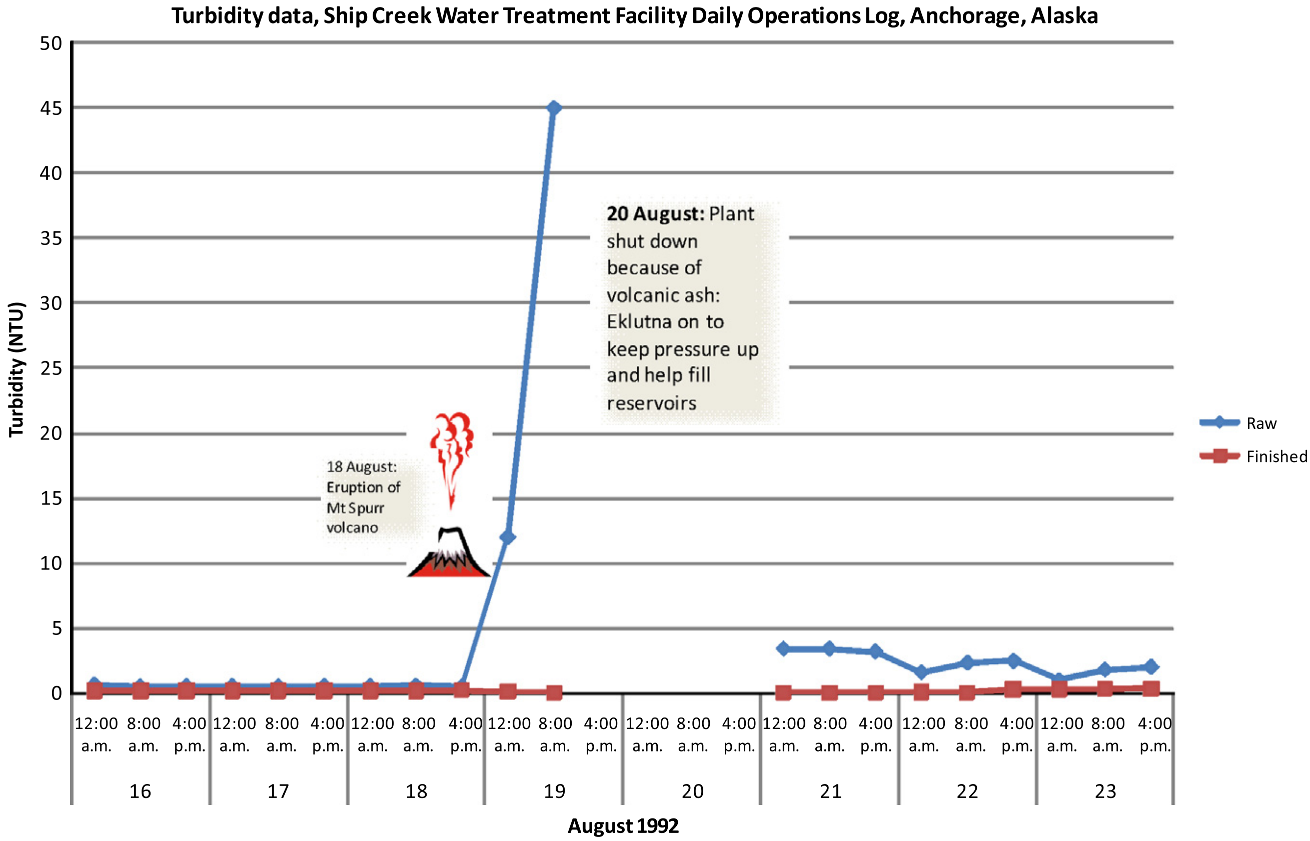

Fig. 7. Turbidity increases at Ship Creek water treatment facility following eruption of Mt. Spurr volcano (data from Anchorage Water and Wastewater Utility, AWWU).

monitored closely throughout the process. Suspended particles can protect micro-organisms from the effects of disinfection of water supplies, and can stimulate bacterial growth. Effective water treatment depends on the control of turbidity. The Anchorage Water and Wastewater Utility (AWWU), for example, maintains a finished water turbidity of 0.1 NTU (compared to the USEPA's maximum allowed level of 0.5 NTU) to reduce the risk of a pass-through of the infectious protozoan parasite *Cryptosporidium* (AWWU, 1995).

Turbidity is managed primarily with the addition of chemical flocculants such as aluminium or ferric sulphate; these serve to aggregate suspended particles so that they settle to the bottom. This is commonly followed up with the addition of lime and soda ash as secondary coagulants and to regulate the acidity of finished water to a slightly alkaline state. Chlorine is typically added to the finished water for terminal disinfection; in the event of turbidity incursions chlorination can be increased to compensate for higher turbidity levels.

Following the eruption of Mt Spurr volcano, Alaska, on 18 August 1992, turbidity levels in raw water at the Ship Creek treatment facility (one of the two main water sources for the city of Anchorage) increased dramatically from normal levels of 0.5–0.6 NTU to 45 NTU the morning after the eruption (Fig. 7). As there was redundant production capacity in the wider system, the AWWU was able to be shut down this plant for a period of approximately 30 h on a precautionary basis. Despite the major changes in turbidity, few other changes in water quality were noted in the daily operations log in response to the ash fall (Stewart et al., 2009b).

3.2.4. Other parameters

Applying the predictive model (Section 3.2) to ash fall from the 1995/1996 eruptions of Mt Ruapehu, which was well-characterised in terms of its leachate composition, yielded some useful insights into other probable changes to water quality in response to volcanic ash fall (Stewart et al., 2006; Johnston et al., 2004). Although fresh ash will release a range of soluble components into surface waters upon contact, those most likely to exceed guideline levels are the metals iron (Fe), manganese (Mn) and aluminium (Al). These elements are not normally considered to pose health risks and thus are regulated by secondary, non-enforceable guidelines aimed at protecting the potability of the water rather than primary standards for elements of health concern. Exceedences of guideline values for Fe, Mn and Al may cause raw water sources to become undrinkable due to a bitter metallic taste and dark colour. However, volcanic ash fall has a highly variable composition with respect to its soluble surface coating (Johnston et al., 2004; Witham et al., 2005) and therefore caution should be used in applying conclusions from a particular event more widely.

3.2.5. Public concern

During and after an eruption a high level of public concern and anxiety about contamination of water supplies by volcanic ash is common (Johnston et al., 2000). A timely, well designed and transparent monitoring programme which is communicated clearly to the public can be very effective in allaying concerns (Stewart et al., 2009a).

3.3. Water shortages

Following a volcanic ash fall, there can be heavy demands placed on water resources for cleanup purposes, and shortages can result if this situation is not managed. This can compromise key services such as firefighting capacity, and can lead to a lack of water for hygiene, sanitation and drinking.

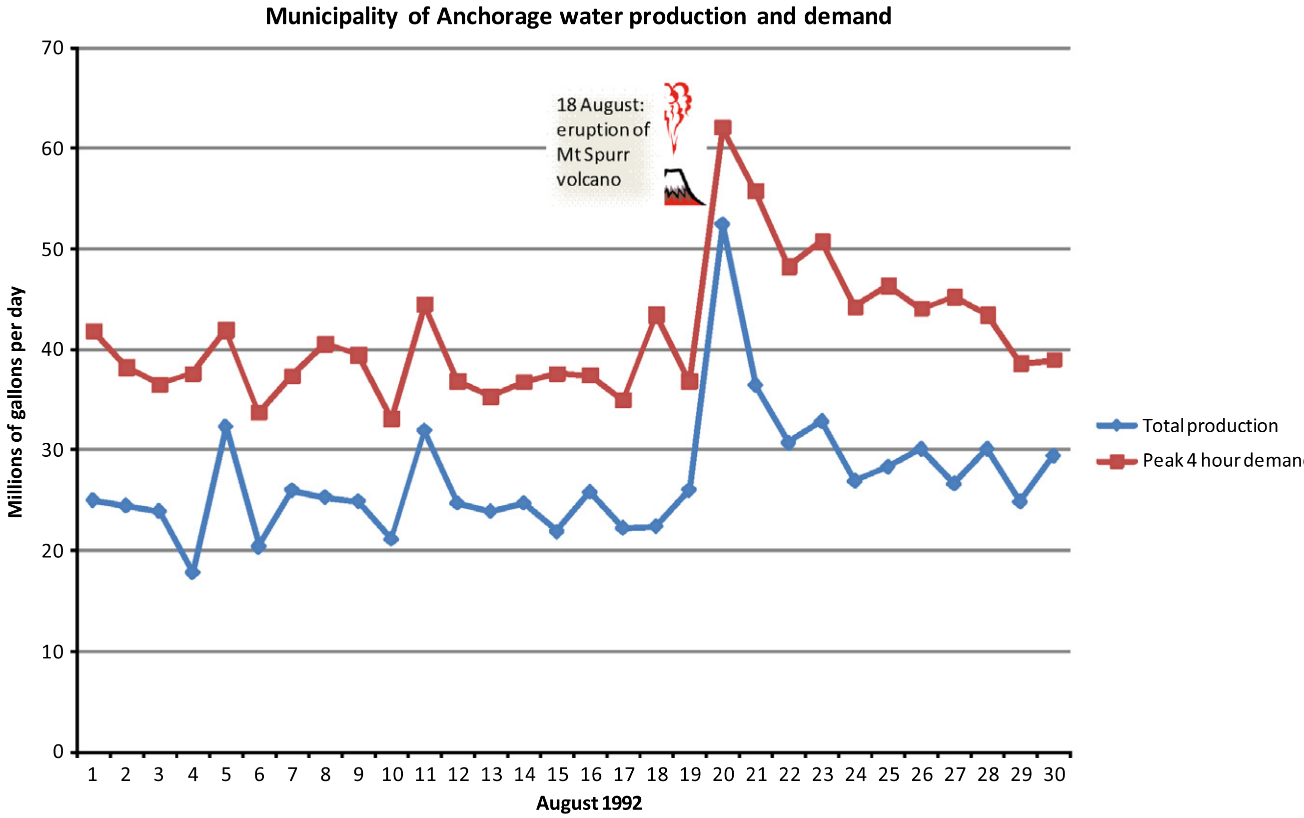

Fig. 8. Water demand and production for the city of Anchorage, Alaska (data from AWWU).

The 1992 eruption of Mt. Spurr volcano in Alaska and its effects on the city of Anchorage presents a well-documented case study including daily operation logs from the city's public utilities (Johnston, 1997). The eruption of Mt. Spurr on 18 August 1992 deposited about 3 mm of fine sand-sized volcanic ash on the city, 120 km to the east. By 10 am the following day, the AWWU was recording a peak water demand rate of approximately 63 million gallons per day (Fig. 8), a 70% increase over normal peak demands. The total daily demand for 19 August was 57 million gallons compared to the normal daily demand of 25 million gallons.

At 4 pm on 19 August, the Ship Creek water treatment facility closed down due to rapidly rising turbidity levels (Fig. 7). However, there was still adequate production capacity to meet peak demand from the other main water treatment facility (Eklutna) plus a well system (consisting of 17 deep wells) that normally serves as a standby source. While the city did have adequate production capacity to meet the peak demand, bottlenecks existed throughout the distribution system and as a result, severe water shortages and loss of pressure occurred right across the city. Levels in several storage reservoirs dropped to dangerously low levels, and AWWU officials were very worried that if building fires had occurred during this period, it was unlikely that water for firefighting would have been available, particularly in the south and west of the city. The volcanic crisis gave the impetus to complete a major upgrade of the city's water transmission network.

4. Impacts on wastewater and stormwater networks

Volcanic ash fall can cause damage and disruption to wastewater systems (both sewage and stormwater). Ash can enter and block pipes and sumps, can cause accelerated wear on motors and pumps, and can cause serious damage to wastewater treatment plants (WWTPs).

4.1. Impacts on sewerage and stormwater drainage networks

When volcanic ash falls on impervious surfaces such as roads, car parks or roofs, even if only several millimetres thick, it can easily be washed into stormwater drains by rainfall, or if water is used for cleanup operations. While stormwater sometimes has its own separate reticulation network, channelling runoff into natural drainages, there is commonly a degree of overlap with sewerage reticulation systems, particularly for older infrastructure. Even if systems are separate, ash can still enter sewer lines by the processes of inflow and infiltration (e.g. through illegal connections such as roof downpipes connected directly to sewer lines, cross connections, ingress through household gully traps, around manhole covers, or through holes or cracks in pipework).

Once ash has entered underground drainage networks, it can form unpumpable masses and be extremely difficult to remove. Consequences can include the failure of equipment such as pumps, and surface flooding. Following the May 27, 2010 eruption of Volcán Pacaya, Guatemala, between 30 and 100 mm of coarse (sand-sized) basaltic ash was deposited across much of Guatemala City, located approximately 30 km to the north. Despite a prompt and comprehensive cleanup operation organised by the city's municipality, heavy rains caused by tropical storm Agatha shortly afterwards washed quantities of ash into the city's storm drains where it caused widespread flooding problems (Fig. 9). One of the city's two main hospitals (Hospital Roosevelt) is located in an area with pre-existing drainage problems. The hospital's basements flooded due to drains being blocked, and services in this area had to be relocated. Guatemala City continues to experience severe flooding problems during heavy rains, with motorway tunnels being particularly prone to flooding (Wardman et al., in press). These floods, in turn, lead to severe disruptions to traffic flow.

Fig. 9. Cleanup of Guatemala City roading network (photo credit: Ing. Alvaro Hugo Rodas Martini, Municipality of Guatemala City, 2010).

4.2. Impacts on wastewater treatment plants

Ash can enter WWTPs both via sewer lines (particularly if these are combined with stormwater lines), and by falling directly on treatment facilities.

4.2.1. Ash ingress via sewer lines

Ash-laden sewage that enters a treatment plant may overload equipment and filters designed to trap solid debris at both the pre-treatment and primary treatment stages. In particular, mechanical pre-screening equipment (such as step, rotating or bar screens) is particularly vulnerable to damage. Ash can abrade moving parts and block screens which can cause motors to burn out. Ash that enters primary treatment (sedimentation) tanks is likely to settle and thus increase the volume of raw sludge. Finer grain sizes may not settle and any pumice fragments (more likely in silicic eruptions) will float. Any residual fine ash persisting further through the treatment system may reduce the transmissivity of the effluent, which could compromise the effectiveness of disinfection.

On 18 May 1980, Mt. St. Helens volcano erupted and the city of Yakima (population 50,000), located 140 km to the east, received about 10 mm of sand-sized ash. By the next day, about 15 times the normal amount of solid matter was being removed from the pre-treatment processes at Yakima's WWTP. This was despite Yakima having just five percent combined stormwater and sewage lines. Ash was also observed in the raw sludge in the primary clarifiers. Throughout the day, it was evident that the facility was suffering damage as vibrations were occurring in the grit classifier and the gear box of the mechanically-cleaned bar screen. Pumping difficulties were experienced and sludge lines became blocked. By the third day, the passage of ash through the plant had stripped filter beds bare and the comminutor failed (Day and Fisher, 1980).

On 21 May, the City Manager announced a decision to bypass the treatment plant and discharge sewage (after chlorination) directly to the Yakima River. The total damage to the treatment plant was estimated to be US$4 million (1980 value; Day and Fisher, 1980).

4.2.2. Direct ash fall

Ash fall can be directly deposited on WWTPs and uncovered equipment, such as open air biological reactors, ponds and clarifiers, is particularly vulnerable. More generally, airborne ash can clog air filtration systems, cause abrasional damage to moving parts of motors and cause arcing and flashover damage to electrical equipment. Heavier ash falls (>150 mm) may collapse long span roofs.

The May 2010 eruption of Pacaya volcano (Section 4.1) had widespread impacts on Guatemala City's wastewater treatment facilities. The city has hundreds of WWTPs ranging in size from those serving just a few households to larger facilities such as the plant serving the University of San Carlos. This system utilises an Imhoff tank (a combined sedimentation and sludge digestion tank). The Imhoff tank was filled with basaltic ash to a depth of 4–5 m, both from direct ash fall and by washing in through sewer lines. Ash was reportedly very dense; the company's own measurements indicate a density of 2.45 kg/l, which is in the range reported for the density of individual particles (2.35–3.3 kg/l, from Shipley and Sarna-Wojcicki, 1982). As a result, the ash mixed with the sewage sludge and sank to the bottom, where it was very difficult to move. Sludge pumps were used to remove the lighter material, but the heavier ash-contaminated sludge had to be dug out with shovels. Wastewater maintenance contractors Mapreco reported that cleaning ponds and tanks typically took two to three days with some systems taking a week to clean out. A further problem was that sludge pump propellers abraded, and their normal lifetime of two years was reduced to 15 days (Wardman et al., in press). The company estimated that additional business caused by the eruption increased their profits by 20%.

5. Impacts on transportation networks

Ash fall may severely disrupt transportation systems over large areas for hours to days, including roads and vehicles, airports and aircraft, railways, and ports and shipping. Additionally, during a volcanic crisis they may also be relied upon for the evacuation of communities exposed to volcanic hazards.

5.1. Ground transport networks

Falling ash will significantly reduce visibility, in some instances to near total darkness. Safe driving becomes difficult or impossible as vehicle headlights and brake lights are barely visible to other drivers. After an ash fall, fast-moving vehicles will stir up ash along roads creating billowing ash clouds up to tens of meters high creating ongoing visibility hazards. The deposition of fine, hard ash particles on road surfaces may reduce traction, particularly when the ash becomes wet. Ash deposits thicker than 1 mm will obscure or cover markings on roads that identify lanes, road shoulders, direction of travel, and instructions (for example, stop or slow) which may confuse and disorient drivers (Durand et al., 2001). Rail transportation is less vulnerable to volcanic ash than roads and highways, with disruptions mainly caused by poor visibility and breathing problems for train crews. Moving trains will also stir up fallen ash, which can affect residents living near railway tracks (Johnston, 1997).

Hard, fine-grained, abrasive and potentially corrosive ash can be highly damaging to vehicles. Fine-grained ash can infiltrate nearly every opening and abrade or scratch most surfaces, especially between moving parts of vehicles. Ash will block air and oil filters, thicken engine oil, and abrade seals and moving parts. Seals on hydraulic components may wear out faster than usual, and brakes and brake assemblies are especially vulnerable to abrasion and clogging from ash. Vehicles subjected to heavy ash exposure, such as those used for cleanup operations, may require frequent brake, filter and greasing maintenance, as seen following the 2008 Chaiten eruption. Ash caught between windshields and wiper blades will scratch and permanently mark the windshield glass, and windows are susceptible to scratching each time they are raised, lowered, and cleaned. Corrosion of paintwork and exterior fittings may also result where ash is in contact with the exterior (Johnston, 1997).

The disruption of transportation networks can have cascading impacts for other critical infrastructure sectors impacted by ash fall. Maintenance crews attempting to access impacted sites may be disrupted or blocked entirely from accessing the site. For example during the Chaitén eruption shift workers were severely disrupted accessing the Futaleufú hydroelectric power dam located approximately 90 km SE of Chaitén volcano in Chubut province, Argentina. Thick falling fine-grained rhyolitic ash reduced visibility to nil. The ash mixed with surface water on the roads and significantly reduced traction, causing several minor accidents. These dangers, and the desire to reduce remobilization of ash around the dam site by vehicle traffic, led to management deciding to maintain operations with a permanent skeleton crew for a period of one month, rather than rotating shifts.

5.1.1. Cleanup and disposal

The fall of a few millimetres of volcanic ash may result in the need for disposal of large quantities of material from road networks. Ash disposal should be undertaken in ways that minimises ongoing public health problems and is cost-effective (Johnston et al., 2001). The time required to clean up ash deposits will depend on the extent and depth of ash deposits and may take from several weeks to several months. Best results are achieved with a coordinated effort, where other agencies, utility companies and residents clean ash from all areas at the same time, which minimizes continued contamination from remobilized ash. Ash should be disposed of in a dedicated ash dump, rather than infilling valuable landfill space (see Johnston et al. 2001 for more information).

On 27 and 28 May, 2010, Guatemala City, received between 20 and 100 mm of coarse (sand-sized) basaltic ash fall from an eruption of Pacaya volcano located approximately 30 km SSW (Wardman et al., in press). Approximately 1 million people live within the city and 2.9 million live in the greater metropolitan area. The south of the city was more severely affected than the north. As the city generates 70% of Guatemala's GNP, there was a strong motivation to initiate a prompt and efficient city-wide cleanup to enable critical transport lifelines to be restored as quickly as possible (Wardman et al., in press). The total quantity of ash deposited on the city was estimated to be 11,350,000 m^3, and 2100 km of roads required cleaning. The cleanup was organised by the Municipality, and all available staff were co-opted along with assistance from the Army (Fig. 9). Factors contributing to the efficiency of the cleanup were: the pre-existence of an earthquake emergency plan which enabled heavy machinery to be mobilised quickly; a good command structure; clear communication to the public (who were asked to clear ash from their own roofs and yards, to be left at designated collection points or picked up from the roadside); and the donation of a large number of bags from sugar and cement companies for ash collection. Costs of heavy machinery hire (trucks, excavators and Bobcats) were estimated at Q1.6 million (US$ 0.2 million in September 2010). Few problems were reported with ash being remobilised, or causing additional wear and tear on machinery. This was probably due both to the coarse and dense nature of the ash, and also that the city experienced heavy rains shortly after the eruption due to tropical storm Agatha. Quantities of ash were washed into storm drains where it has caused ongoing flooding problems (Section 4.1).

5.1.2. Potential re-use

Volcanic ash can be used for a range of purposes, from building aggregate to landscaping fill. Ash is mined from pyroclastic density current deposits at Merapi volcano, Indonesia, and lahar deposits from the 1991 Pinatubo eruption, Philippines, as a valuable building aggregate for cinder block construction. Following the 1973 eruption of Eldfell, Iceland, the coarse volcanic ash and lapilli was a valuable source of fill on the island of Heimaey and used for infilling valleys for new urban development.

However in the case of the 27 May, 2010 eruption of Pacaya volcano, testing conducted on the ash deposited on Guatemala City indicated it was unsuitable for use as aggregate due to its friability (low mechanical strength).

5.2. Airports

An authoritative recent review by Guffanti et al. (2009) of volcanic hazards to airports found that between 1945 and 2006, 101 airports in 28 countries were affected on 171 occasions by eruptions at 46 volcanoes. These authors conclude that these hazards are not rare on a worldwide basis, as since 1980, five airports per year on average have been affected by volcanic activity. The main hazard to airports is ash fall, with accumulations of only millimetres is sufficient to force temporary closures of some airports. A substantial portion of incidents has been caused by ash in airspace in the vicinity of airports, without accumulation of ash on the ground. This was dramatically exhibited by the Eyjafjallajökull eruption in April–May 2010 which caused widespread airport closures in the UK, European and North Atlantic airspace. There were closures for six consecutive days in April 2010 and further disruptions and closures into May as air traffic controllers and airlines followed the ICAO rule of zero ash tolerance. Research following this crisis has served to better inform ash concentration tolerances for jet turbines (Gislason et al., 2011; Drexler et al., 2011). By 21 April, 95,000 flights had been cancelled in European airspace causing large economic losses to airline companies, the insurance industry and many industries dependent on gaining access to European markets (Sammonds et al., 2010). In contrast, long term experience at Anchorage airport, Alaska, has led management to close the airport only when ash falls on the runway.

On a few occasions, airports have been impacted by hazards other than ash (pyroclastic flow, lava flow, gas emission, and phreatic explosion). A consideration of ash impacts on airborne aircraft is beyond the scope of this paper. Refer to Casadevall (1994) and Guffanti et al. (2010) for further information on this topic.

5.2.1. Case study: Guatemala City

Guatemala City's international airport (La Aurora) received its first warning of impending ash fall at 6:30 pm on 27 May, 2010. The airport was officially closed at 7:23 pm the same evening, and re-opened at 1:18 pm on 1 June (Airport Manager, Direccion General de Aeronautica Civil). Approximately 20–30 mm of coarse (sand-sized) basaltic ash fell on La Aurora airport. The main reason for the airport closure was to allow for cleanup of the airport, rather than because of airborne ash hazards to aircraft. The personnel requirements for the cleanup were 30 staff from DGAC plus an additional 500 staff loaned by the army and air force. A staged cleanup of the runway and apron involved firstly using bulldozers to scrape ash into piles, where it was then shovelled into trucks both manually and using Bobcat loaders, followed by cleaning with street sweepers and finally cleaning with compressed air. The new bituminous runway surface (which cost $1.7 million USD in December 2009) was destroyed by abrasion damage. Markings on the runway and apron were also severely damaged by abrasion and had to be completely repainted before the airport could reopen. An estimated 56,000 m^3 of ash was removed from the runway and apron. Costs of the airport closure were estimated to be $250,000 USD (2010) in loss of income to businesses based at the airport. The airport buildings were also damaged by the ash fall. Gutters and downpipes were clogged with ash and caused leaks in the ceiling which were continuing some four months later, and the paint coating on the roof suffered abrasion damage.

5.3. Marine transportation

Marine transportation can be affected by volcanic ash in three main ways: direct physical impacts from falling ash, visibility disruption and physical impacts from pumice rafts. Similar to ground transportation, volcanic ash may clog air intake filters and abrade moving parts if ingested into engines. Thick ash falls will also reduce visibility creating a hazard to navigation. The third impact is unique to marine transport. Vesiculated ash (pumice and scoria) will float on the surface of water bodies in 'pumice rafts'. These rafts can clog salt water intake strainers very quickly, which can result in overheating of shipboard machinery dependent on sea water service cooling.

The 2008 Chaitén eruption in Chile prompted mass evacuations, which were largely carried out by marine transport. Small outboard motors were reportedly severely abraded and exhaust and cooling vents clogged by the floating pumice in Chaitén harbour. Larger vessels also suffered problems when floating ash pumice was sucked into the salt water service system, clogging sea strainers and leading to engine overheating.

6. Impacts on telecommunication networks

Impacts of volcanic ash on telecommunication and broadcasting networks include: (1) attenuation and reduction of broadcast signal strength; (2) ash damage to equipment; (3) indirect impacts, including overloading of networks through high user demand.

6.1. Signal attenuation and interference

It has been recorded that telecommunications signals have been disrupted during volcanic eruptions, notably following the 1969 Surtsey eruption and 1991 Pinatubo eruption. Scientists responding to the 1991 Pinatubo eruption in the Philippines reported VHF (160–175 MHz) telemetry was interrupted on 15 June when co-ignimbrite ash rose into the line of sight of seismic data transmissions (typically received at powers 30–40 dB above squelch, $\sim$1 μV). This may have been due to the large concentration of charged particles within volcanic plumes causing signal attenuation. The team had "uninterrupted communications via a commercial cell phone network" (J. Ewert and A. Lockhart, USGS/OFDA Volcano Disaster Assistance Programme, pers. comm., 2010).

However the phenomenon is not well documented in other eruptions. There have been numerous examples of telecommunications transmissions continuing to work during volcanic ash falls (Section 6.4). A recent analysis by telecommunications engineers for the New Zealand-based Auckland Engineering Lifelines Group concluded theoretically that impacts on electromagnetic signal transmissions would probably be limited to low frequency services such as satellite communications (Wilson et al., 2009). Interference (such as static) to signal transmission may also be caused by lightning, as lightning is frequently generated within volcanic ash plumes (McNutt and Williams, 2010).

6.2. Ash damage to equipment

Direct damage to network components (such as electronics) has been observed during several eruptions. Modern telecommunication systems require constant cooling for their electronics. Disruption of these HVAC systems can occur either by air-intake blockage or by precautionary shut-down to avoid problems (Johnston, 1997). The vulnerability of HVAC systems is described further in Section 7.2. Transmitting equipment, such as antennas and radio masts, may experience flashover when contaminated with moist ash (Wilson et al., 2009). Abrasion, clogging and corrosion damage to mechanical switches has also been reported (FEMA, 1984), although with the trend towards solid state electronics, this is arguably a reducing vulnerability.

Heavy ash falls may cause lines, cables, masts, aerials, antennae, dishes and towers to collapse due to ash loadings or the collapse of overhanging branches. Long-term exposure (weeks to months) of sensitive equipment to airborne ash can also lead to accelerated corrosion (Wilson et al., 2009; Barnard, 2009). Lightning strikes (mentioned in Section 6.1) associated with ash plumes may also damage telecommunications equipment. Following the August 1991 eruption of Volcán Hudson, Chile, HF and VHF radio receiver masts within 80 km of the volcano were struck by lightning, which destroyed the systems and affected the operation of the radio telephone system in the region (Wilson et al., 2010c).

6.3. Network overloading

Observations and reports from recent eruptions suggest that the largest single communications disruption is network overloading due to high user or data demands during an ash fall (Wilson et al., 2009). This is a common feature of many natural disasters.

6.4. Case study: May 2008 eruption of Chaitén volcano, Chile

After more than 9000 years of inactivity, Chaitén volcano, Chile, began erupting on 2 May 2008 with emissions of ash to an altitude of 20 km. On 6 May, the eruption intensity increased markedly with the eruption column reaching 30 km. This was the largest event worldwide since the eruptions of Pinatubo and Hudson volcanoes in 1991. Experiences from this event provide a useful case study of the performance of telecommunications networks during a major eruption. Our team visited the affected areas during January/February 2009.

In general, telecommunications networks were highly resilient to ash fall impacts, even though significant ash falls were received in towns such as Futaleufú (initial ash fall of 30 mm, total ash fall during May of approximately 150 mm). There were no reports of interruptions to service within the zone that received ash fall. In Futaleufú, emergency management staff reported that cellular and satellite phones, UHF radio and telemetered sites all continued to broadcast and receive signals throughout the eruption. Satellite dishes did experience some problems due to ash accumulation but this was easily mitigated by regular cleaning or covering dishes with a thin membrane. The only notable problem for cellular and landline networks was overloading due to high user demand.

The fine rhyolitic ash did cause damage to equipment. Cellular phones stopped working when ash penetrated their interiors and possibly short-circuited electronics or clogged keys. Video and still cameras also stopped working in the ashy conditions. However, if gently cleaned with compressed air or nitrogen and wiped with a damp cloth most reportedly resumed working. There were no reports of exchanges or transmitters suffering damage from ash ingestion.

7. Impacts on critical components

This section describes impacts on components which are common to most critical infrastructure sectors, and on which they may be heavily reliant.

7.1. HVAC

Heating, ventilation and air conditioning (HVAC) allows environmental control within structures. They are an essential and widespread part of critical infrastructure. They are essential for a healthy working environment inside inhabited buildings and for maintaining critical components of infrastructure in working order. In particular, HVAC systems are a critical component of much modern infrastructure. Most electronic control systems cannot function without external cooling, due to the heat generated by internal computers. For example, nearly all telecommunication exchange and cell sites require constant air conditioning. Other systems dependent on HVAC include medicine stores in hospitals and storage facilities for perishable food. Large commercial or public buildings also require interior temperatures to be controlled, so require large HVAC systems.

Air conditioners are known to be vulnerable to ash blockage, corrosion and arcing of electrical components, and air-filter blockage, especially if air intakes are horizontal surfaces. The type of HVAC system varies greatly depending on requirements. Sealed structures using an internal HVAC system (with external condenser) are less at risk than structures relying on external fresh air intakes, which blow ash directly onto electronics or filters can become blocked. Air filters used at communications sites are typically not designed to cope with the volume of material seen in an ash fall.

Following the 1992 eruption of Mt Spurr volcano, Alaska, HVAC intakes in the Anchorage telephone exchange experienced blockages, resulting in all air handling units being manually shut down after an ash fall of approximately 3 mm thickness. Fortunately, the cool temperatures in Anchorage were sufficient to prevent exchanges overheating, so shutdowns were not necessary (Johnston, 1997). Shutdowns of air handling units were on a precautionary basis.

During the 1995/1996 eruptions of Ruapehu volcano, ash falls were widespread over the North Island of New Zealand. In Ruatoria, 280 km distant, high temperature alarms in a small roadside exchange cabinet were triggered after air-conditioning filters were clogged with ash, following 1–2 mm of ash fall in this area (Johnston, 1997).

There have also been many instances of HVAC systems showing resilience to airborne ash. The city of Kagoshima, Japan, has received frequent light ash falls (<5 mm) from Sakurajima volcano 10 km to the west during the 1980s and 1990s. Exterior mounted HVAC units suffered no impacts and required no particular protective measures (Durand et al., 2001). Similarly, the city of Catania, Italy is also subject to frequent, small ash falls from Mt Etna. HVAC units are reported to function normally with no special protection beyond regular cleaning (Barnard, 2009).

7.1.1. Quantitative testing of HVAC systems

To better characterise ash impacts on HVAC systems, laboratory testing was carried out by Barnard (2009). The testing found that modern split system units were more vulnerable to ash blockage than older style wall-mounted units. Split system units have a high condenser surface area and slower fan speed (to reduce noise) and therefore have lower airspeed through the condenser; whereas older systems have a higher airspeed. It was found that high humidity or moisture on the condenser significantly increased ash adherence to the condenser, accelerating blockage. Results suggested that air conditioners are likely to remain viable during light ash fall (<20 mm), provided monitoring and regular maintenance are carried out.

7.2. Computers

Computers are critical to the functioning of modern society. Generally, computers are housed in protected locations inside structures so are not exposed to direct ash fall. As a result there have been few reports of ash causing problems for personal or mainframe computers over the past 20 years. Exposure may occur when ash penetrates structures (through HVAC systems for example) and through the increasing use of laptop computers for field applications.

Known impacts from volcanic ash fall have included abrasion of moving parts, such as fans; clogging and jamming of mechanical components, including cooling systems; shorting or grounding of circuits; etching of painted and metal surfaces; and generation of excessive heat under a blanket of dust or because of obstructed vents (FEMA, 1984). External components and connectors, such as USB ports may be abraded or clog with ash. Fine ash will also get stuck under keyboard keys, blocking the contacts. In 2007, high power computers within Montserrat Volcano Observatory overheated and failed due to HVAC systems blocking from fine volcanic ash. Ash ingress also causes corrosion and system blockages in interior computing equipment, which has been somewhat mitigated with regular cleaning and maintenance, operating a double-door, single point of entry policy into the building and preventing ashy field clothes from being worn in operating rooms. Computers are cleaned of ash annually as a preventative measure to protect equipment (Sword-Daniels, 2010).

Gordon et al. (2005) conducted a series of experiments with different types of volcanic ash (basalt and rhyolite) to experimentally assess their abrasiveness, conductivity and corrosiveness to computer equipment. They found the three ‘286’ personal desktop computers did not fail under normal ash fall conditions (defined as average 174,488 $\mu g/m^3$; maximum 219,536 $\mu g/m^3$). Even when ash fall rates were increased to simulate the catastrophic entry of ash into the building (e.g. from roof collapse) the computers continued to operate for between 100 to 150 h. Most failures only occurred when humidity was increased by spraying water mist into the airflow. Significantly, if dried out the computers continued to operate again. Card slot edge connectors proved to be one of the weakest links, as a bridge of ash formed across the gap. They were also subject to abrasion with some of the gold plating being removed, although this did not cause operating problems. The bearings within the computer cooling fan continued to work even after 720 h of testing and there was no significant abrasion of the fan-shaft bearing.

Following ash falls from the 1980 Mt. St. Helens eruption hard disk drives (HDD) were found to be susceptible to ash damage, with fine ash particles found in the hard disks and, importantly, under the read–write head (Labadie 1994). However, the study by Gordon et al. (2005) assessed more modern HDD as being relatively resilient to volcanic ash, due to modern filtering and sealing technology.

8. The interdependence of infrastructure

It is important that ash fall impacts are viewed in a more holistic way, to better understand the relationships and dependencies between affected infrastructure sectors – their interdependency (Meheux et al., 2007; Sword-Daniels, 2010). An understanding of how each component or impact-area interfaces and is connected with others is critical for addressing real problems and devising effective mitigation strategies to reduce infrastructure vulnerability. The use of systems thinking allows a flexible and holistic approach to be applied to any conceptualised system; by considering the elements within it and the interactions between them (Fig. 10).

8.1. Systems thinking

Systems thinking is a way of tackling complex issues (Aronson, 1996). It allows understanding of how changes in one part of the system can cause changes in another part, and that these changes

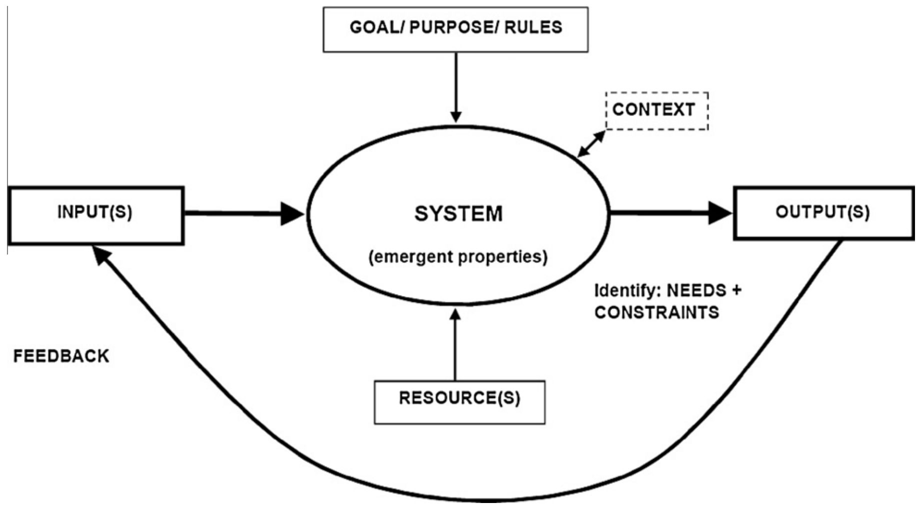

Fig. 10. An input–output model for systems thinking.

can have positive or negative effects. A broad approach must be taken to understand the dependency between systems and how any 'solution' to the problem may have consequences for the rest of the system. The aim of this approach is to pre-empt any cascading problems, and achieve overall improvement in system performance.

The cascading effects to other sectors constitute the dynamic vulnerability of the system and its environment. For example, ash-blocked drains can cause secondary flooding that may recur for weeks or months following an eruption, until the system is cleared of ash. The secondary flooding can cause road access problems, and can prevent access to impacted infrastructure for maintenance or repair. In this way the ash fall impacts on the water infrastructure system can have a knock-on effect to the functionality of transport systems. Equally the external context or environment can affect any particular system. For example infrastructure management protocols may be dependent on communications systems that can become overwhelmed and inoperable during crises, as a result of high user demand.

Both direct and indirect effects contribute to any system's vulnerability. Using a systems thinking approach to physical vulnerability, the internal and external influences on a system and their interdependencies, as well as the cascading impacts on other sectors beyond the system boundaries are taken into account. Disruptions may have a feedback mechanism to the original system, resulting in secondary impacts on a sub-system facility and longer-term disruptions or delayed recovery.

8.2. Case study in infrastructure interdependency: Montserrat

In order to demonstrate the intricate relationships and interdependencies between critical infrastructure sectors, we present a case study from Montserrat. Since 1995 the Soufrière Hills volcano has been in eruption causing dramatic impacts to the small Caribbean island of Montserrat. Pyroclastic density currents and subsequent lahars have devastated much of the southern part of the island. In addition, intermittent ash falls have caused a range of impacts to critical infrastructure in the inhabited regions to the north. A study in early 2010 investigated ash impacts on critical infrastructure and their interdependencies (Sword-Daniels, 2010).

The study found that electrical power failures by ash contamination of insulators causing flashovers had significant knock-on (cascading) effects. These included power surges when the power was restored and subsequent failure of electrical appliances, as well as impacts to critical infrastructure system functionality, communications networks, and HVAC units. Financial costs associated with this disruption include replacing appliances, business interruption costs, repair work on the electrical system, and the cost of regular maintenance.

The relative importance of the infrastructure in question must also be thoroughly understood in order to address the real problems that are caused by volcanic ash fall. Importance and interdependency are intricately linked; where complex secondary or tertiary impacts may lead to heightened system stress, in comparison with the primary impact alone. This is highlighted in Montserrat, where power failures are perceived to be a minor nuisance by the local population (where disruption is only for a few hours, once or twice a month). However, the functionality of HVAC depends on power. HVAC allows for comfort in tropical climates, but it also prevents critical (and expensive) computer systems from overheating and helps to mitigate ash ingress into buildings. Continuous power supply is therefore critical to preserving the longevity of computer systems and electrical equipment and reducing interior corrosion.

The cumulative effect of ash fall impacts highlights the importance of a holistic approach. Research on interdependent impacts and across disciplines is more likely to develop practicable assessment methodologies and adaptation or mitigation solutions, for use by practitioners such as utility providers, infrastructure engineers, system architects and emergency managers.

9. Discussion and conclusions

This paper has summarised ash impacts on critical infrastructure, identified key points of vulnerability and compared the relative vulnerability of different sectors under a range of different ash fall scenarios. Understanding these vulnerabilities is an essential first step to build resilience into infrastructure systems.

9.1. Summary of impacts by sector

Electricity networks are very vulnerable to disruption from volcanic ash falls. This is particularly the case for fine ash because it has a greater tendency to adhere to line and substation insulators, where it can cause flashover (unintended electrical discharge) which can in turn cause widespread and disruptive outages. However, weather conditions are a major determinant of flashover risk. Dry ash is not conductive, and heavy rains will wash ash from insulators; but light wet weather conditions will mobilise readily-soluble salts on the surface of the ash and lower its resistivity. Wet ash is also heavier than dry ash, increasing the risk of line breakage or tower/pole collapse.

Particular issues for water supply managers are likely to be monitoring turbidity levels in raw water intakes and if necessary increasing chlorination to compensate for higher turbidity; managing water demand; and communicating monitoring results with the public to allay fears of contamination.

Ash can also cause major damage to wastewater disposal systems. Ash deposited onto impervious surfaces such as roads and car parks is very easily washed into storm drains, where it can form intractable masses and lead to long-term flooding problems. It can also enter wastewater treatment plants, both through sewer lines and by direct fallout. Damage to modern WWTPs can run into millions of dollars.

Ash falls reduce visibility creating hazards for ground transportation. Dry ash is also readily remobilised by vehicle traffic and wind. Dry and wet ash deposits will reduce traction on paved surfaces, including airport runways. Ash cleanup from roads and airports is commonly necessary, but the large volumes make it logistically challenging. Vehicles are also vulnerable to ash; it will clog filters and brake systems and abrade moving parts within engines.

Finally, modern telecommunications networks appear to be relatively resilient to volcanic ash fall. Signal attenuation and interference during ash falls has not been reported in eruptions over the past 20 years, with the exception of interference from ash plume-generated lightning. However, some telecommunications equipment is vulnerable to airborne ash, in particular HVAC systems which may become blocked from ash ingestion leading to overheating.

9.2. Critical parameters for assessing ash impacts

Volcanic ash has a wide range of possible physical and chemical characteristics, largely controlled by magma chemistry and eruption conditions. Climatic and environmental conditions will also control its dispersion and influence its properties from site to site. This variability both between different eruptions and within the same eruption makes it challenging to develop generic estimates of ash impacts controlled by one parameter. Ash fall thickness has been the common parameter used for assessing the intensity of ash fall damage (e.g. Blong, 1984; Neild et al., 1998; etc.). Generally this has been appropriate for relatively coarse level assessments of ash vulnerability. However, it tends to overlook other ash characteristics, which will influence or even control the level of damage incurred. However, this review, along with various other recent works (e.g. Johnston et al., 2000; Cronin et al., 2003; Witham et al., 2005; Stewart et al., 2006; Wilson et al., 2010a,b; Wardman et al., 2011), highlights that grain size, surface coating composition, density and abrasiveness are also major controls on the type and intensity of impact which can be expected following ash fall.

There has been significant attention paid to the presence of a thin surface coating on freshly-fallen volcanic ash, containing a range of readily-soluble salts as well as more slowly soluble components (Witham et al., 2005; Delmelle et al., 2007; Flaathen and Gislason, 2007; Jones and Gislason, 2008). The composition of this surface coating is important in determining the toxicological hazard posed by the ash (with fluoride considered to be the primary toxicological hazard) as well as the potential for contamination of water supplies (Stewart et al., 2006, 2009a; Cronin et al., 2003). These readily-soluble salts are also thought to be important in controlling both the electrical conductivity and the corrosiveness of freshly-fallen ash although the relationships between these properties and the surface coating composition are less well characterised than for contamination of water supplies.

We highlight ash grain size as a key impact parameter, but one which has arguably had less attention than ash thickness or surface coating composition. Fine-grained ash is generally dispersed farther from the erupting vent and thus can potentially affect more infrastructure components and systems. It is also more likely to penetrate equipment, adhere to equipment surfaces (including downwind and undersides of surfaces), carry a proportionally higher load of soluble salts due to its higher surface area, be more easily eroded and remobilised, and present a greater health hazard.

Other properties of ash that have also had less systematic attention are abrasiveness, density and friability. The abrasive properties of ash grains are a function of their hardness and shape. A high degree of abrasiveness greatly increases the potential for damage by both waterborne ash (turbines, sludge pump propellors) and airborne ash (air-cooled motors, cooling fans) and when ash is cleaned from surfaces such as airport runways and roofs. The density of individual particles influences their behaviour, particularly during cleanup operations, with denser particles being more difficult to move with a hose and more likely to form intractable deposits in underground drainage networks. However, denser particles are less likely to be remobilised readily by wind. Bulk density of ash fall deposits (dry and wet) is also an important consideration in predicting ash loadings on buildings. Friability refers to the mechanical strength of ash grains; more friable particles may be compacted and ground up (e.g. by vehicles) and may affect the re-use potential of the ash (e.g. as aggregate in concrete manufacture).

The remobilisation of volcanic ash can also lead to disruption and damage to critical infrastructure. It is a well-acknowledged hazard for transportation networks (Section 5). However, remobilisation of thick ash deposits can occur over sustained periods at a regional scale, especially in dry, windy environments, which leads to ongoing ash impacts on exposed critical infrastructure and which may be significantly worse than the initial ash fall (Wilson et al., 2010b). We highlight this as an important consideration for future ash risk models, emergency planning and response.

These considerations strengthen the argument for ash hazard model outputs to include deposit thickness and grainsize in spatial and temporal contexts, and for damage curves (fragility functions) to capture other important characteristics of ash.

Finally, the condition of infrastructure prior to impact and the changing demands following an eruption (direct or indirect) may also affect the potential for failure post-eruption.

9.3. Ash fall impact data collection

Ash fall impact data gathering can be standardized based on the methods used for this work, so that data can be collected collaboratively and reliably by institutes across the world, and covering all aspects of ash fall impacts from any one event. Reliability of data is essential and the methods used for data gathering should be standardized to ensure high data quality. This will allow data sharing, collaborations and a repository of information for specific studies, without leaving blind spots in knowledge from any significant ash fall event. Similarly protocols for laboratory testing of vulnerable components should be developed. These measures will broaden the knowledge on the consequences of volcanic ash falls, further our understanding of system vulnerability using field and laboratory methods, and allow a database to be built for use across areas of interest within ash impact studies. Such standardisation is being addressed by the Volcanic Ash Fall Impact Working Group of the Cities and Volcanoes Commission of the International Association of Volcanology and Chemistry of the Earth's Interior. Once vulnerability is better understood, mitigation measures can be designed using systems thinking tools and accounting for both direct and indirect ash fall impacts, to develop sustainable and complete solutions to increase system resilience.

9.4. Mitigation

Developing an understanding of the ways in which volcanic ash can cause impacts on critical infrastructure may then enable managers to identify points of vulnerability within these systems, which may in turn suggest measures to reduce vulnerability to ash fall. For example, in Quito, Ecuador, previous volcanic crises have led to successful mitigation measures being adopted by water treatment plant managers. Covers have been built over exposed plant such as clarifiers, treatment chemicals have been stockpiled and water supply lines have been re-routed to avoid known lahar hazard zones (Leonard et al., 2005).

In a general sense, mitigation measures can include:

- Covering exposed equipment (such as well-head pumps, storage tanks in water supply systems).
- Monitoring key parameters (e.g. wear, contamination, distribution, duration, thickness, ash characteristics).
- Considering critical dependencies such as a continuous power supply and making provision for backup generation
- Maintaining equipment and plant in a good state of repair (for instance, clean insulators are less at risk from ash-induced flashover).
- Ensuring that supplies of essential equipment are well-stocked (e.g. spare filters, water supply treatment chemicals).
- Ensuring that emergency plans for volcanic ash falls have been developed and practiced in advance of a volcanic crisis.
- Having a system in place (typically via volcanic monitoring agency) for rapid ash analysis of physical and chemical characteristics of ash, and distribution of ash in space and time.

9.5. Knowledge transfer

Our group has made it a priority to communicate the findings of our reconnaissance trips, supplemented by our laboratory-based work, to infrastructure managers, with the aim of reducing the vulnerability of critical infrastructure to volcanic ash fall. In conjunction with the Auckland Engineering Lifelines Group, we have produced a series of posters providing advice for infrastructure managers. The content of these posters has been reviewed for accuracy and relevance by key staff from each infrastructure sector. These posters are publicly available from the website www.aelg.org.nz, or from the authors of this paper.

A further web-based resource with useful information on volcanic ash impacts on infrastructure is maintained by the US Geological Survey (http://volcanoes.usgs.gov/ash). This site also covers ash impacts on human health, buildings and aviation. The United Kingdom-based website www.ivhhn.org has its main focus on health impacts of volcanic ash, but also includes useful resources such as guidelines on preparedness for households, ash clean-up operations, and ash sampling, collection and analysis guidelines.

9.6. Research gaps and future directions

In general, despite improved knowledge from reconnaissance trip work, there is a lack of systematic and comprehensive documentation of the behaviour of critical componentry and systems under a wide range of volcanic ash conditions. This is being addressed by the Volcanic Ash Fall Impacts Working Group mentioned in Section 9.3. Following on from this, understanding the interdependency and overall system functionality for modern society remains an important strategic goal.

Modern volcanic risk assessment and strong end-user information needs before, during and after an eruption crisis will continue to require the research community to provide robust estimates of probable impacts. Thus the ultimate goal of this research is to able to provide accurate information for any type of volcanic ash and any impact intensity, ranging from minor nuisance to significant disruption or even total destruction. This presents a significant challenge given the wide range of physical and chemical properties of volcanic ash (as discussed above), and the rapid growth and evolution of modern society. In particular, rapidly evolving technology, increasingly interdependent systems and the low frequency of eruptions makes it difficult to determine whether existing mitigation recommendations are relevant for modern or future equipment.

Thin, distal ashfall is the volcanic hazard most likely to be experienced by exposed critical infrastructure. However, previous studies have often focused on very large eruptions and impacts associated with ash falls >10 mm and do not report effects from ashfall <2 mm. As a result ashfalls of this thickness are a source of uncertainty for emergency management planning and loss assessment models.

Acquiring a better understanding of the geotechnical and geochemical properties of ash is a current gap in understanding. There is a lack of empirical knowledge of how ash properties such as abrasiveness and corrosiveness will affect critical infrastructure components.

The provision of useful, relevant, understandable and timely information for infrastructure managers and the public is an ongoing challenge for researchers, and emergency managers alike. Specific research into ash and infrastructure public education, engagement and training strategies has so far been limited, but will be of benefit in the future. The format, content detail and delivery media for impact and mitigation data all need analysis in the face of rapidly changing internet and mobile communications technologies.

While post-eruption impact assessment trips will continue to strengthen and diversify our understanding of volcanic ash impacts, this reactive research model rarely allows for detailed analysis to determine with any certainty how and why observed impacts occur. It is difficult to explore impact thresholds in the field due to limited time, access difficulties and incomplete ranges of ash parameters such as thickness, grain size and surface coating composition. One solution is empirical performance testing of critical components using varying intensities and types of volcanic ash under laboratory conditions. This allows performance thresholds to be assessed for different configurations of equipment. Crucially, it also provides a setting for proactive experimentation of potential mitigation methods. As a consequence we have developed the Volcanic Ash Testing Laboratory (VAT Lab) as a multi-institutional consortium of research organisations investigating the impact of volcanic ash fall (see http://vatlab.org/).

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