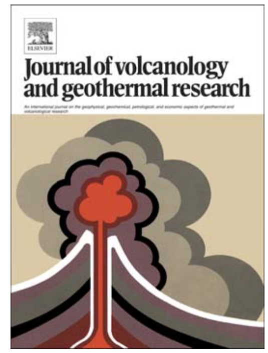

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Tephra fall clean-up in urban environments

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Abstract (223 words)

Tephra falls impact urban communities by disrupting transport systems, contaminating and damaging buildings and infrastructure, and are potentially hazardous to human health. Therefore, prompt and effective tephra clean-up measures are an essential component of an urban community's response to tephra fall. This paper reviews case studies of tephra clean-up operations in urban environments around the world, spanning 50 years. It identifies methods used in tephra clean-up and assesses a range of empirical relationships between level of tephra accumulation and clean-up metrics such as collected tephra volume, costs, and duration of operations. Results indicate the volume of tephra collected from urban areas is proportional to tephra accumulation. Urban areas with small tephra accumulations (1,000 m^3/km^2 or an average of 1 mm thickness) may collect <1% of the total deposit, whereas urban areas which experience large accumulations (>50,000 m^3/km^2 or an average of 50 mm thickness) remove up to 80%. This relationship can inform impact and risk assessments by providing an estimate of the likely response required for a given tephra fall. No strong relationship was found between tephra fall accumulation and clean-up cost or duration for urban environments which received one-off tephra falls, suggesting that these aspects of tephra fall clean-up operations are context specific. Importantly, this study highlights the advantage of effective planning for tephra clean-up and disposal in potentially exposed areas.

Keywords: Volcanic ash fall, response planning, hazard, risk, impact assessment, disaster waste

1. Introduction

Tephra fall can damage and disrupt critical infrastructure networks, impact buildings (interior contamination, as well as more severe damage to services and structural components), and affect human health (Table 1) (Blong, 1984; Spence et al., 2005; Horwell and Baxter, 2006; Wilson et al., 2012; Lombardo et al., 2013; Jenkins et al., 2014). All of these impacts can lead to flow-on effects such as disruption of social and economic activities (Sword-Daniels et al., 2014). Furthermore, tephra fall is one of the most widely dispersed volcanic hazards; at times affecting communities hundreds of kilometres away, sometimes for many years due to on-going eruptions or remobilisation of deposits (Wilson et al., 2012). Remobilisation of tephra deposits can be a particular challenge, creating an on-going hazard to exposed communities (Wilson et al., 2011). Clean-up operations have been widely utilised in urban environments following tephra falls to reduce impacts. However, such operations can be challenging, time consuming and expensive (Blong, 1984; Wilson et al., 2012).

There are typically four components to tephra clean-up operations:

1. Planning – Scoping undertaken to determine resource requirements and to prioritise affected areas

2. Removal – Physical removal of tephra from impacted surfaces (e.g. roads and roofs)

3. Collection – Consolidating tephra (e.g. piling or placing in bags) and loading onto vehicles for transportation to disposal sites

4. Disposal – Compiling tephra at either a single or multiple disposal site(s) and undertaking stabilisation measures (e.g. soil capping or establishing vegetation)

There can be some overlap between components, and often the removal and collection components run concurrently, e.g. tephra removed from roads is typically transferred directly to trucks without intermediate stockpiling.

The objective of tephra fall clean-up operations in urban environments is to hasten restoration of social and commercial functions by reducing health, property and infrastructure impacts from in-situ and remobilised tephra. Efficient and coordinated tephra clean-up operations have been identified as a crucial aspect of responding to a tephra fall event, yet many communities who have experienced tephra falls have relied on trial and error approaches due to a lack of pre-event planning; this can increase costs and reduce efficiency (Blong, 1984; Wilson et al., 2012). Previous studies have identified clean-up operations as challenging to execute due to: uncertainty regarding the duration, frequency, and spatial distribution of tephra falls; tephra remobilisation (i.e. by wind or traffic); disruption of necessary infrastructure (e.g. transport or utility networks); lack of adequate resources (e.g. personnel, street sweepers or trucks); and identification of disposal sites which met economic, environmental, and social needs (Blong, 1984; Johnston et al., 2001; 2009; Magill et al., 2013; Sword-Daniels et al., 2014). Therefore, establising an effective strategy for tephra clean-up can contribute to allow communities to reduce the consequences of tephra fall.

Successful planning for future tephra fall clean-up includes assessing the likely volume of tephra requiring collection, appropriate methods for clean-up, resource requirements, and estimated costs. However, there are few available studies to inform such planning, largely due to a lack of systematic review of previous operations globally and from a range of eruption types and deposition environments (Blong, 1984; Paton et al., 1999; Magill et al., 2006). This paper undertakes a systematic review of methods used and experiences during tephra fall clean-up operations in urban environments around the world for the purpose of creating an evidence base for impact assessments and guidance for planning. This will be achieved through consolidating and analysing the published and unpublished literature on tephra clean-up experiences. This review first undertakes an assessment of the following clean-up metrics and their relationships for use within impact assessment:

- Volumes of tephra deposited in urban environments
- Potential sources of tephra compaction
- Collected volumes of tephra
- Duration of clean-up operations
- Clean-up operation costs

Next, a review of tephra clean-up methods, disposal stabilisation methodologies, and tephra properties is presented.

2. Methods

2.1 Catalogue and information sources

To achieve our objectives a catalogue was created that records case-studies of tephra fall clean-up and disposal in urban environments. This includes: the volume of tephra fall deposited in the urban area; volume of tephra collected during clean-up; clean-up methods; duration and cost of operations; and methods for disposing of tephra (Table 2). The catalogue was created after reviewing a) published sources including research papers books and reports; and b) unpublished information collected from our international volcanic impacts research group, which has undertaken impact assessments in areas affected by volcanic eruptions.

The catalogue distinguishes between communities which have conducted a) clean-up operations in response to a single tephra fall event (duration typically less than 3 months and separated from other events by a period of at least 12 months) and, as a consequence, potentially inexperienced in clean-up activities; and b) clean-up in Kagoshima, Japan, where regular tephra falls of variable accumulations from Sakurajima volcano have occurred since the 1950s (Japan Meteorological Agency, 2013) allowing the city to become experienced and adapted in dealing with tephra clean-up (Durand et al., 2001). This distinction is necessary as a community's tolerance and capacity to manage tephra falls may differ in different social contexts and/or change with more frequent tephra falls (Sword-Daniels et al., 2014).

Some quality limitations exist within the catalogue. Much of the material has been sourced from semi-structured interviews with residents, emergency managers, or city/municipal engineers. This data collection method introduces the potential for interviewer or interviewee biases (e.g. preferred social responses, equivalence of meaning; Barriball & While, 1994). Further, recorded or reported data are often only available at relatively crude accuracy (i.e. order of magnitude estimation for tephra collection volumes and clean-up operation duration). Therefore, some care must be taken with interpretation of data.

2.2 Quantifying tephra accumulation – single tephra fall event

Tephra accumulation is used within this review as one measure of tephra fall hazard. We define tephra accumulation as volume (measured in m^3) per km^2 of urban area. We chose this measure over total volume deposited in an urban area as we assess communities with variable extent (cities such as Portland, USA, and Yogyakarta, Indonesia, and towns such as Moses Lake, USA). The spatial distribution of tephra impacts over an urban environment is known to influence how operations are conducted by requiring prioritisation of areas of high importance, and resources (loaders, trucks, and workforce) to be appropriately distributed (Wilson et al., 2012). Additionally, the requirement of different types of clean-up machinery (e.g. graders, loaders, dump trucks, street sweepers) will vary depending on the level of tephra hazard. Estimating tephra accumulation for case study communities used the following methodology:

1. The urban area (km^2) subject to tephra deposition and tephra thicknesses over this area were obtained from published isopach maps, literature, and geospatial analysis (Table 2). In cases where accummulation was presented as isomass maps (contours based on weight per unit area rather than thickness), tephra load was converted to thickness using published deposit densities.
2. Tephra accumulation (Ac) (m^3/km^2) was calculated using:

$$\mathbf{Ac} = \frac{\boldsymbol{T\ x\ UA_1}}{\boldsymbol{UA_2}} \tag{1}$$

$$\text{Ac} = \text{Tephra accumulation}$$

$$\text{T} = \text{Reported thickness (m) Where a range given (e.g. 10} - \text{20 mm, a median value was taken (e.g. 15 mm)}$$

$$UA_1 = \text{Urban area impacted by tephra fall (m}^2\text{)}$$

$$UA_2 = \text{Urban area } (km^2)$$

2.3 Quantifying tephra accumulation - repeated tephra fall in Kagoshima, Japan

Due to data availability, methods for assessing tephra clean-up in Kagoshima, Japan, were adjusted to consider annual totals of accumulation and collection. This means that information on Kagoshima clean-up does not represent individual clean-up operations. Taking this approach means that direct comparisons between Kagoshima and communities which experienced single tephra fall events was not possible. Available information detailing annual tephra fall load (g/m^2) was recorded at 22 observation points around the city (Kagoshima City, 2013). Using this information, a mean annual load (g/m^2) was calculated for the city area. The average bulk density of tephra layers on Mount Sakurajima ranged from

1.2 g/cm^3 to 1.4 g/cm^3 between 1972 and 2008 (Teramoto & Shmokawa, 2011) and we assumed a bulk density of 1.3 g/cm^3 to convert the average tephra load to thickness (m). Assuming uniform tephra impact over the area of 547 km^2 (urban area of Kagoshima), annual tephra accumulation could then be estimated (equation 1).

2.4 Clean-up cost

A difficulty comparing clean-up costs is that the case studies investigated span 50 years and from many different countries. For consistency, all reported costs were converted to US Dollars of 2013 value. If costs were reported in a currency other than US Dollars (only Kagoshima and Yogyakarta), they were first converted to the 2013 local currency value, then converted to US Dollars of 2013 value. All other costs were given in US Dollars after converted to US Dollars of 2013 using an inflation calculator.

3. Tephra clean-up metrics for impact assessment

3.1 Tephra volume collected

International case studies, including both single and ongoing (Kagoshima) tephra fall events indicate that as tephra accumulation increases, so too does the proportion of tephra that is collected (Figure 1). Very low tephra fall accumulation (<500 - 1,000 m^3/km^2 , ~0.5 – 1 mm) may require no coordinated clean-up operation, such as in Anchorage following the 2009 Redoubt eruption (T.M. Wilson & G.S. Leonard *unpublished field notes*). An increasingly higher proportion of deposited tephra appears to be removed as tephra accumulation increases. At tephra accumulations of around or greater than 100,000 m^3/km^2 (~10 cm), such as at Heimaey, Iceland (1,920,000 m^3/km^2), or Chile Chico, Argentina (100,000 m3/km2), more than 50% of tephra is removed, which both required large coordinated efforts towards tephra removal and collection in order to restore functionality to communities.

Collection of tephra in Kagoshima also shows a similar relationship where the proportion of tephra removed decreases as tephra accumulation decreases. Kagoshima also appears to remove an overall lower proportion than other communities experiencing single tephra fall events. However, this information may be influenced by very small tephra falls where little or no tephra is removed. Further, it is possible that the area of impact used in this research (547 km^2) is over-estimated, as individual tephra falls may not all affect this entire area; this would influence the results to make the calculated proportion of tephra collected lower than in reality.

3.1.1 Tephra compaction

There is some variability between points in Figure 1 which could partly be due to data quality as some collection estimates are only estimated to an order of magnitude (See footnotes Table 2). Additionally, tephra can compact by as much as 50% of the initial thickness after deposition due to a range of factors, including precipitation and aeolian processes, animal movement and human interactions (e.g. walking or driving on deposits) (Blong and Enright, 2011; Engwell et al., 2013). Tephra thickness variability could be due to measurements being taken at variable times after deposition and the deposit being subject to variable degrees of compaction. Tephra clean-up records are also often limited, so it was difficult to determine when tephra thickness measurements were taken. It is also possible for tephra to compact post-removal (i.e. bulk density increases due to settling during transportation, dumping and compaction at disposal sites), which could influence the estimates for the amount of tephra collected if they had been estimated post-removal.

3.2 Clean-up operation duration

Clean-up operations can be disruptive events, requiring road closures, coordinated property cleaning and parking restrictions while clean-up crews remove tephra (Blong, 1984; Wilson et al., 2011). In Yakima, ~70 mm (70,000 m^3/km^2) of tephra fell on the city following the Mt. St. Helens eruption in 1980, causing the central business district to be closed to non-essential personal for three days during clean-up operations (Blong, 1984). Therefore, the duration of clean-up is an important planning and impact assessment consideration. There is limited information available regarding clean-up duration, but available information indicates large variability (Figure 2).

Supporting qualitative descriptions indicate that in some situations clean-up can be prolonged as a result of sporadic and recurring tephra falls. An estimated 50,000 m^3/km^2 (total ~45,000 m^3) of tephra fell on Futaleufu, Chile, after the 2008 eruption of Chaiten volcano. This took approximately 9 months to clean up and intermittent remobilisation required occasional attention for a further 6 months. However, ongoing tephra fall is not the only reason for prolonged clean-up. Clean-up in Yakima, following the 1980 eruption of Mt St. Helens, had accumulation of 70,000 m^3/km^2 (~4,900,000 m^3) of coarser tephra fall (median grain size ~125 µm; Carey & Sigurdsson, 1982), and took seven days (twenty four hour operation) to collect and dispose of ~2% (109,000m^3) of the tephra (Blong, 1984). In comparison, Portland tephra clean-up lasted 10 weeks even though tephra accumulation was on average only 1,500 m^3/km^2 (total ~825,000 m^3) and less than 1% (~5,400 m^3) was removed. The long duration was attributed to the very fine grain size (median size ~31 µm; Shulters & Clifton, 1981), which reduced the performance of street sweepers (Blong, 1984). However, the much smaller tephra accumulation likely also meant there was less urgency to clean-up tephra.

3.3 Tephra clean-up costs

Clean-up operations can be expensive undertakings due to extensive areas requiring attention and large volumes of tephra needing to be removed. For example, clean-up costs in Bariloche, Argentina (Cordón-Caulle, 2011) were reported to be US$35 million (Wilson et al., 2013). However, it can be difficult to determine the true cost of clean-up as often only direct costs such as worker wages, machinery hire or transportation and dumping costs are reported (Blong, 1984). Indirect costs, such as business disruption, can also occur because of closures to areas while clean-up is conducted or staff being reassigned to clean-up activities. Volunteer labour is also rarely considered in cost estimates. Analysis of clean-up costs presented in the following sections only considers direct costs and particular focus has been given to Kagoshima due to information availability. It is important to consider that Kagoshima's clean-up costs are aggregated annually, therefore direct comparisons between costs in Kagoshima and communities affected by single falls is not possible.

3.3.1 Road length

Roads were cleaned in every instance where coordinated clean-up operations were initiated. Therefore, analysis of how clean-up costs change depending on the distance of roads requiring tephra removal and collection is useful for impact assessment. Clean-up costs and the estimated total length of roads that required tephra clean-up are presented in Figure 3. A reason for variability between single tephra fall event communities is that it was not always possible to distinguish between different road characteristics at the time of eruption (e.g. local vs highway, width or surface). These distinctions are important as these characteristics will influence the urgency for clean-up, quality of road cleaning required and the relative ease with which it can be undertaken. Major roads or those critical for emergency response will require a greater level of clean-up than local or low-use roads; these roads will need to be cleared quickly and may require multiple clean-up operations due to ongoing falls or remobilisation. Additionally, asphalt and gravel surfaces are likely to be of varying levels of difficulty to clean-up, and this will influence clean-up costs. For example, Grant, Spokane, and Whitman Counties in the United States found that when removing tephra after the 1980 Mt. St. Helens eruption, gravel was also removed in the process (McLucas, 1980). This increased the volume of material removed and required new gravel to be placed. Unpaved roads also presented a challenge for clean-up in Futaleufu (Chaiten, 2008), as when tephra was wet it mixed with the road gravel mix, but when dry it was easily remobilised (T.M. Wilson *Unpublished field notes*). The solution for Futaleufu was to dig up the gravel and tephra mix and replace with clean gravel.

The Kagoshima road network clean-up information shows good association between the length of road per annum that required cleaning and the cost of that clean-up. Kagoshima data are likely to be more consistent, as the same method was used each year (and presumably, each clean-up operation). Single event tephra fall clean-ups had a broader range of possible sources of costs and uncertainty, such as transportation, disposal, machinery hire, and health and safety equipment. For example, it is likely that as distance to a disposal site increased so too did the cost of removal. The single event tephra fall clean-up case studies have disposal sites located at variable distances from the clean-up area due to a range of factors (e.g. site availability, urban geography, and cultural factors), which results in additional variability between the case studies. Additionally, similar road types (arterial, highway, rural) are impacted in each event for Kagoshima. Due to this information for Kagoshima showing averaged clean-up over the entire year, simply increasing the area of road that was cleaned or the volume of material to remove would increase the cost of clean-up.

3.3.2 Total volume collected

As expected, clean-up costs generally increase as the volume of tephra removed increases (Figure 4). Two sets of Kagoshima tephra clean-up information were available for analysis: (1)1990-1998 details the volume and cost of tephra clean-up from just residential areas, and (2) 1999-2011 details volume and clean-up costs from both residential and road areas. Both show a strong relationship between volume removed and clean-up cost (Figure 4). Residential operations have accounted for most of the costs in Kagoshima, with a component of this from manufacturing and distributing large quantities of plastic bags for tephra collection. In total, close to six million bags were distributed for all clean-up activities (including for commercial premises) between 2010 and 2011 (Kagoshima City, 2013).

Reported costs for single tephra fall event clean-up operations are also shown in Figure 4. However, the relationship is much weaker than seen in Kagoshima. This could be due to factors such as differing measurement or recording methods between case studies, resource availability, clean-up methods, operation duration, and distance to disposal sites.

3.4 Reliability of information

A challenge when compiling information from a number of sources is the range in reliability of the information. For example, measurements of tephra thickness between the different urban areas could have been made at different times after deposition which, due to tephra compaction and/or remobilisation, could influence the measured or estimated thicknesses. To maintain transparency we have assessed and ranked the quality and reliability of the data presented in this paper based on criteria outlined in Table 3.

Figure 5 indicates two main points: 1) Consistent recording of clean-up volumes and costs in Kagoshima reflects the low variability seen in data points for Kagoshima clean-up metrics; and 2) the range of information reliability could explain the variability seen within Figures 1-4.

4. Tephra clean-up methods and management catalogue

This section reviews the methods and experiences of tephra clean-up for the purpose of providing context for clean-up operation planning. In general, communities that had a clean-up plan prior to eruption or experience from ongoing eruptions were found to undertake more efficient operations; particularly in regard to establishing agency roles and responsibilities and in identifying resource requirements (e.g. Guatemala City; Wardman et al., 2012a, and Kagoshima; Durand et al., 2001). Some of the communities within the catalogue have had experience with snow clean-up prior to tephra fall clean-up (particularly Anchorage). Having ready access to heavy machinery and operational management for clean-up activities is likely to be beneficial. However, tephra fall clean-up has different challenges, such as remobilisation and long term disposal, suggesting that experience with snow clean-up does not necessarily mean that tephra clean-up operations will be without problems.

4.1 Urban tephra clean-up operations

A broad range of clean-up methods were used by the case-study communities. Multiple factors influenced the selection of tephra clean-up methods (Table 3) and performance, including: the volume and characteristics of accumulated tephra; the disruptions caused by tephra accumulation; the likelihood of further tephra falls; amount of remobilisation (climatic and anthropogenic); available resources (e.g. dump trucks, graders, and sweeper trucks), availability and land-use of the receiving/disposal sites; climate, level of planning and experience, and community tolerance to tephra accumulation and remobilisation (Figure 5) (Blong, 1984; Wardman et al., 2012a; Wilson et al., 2012, 2013; Magill et al., 2013). Physical properties of tephra (grain size, mechanical strength, cementation, abrasiveness, mineral composition, morphology and leachable elements) and environmental effects on the tephra deposit (e.g. moisture level, wind and water erosion, etc.) can affect clean-up operations by:

varying the ease in physically removing tephra from surfaces, affecting the degree of remobilisation, and causing various levels of damage to surfaces and machinery during cleaning (Table 4).

Specific thresholds of tephra accumulation for determining when different clean-up responses are initiated are unique to individual communities, although some trends emerge from the case-studies (Table 5). At very low tephra accumulations (<500 m^3/km^2 - < 1 mm) coordinated clean-up operations might not be necessary, other than possible removal of tephra from major roads (e.g. Anchorage, Redoubt 2009, and Te Maari, Tongariro 2011). Tephra thickness of 0.5-1 mm (500 - 1,000 m^3/km^2) is consistently reported as initiating the necessity for clean-up of sealed roads as this thickness can result in obscured road markings, loss of visibility and a reduction of traction between wheels and road surface leading to hazardous driving conditions (Magill et al., 2011; Wilson et al., 2012). At low tephra accumulations (~1,000 m^3/km^2) coordinated removal and collection from roads is required in urban areas, such as in Portland, Oregon (Mt. St. Helens, 1980). Total tephra volumes for individual properties are usually quite low at these accumulations and, as such, property owners can usually cope without assistance from local authorities; although, municipal assistance with collection could be required. Moderate accumulation levels (10,000 m^3/km^2 – 50,000 m^3/km^2 - ~10 – 50 mm) require coordinated clean-up operations to remove tephra from roads. At these accummulations there will likely be increased demand for heavy earth moving machinery and trucks. Removal from private properties can either be assisted by municipal authorities and/or outsourced to private clean-up operators. At high accumulation levels (>50,000 m^3/km^2 - > 50 mm), most surfaces within an urban environment will require clean-up because of potential impacts such as to human health and building safety. This will require a coordinated approach and management of large workforces. However, tephra removal and collection in areas of land that is very heavily impacted (e.g. parts of Heimaey with tephra > 1,000 mm) might not be considered an immediate response priority or could be considered too expensive and cumbersome to conduct as part of the recovery phase.

4.2 Tephra clean-up operation process

A common clean-up process can be drawn from case studies (Figure 6), which indicate four major components: (1) planning, (2) removal, (3) collection, and (4) disposal. Each component will be outlined in the subsections below.

4.2.1 Planning

The planning phase involves scoping the response required for a coordinated clean-up operation. In case studies, if pre-event plans were already in place, clean-up could begin relatively quickly following tephra fall as lines of communication between relevant authorities were established. In Guatemala City (Pacaya, 2010), clean-up plans were compiled after consideration of the response to the 2009 Haiti earthquake, and these plans were credited with speeding up operations (Wardman et al., 2012a). One of the earliest decisions that officials will have to make in the case of a future eruption is when to begin clean-up. Following the 2002 eruption of Mt. Etna, authorities were hesitant to begin operations due to uncertainty regarding how long the eruption would continue and an unwillingness to pay overtime to workers for repeated clean-up operations (Barnard, 2004). In Jacobacci, after the 2011 Cordón-Caulle eruption, visibility was so low due to suspended tephra (primary fall and remobilised) that clean-up could only start one week after tephra began falling (Wilson et al., 2013). The clean-up of Heimaey following the 1973 Eldfell eruption was delayed approximately 2 months (Morgan, 2000), although this was due to the large scale evacuation that occurred from the island.

4.2.1 Removal and collection

It is commonly reported that buildings and properties should be cleaned from the roof to ground level to reduce cleaning surfaces multiple times (USGS, 2012). Coordinated cleaning of buildings within close proximity is also desirable to prevent re-contamination. This has been a source of conflict where some property owners did not clean their roofs within a specified timeframe (i.e. Yakima, Blong, 1984). Further difficulty coordinating community clean-up can arise where absentee ownership is high, for example rented or empty properties (Kartez et al., 1980).

Resources used for tephra removal include hand held brushes and shovels, heavy earth moving machinery (e.g. loaders and graders), street sweepers and trucks. Vehicles can break down tephra particles into finer sizes, which become suspended, making removal more difficult (Blong, 1984). Temporary stabilisation may be necessary depending on the grain sizes of the tephra deposit. Moistening tephra (i.e. to 1-5 wt. %; Paton et al., 1999) is an effective and efficient method. However, when water shortages occur (e.g. Anchorage following the 1992 Mt Spurr eruption) (Johnston, 1997), this may not be possible. Conversely, too much water added to the tephra may increase its weight and cause it to cement to surfaces (Casadevall, 1993) making manual removal more difficult.

Some surfaces have a higher cleaning priority for municipal authorities than others, such as roads in central business districts compared to vegetated land within rural areas. Kartez et al.

(1980) interviewed a number of jurisdictions affected by the Mt. St. Helens eruption and found that downtown business districts and arterial roads were considered the highest priority for cleaning, followed by hospital areas, public buildings, high density residential areas, and neighbourhood roads. Kagoshima prioritises clean-up by having predefined zones which are assessed by Road Maintenance Division officials for severity of impact following a tephra fall (Ishinmine et al., 2012). The initial focus of clean-up in Bariloche (Cordón-Caulle, 2011), which had around 40 mm (35,000 m^3/km^2) of tephra fall, were high tourism areas such as downtown business streets (Wilson et al., 2013). Clean-up priorities can also be based on resource availability. For example, in Moscow, Washington (St. Helens, 1980), this maximised volunteer labour as public resources were very limited and involved dividing neighbourhoods into 6 zones, each with access to one front-end-loader and a dump truck. When a street had finished piling tephra at the kerb side the loader and dump truck were requested.

Caveats to utilising volunteer workforce are inexperienced operation of equipment, and health and safety regulations (Wilson et al., 2012). Injuries that occur as a result of tephra fall are often associated with clean-up activities (e.g. falling from roofs) (Leonard et al., 2005; Wardman et al., 2012a; Magill et al., 2013). Clean-up activities in Miyakonojo and Takaharu (Shinmoedake, 2011) resulted in 36 reported injuries related to slips or falls from ladders or roofs (Magill et al., 2013). Further, health and safety equipment, such as dust masks and overalls, must be available to individuals conducting clean-up operations.

In Cheney (St. Helens, 1980), 10 fire hydrants were damaged by incorrect usage, and over 1,200 metres of fire hose destroyed due to abrasion by tephra; this raised concerns surrounding the capabilities of fighting a major fire (Kartez et al., 1980). Damage to surfaces being cleaned has also been observed. The runway at Guatemala International Airport

(Pacaya – 2010) was badly damaged, requiring resurfacing, during clean-up operations due to the high mechanical strength and abrasiveness of the tephra (Wardman et al., 2012a).

Typical resources used to conduct city street clean-up are heavy earthmoving machinery, dump trucks, street sweepers and manual labour (Figure 7). Although, no specific thresholds have been found which dictate the methods of clean-up, it can be seen that areas that experienced thick tephra deposits (e.g. > 10,000 m^3/km^2; broadly equivalent to >10 mm) required graders and loaders to first remove the bulk of the tephra (Figure 8c) before street sweepers were used to clean up the residue (Figure 8d). Areas affected by thin tephra deposits (e.g. less than 10,000 m^3/km^2 or <10 mm) usually implement an intensive street sweeping program until particulate levels return to acceptable levels. However, street sweepers in Portland, following the eruption of Mt. St. Helens in 1980, were reported at being only 50% effective in picking up these fine grains (Blong, 1984). This resulted in multiple sweeper runs, and prolonged clean-up operations in the city (Blong, 1984).

Manual cleaning (using brooms and shovels) is resource intensive and time consuming, but is important for areas that are difficult for machinery to reach, such as properties (driveways and roofs) or small roads (Figure 8e), or to remove the left over residue after bulk tephra removal. Manual cleaning was of particular importance in the clean-up of San Jose, where over 20,000 m^3 of tephra was deposited in the city following the eruption of Volcán Irazú in the 1960s and where street sweepers could operate in only 40% of streets because they were not wide enough for the street sweeper trucks to navigate (Clark & Lee, 1965)

4.2.3 Disposal and permanent stabilisation

A wide range of disposal methods have been implemented across case study areas (Table 6). Existing waste disposal sites have been used when tephra volumes are low enough for this to be feasible. However, disposal of large volumes of tephra can put pressure on, or exceed, the capacity of existing sites, significantly reducing their design life. One of the most common alternative methods is to fill in open spaces such as abandoned quarries, valleys, or fields. Although there are no known instances of disposal of tephra in marine environments, there have been examples where tephra has been disposed of in water bodies. For example, in Villa la Angostura, Argentina, 95,000 m^3 of tephra from the 2011 Cordón-Caulle eruption required disposal. Initially, provisional disposal sites were located in each neighbourhood but, eventually, tephra and small amounts of lahar deposits were used to fill in an old quarry which had become a lake (Figure 8a-f). Durand et al. (2001) reported potential land reclamation of water front areas in Kagoshima, although, this has not be verified. Dolan et al (2002) suggested that marine disposal of tephra was likely to be cost prohibitive and environmentally undesirable in the context of Auckland, New Zealand. However, specific reasoning for this was not evident in the report. In fact, we suggest that investigation of such disposal methods would be a useful future contribution to the field of disaster recovery.

Occasionally, no permanent disposal is undertaken and the tephra is allowed to be removed naturally. For example, clean-up of State Highways 1 and 46 following the Te Maari (Tongariro) eruption in 2012 only involved brooming tephra to the side of the roads and this was left to naturally erode. In this instance, the amount of tephra deposited was sufficiently low (~1 mm) and in an area of relatively low human occupation so that tephra was not sufficient to cause serious impacts.

Prior planning to identify potential disposal sites would be of great benefit to communities at risk of tephra fall. This is because identification during or just after an event will require quick decisions to be made at the expense of rigorous assessments of potential long term impacts. Dolan et al. (2003) assessed potential tephra disposal sites in Auckland, New Zealand using GIS (Geographic Information Systems) multi-criteria analysis. Criteria for ideal disposal sites were used including:

- land ownership (only sites owned by local government considered)
- area of the site (>10 hectares)
- not within areas susceptible to flooding
- not near water supply catchments
- not susceptible to leaching into groundwater
- not near 'sites of natural significance'
- not near areas of 'cultural significance'

- Minimal slope
- good vehicle access (especially trucks)
- low susceptibility to erosion
- low transport costs, and
- low potential nuisance to neighbours

Once a disposal site has been established and disposal has begun, compaction and stabilisation of the tephra is often undertaken (Table 7). The purpose of stabilisation is to prevent remobilisation of the tephra over the long term. Methods of stabilisation need to consider the environmental standards of the community. The most common form of stabilisation involves compaction and then capping deposits with soil and/or planting vegetation which helps bind tephra together (Wilson et al., 2011).

If no stabilisation efforts are taken to prevent remobilisation, disposal sites can create an additional hazard to communities. No stabilization was conducted at the disposal site in Perito Moreno following the 1991 Hudson eruption, and tephra disposed at the site was remobilised by wind causing further impacts for downwind residential properties and farms (Wilson et al., 2011).

Using tephra as a resource (e.g. for construction material) can reduce the total volume of material requiring disposal and has been utilised in some communities after a volcanic eruption. In Miyakonojo (Shinmoedake, 2011), sand bags were filled with tephra for lahar protection (Magill et al., 2011). Following the 1992 Spurr eruption, authorities in Anchorage used tephra as road grit by placing it on top of icy roads. However, tephra cleaned from urban environments often includes a variety of other urban waste mixed into the deposit, so screening may be necessary.

Tephra was also utilised as a more economic and environmental replacement for fly ash in cement used for rehabilitation projects in Reboul, Papua New Guinea, following the eruption of Mount Tavurvur in 1994 (Hosssain, 2003; Hossain, 2004). Hossain (2007) reported that concrete with tephra sourced from Mount Tavurvur showed better durability compared to a control concrete with no tephra component. It has also been reported that builders in Imperial Rome included tephra from Alban Hills Volcano in Central Italy in cements used to construct many well-known landmarks that have since survived multiple earthquakes and floods (e.g. Pantheon, Markets of Trajan, Theater of Marcellus, Mausoleum of Hadrian, Baths of Diocletian) (Marra et al., 2011; Jackson et al., 2014). Investigations into the mechanical resilience of this mortar suggest that cementious processes due to the tephra component impede crack propagation (Jackson et al., 2014). However, it is common for other debris (e.g. concrete, vegetation, gravel, and urban waste) to become mixed with collected tephra, which has precluded re-use in some areas, such as in Bariloche, Argentina, following the 2011 Cordon-Caulle eruption (Wilson et al. 2012), or required tephra to be screened.

5. Implications of these findings

Tephra fall clean-up operations are important for mitigating impacts to urban environments and public health following tephra fall events. There have been attempts to include clean-up considerations within impact/risk modelling assessments, as well as integrating them into volcanic contingency or response plans.

5.1 Implications for impact and risk assessment

Clean-up activities are a critical aspect in mitigating impacts to urban areas following tephra fall, but are often expensive and time consuming. It is thus important to consider tephra clean-up operations within volcanic impact and risk assessments. Previous studies have assessed the resource requirements for tephra clean-up in urban environments (e.g. Paton et al., 1999; Magill et al., 2006); however, both were limited by a lack of evidence to inform previous tephra collection volumes. Paton et al. (1999) assumed that either the total volume of tephra fall on an urban area would be removed or only road surfaces would have tephra removed. Magill et al. (2006) assumed that properties with tephra volumes less than 1 m^3 would not remove tephra.

This paper helps to inform and refine the assumptions made in volcanic impact and risk assessment by compiling an evidence base for clean-up operations. In order to obtain practical and useful discussion on this topic a combination of information sources of variable quality have been used in this review. To maintain transparency, reliability of information sources was assessed and found considerable reliability of information. This highlights the need for consistent recording and reporting of volcanic impact information after volcanic eruptions.

The consideration of tephra collection volumes in this paper indicates that the scale of response will be influenced in part by the volume of tephra accumulation in an area but also by other properties, such as grainsize, as listed above in Section 4.1 (Table 5). Tephra fall impact assessments and planning for urban environments should consider a) clean-up as a key consideration, b) that clean-up scale and complexity will increase as tephra fall accumulation increases, and c) that clean-up methods and needs will often be community specific, so that planning and assumed thresholds should be developed with community participation

5.2 Considerations for response planning

Planning for clean-up operations will assist communities in achieving a faster recovery from tephra fall events. There are also considerable physical (respiratory, skin, eye; Baxter and Horwell, 2009 and mental (anxiety, frustration and depression; Brown et al. 2011; Wilson et al. 2011; Sword-Daniels et al. 2014) public health benefits. To get the most benefit from response plans it will be necessary to consider local contextual factors such as:

- tephra fall hazard estimation, including: volcanic sources, expected volumes/unit area and particle characteristics (e.g. grain size, mechanical strength, abrasiveness);
- areas that will need to be prioritised for clean-up (e.g. tourism areas, business districts, important transport corridors);
- environmental and logistical requirements for disposal sites (e.g. location of sites, stabilisation methods, hours of operation); and
- potential mutual support agreements with industry (e.g. mining, construction) and other local authorities (e.g. neighbouring regions) for assistance in providing required resources.

Unlike many other natural hazard events which have a relatively clear start and end point (e.g. tsunami or floods), volcanic eruptions can have durations varying from hours to decades and can be characterised by multiple instances of tephra fall on a community. This presents a challenge to authorities as they must decide when to begin clean-up operations. If operations begin too early there is the possibility of having to clean surfaces many times due to ongoing falls and remobilisation. This reduces efficiency and increases costs. However, delaying clean-up can also lead to extended infrastructure disruption or damage, and health impacts which would not have occurred if clean-up began promptly following deposition.

Municipal authorities will need to provide prompt advice to those undertaking clean-up activities. This will require two components: 1) logistical and operational advice; and 2) health and safety advice. Logistical and operation advice should focus on when and how tephra should be cleaned up and where it should be disposed. Health and safety advice should make those involved aware of:

- the potential for slips, trips, and falls from slippery or damaged surfaces or roofs;
- health implications of being exposed to tephra (i.e. skin, eye, and respiratory problems);
- required personal protection equipment that should be worn;
- potential for back injuries when moving heavy tephra loads; and
- the potential for heavy machinery operating nearby.

6. Conclusions

This paper has systemically reviewed published and unpublished literature on tephra clean-up experiences and provides an evidence base for conducting tephra clean-up impact assessments and response planning. Evidence from reviewed case studies indicates tephra clean-up operations can be challenging, potentially prolonged, and expensive. There appears to be a strong relationship between the case studies showing that the proportion of tephra removed and disposed of increases as tephra accumulation increases. Kagoshima appears to remove a smaller proportion of tephra than other communities, although this could be due to the influence of many small eruptions and/or over-estimating the urban area impacted. However, Kagoshima does show the same trend of increasing proportion of clean-up as tephra accumulation increases.

Relationships between the cost and duration of clean-up were weak for single tephra fall clean-up operations. This suggests that cost and duration of clean-up rely on local contextual factors such as resource availability (e.g. trucks, diggers, and street sweepers), disposal site location, and prior planning. Consequently, impact assessments will need to consider potential local factors when considering the potential cost and duration of clean-up operations.

There is a general common process to tephra clean-up operations (planning, removal, collection, and disposal), although globally, variable approaches to clean-up suggest local context (climate, land-use and community tolerance of residual tephra) is a key factor in clean-up planning. Some communities have been able to quickly mobilise resources and clean up large volumes of tephra in short periods of time. Other communities have faced significant challenges and prolonged clean-up operations. Factors that contribute towards the variance in tephra clean-up experiences range from the physical characteristics of volcanic eruptions and deposits, such as eruption magnitude and particle grain sizes, to social considerations such as previous experience or having established clean-up plans. Planning and coordination of clean-up operations are identified as a priority for tephra fall risk management.

Effective planning for tephra clean-up in urban environments requires understanding:

- tephra fall hazard including: tephra sources, expected volume/unit area and, ideally, estimates for particle characteristics (e.g. grain size, mechanical strength, abrasiveness);
- priority areas for clean-up and available assets/resources;
- identification of tephra disposal sites and ideal tephra disposal site characteristics (e.g. volume, road access, ownership, environmental considerations);

- an understanding of societal factors such as economic, environmental, public health and cultural values. These will influence areas of prioritisation for clean-up, potential tephra disposal locations, and quality of clean-up; and
- identification of resource requirements and development of mutual support arrangements.

Development of robust plans will assist communities in establishing lines of communication between stakeholders (e.g. city managers, contractors, property owners) and help determine the resources required to restore functionality to facilities, reduce infrastructure and property damage, and limit human exposure to tephra.

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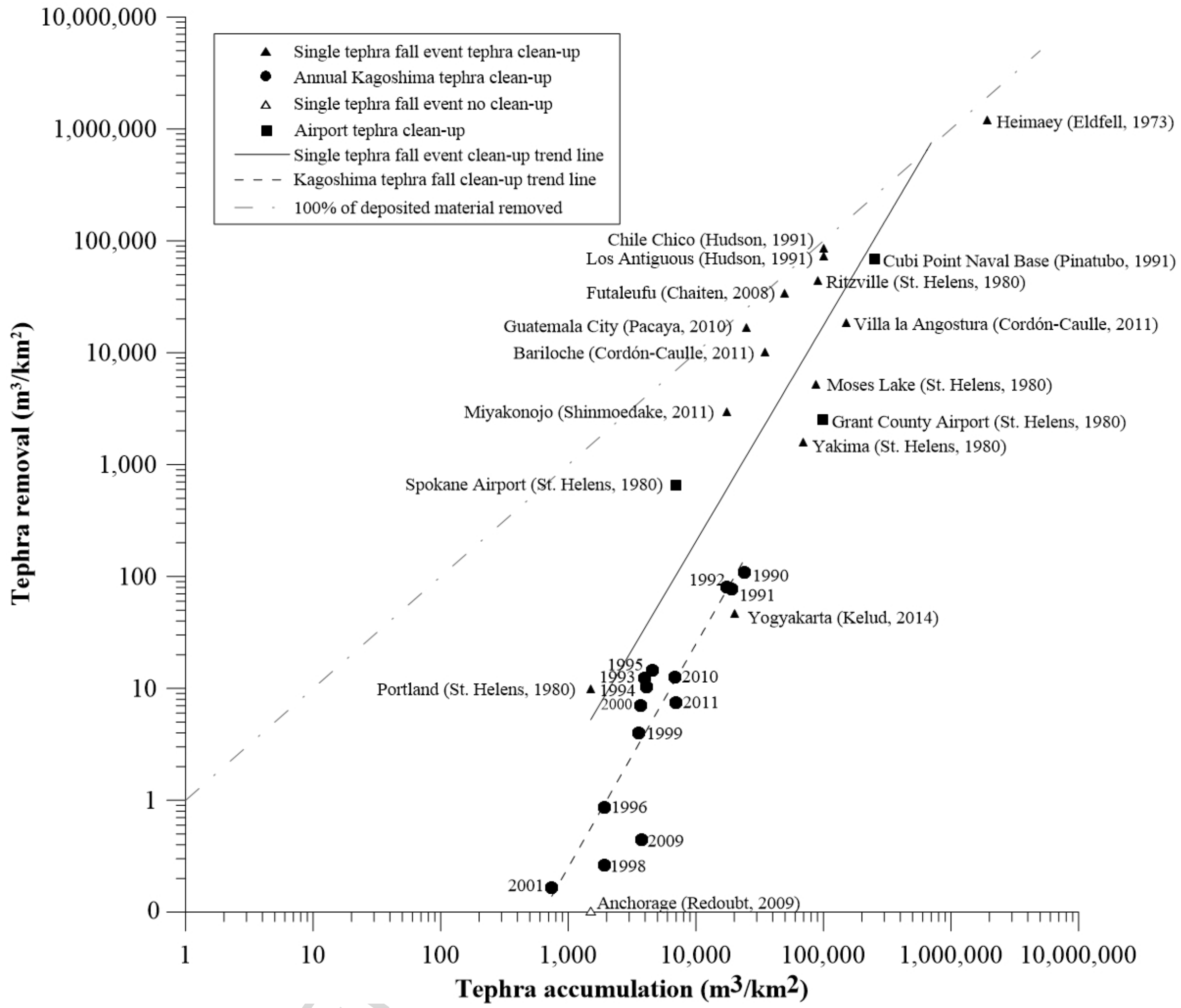
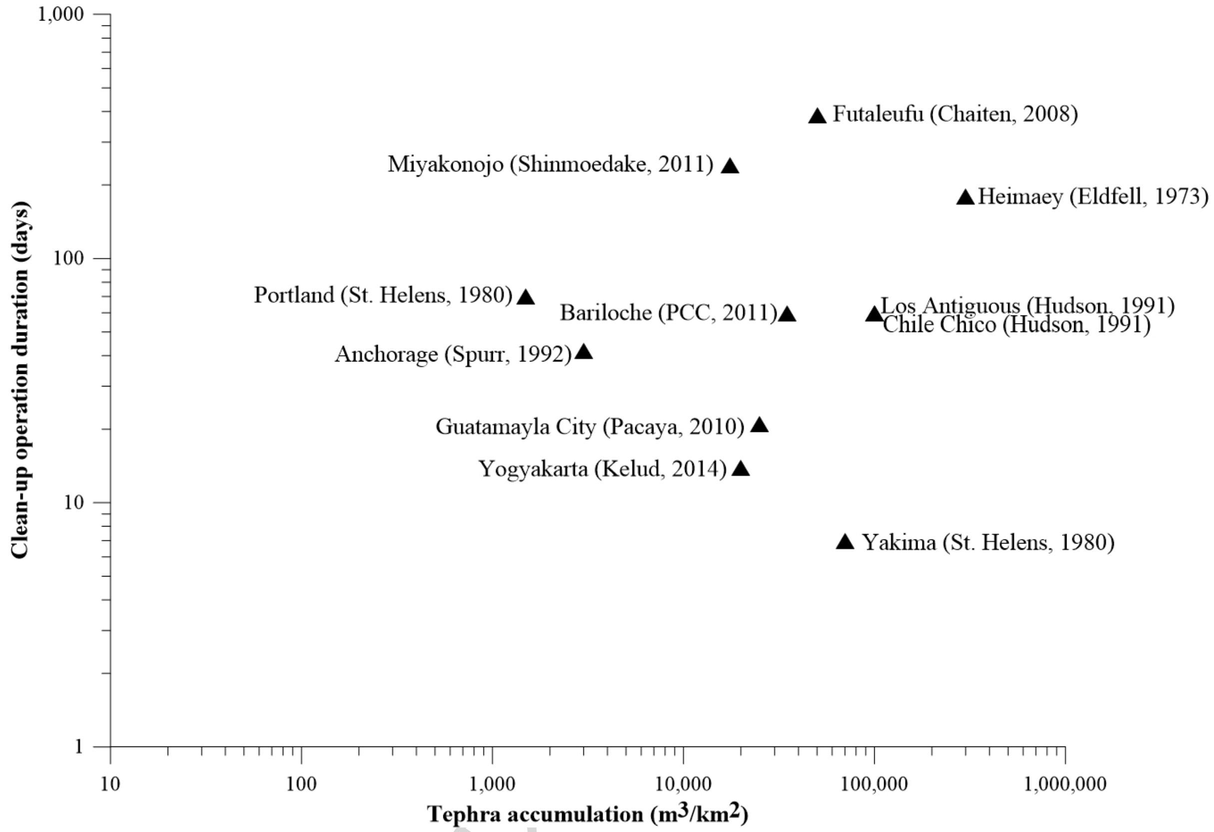


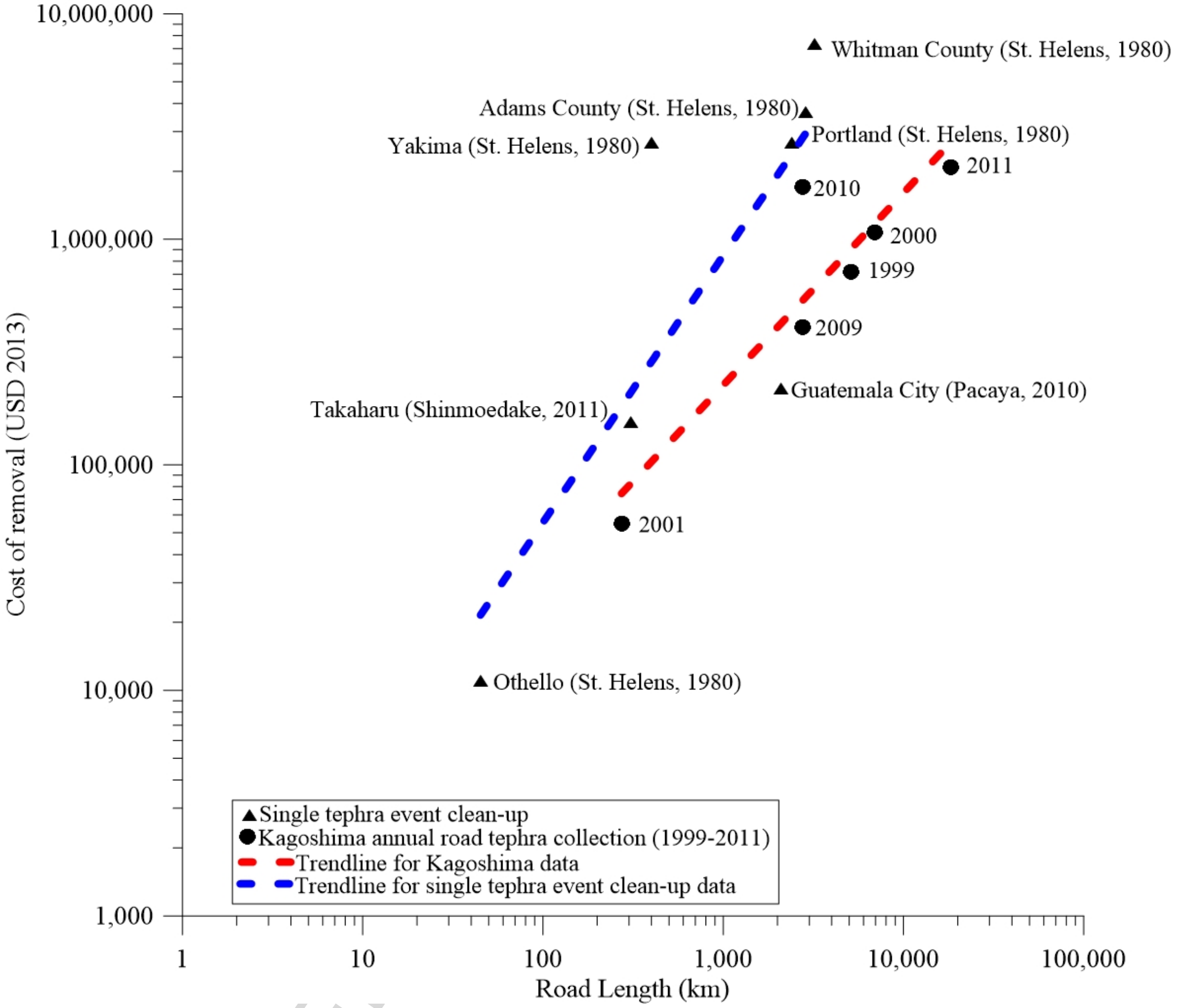
Single tephra fall event tephra clean-up
Annual Kagoshima tephra clean-up
Single tephra fall event no clean-up
Airport tephra clean-up
Single tephra fall event clean-up trend line
Kagoshima tephra fall clean-up trend line
100% of deposited material removed
Heimaey (Eldfell, 1973)
Chile Chico (Hudson, 1991)
Los Antiguous (Hudson, 1991)
Cubi Point Naval Base (Pinatubo, 1991)
Ritzville (St. Helens, 1980)
Futaleufu (Chaiten, 2008)
Guatemala City (Pacaya, 2010)
Villa la Angostura (Cordón-Caulle, 2011)
Bariloche (Cordón-Caulle, 2011)
Moses Lake (St. Helens, 1980)
Miyakonojo (Shinmoedake, 2011)
Grant County Airport (St. Helens, 1980)
Yakima (St. Helens, 1980)
Spokane Airport (St. Helens, 1980)
1992
1990
1991
Yogyakarta (Kelud, 2014)
1995
1993
1994
2000
2010
2011
Portland (St. Helens, 1980)
1999
1996
2009
1998
2001
Anchorage (Redoubt, 2009)
Tephra removal (m³/km²)
10,000,000
1,000,000
100,000
10,000
1,000
100
10
1
0
1
10
100
1,000
10,000
100,000
1,000,000
10,000,000
Tephra accumulation (m³/km²)

Figure 1



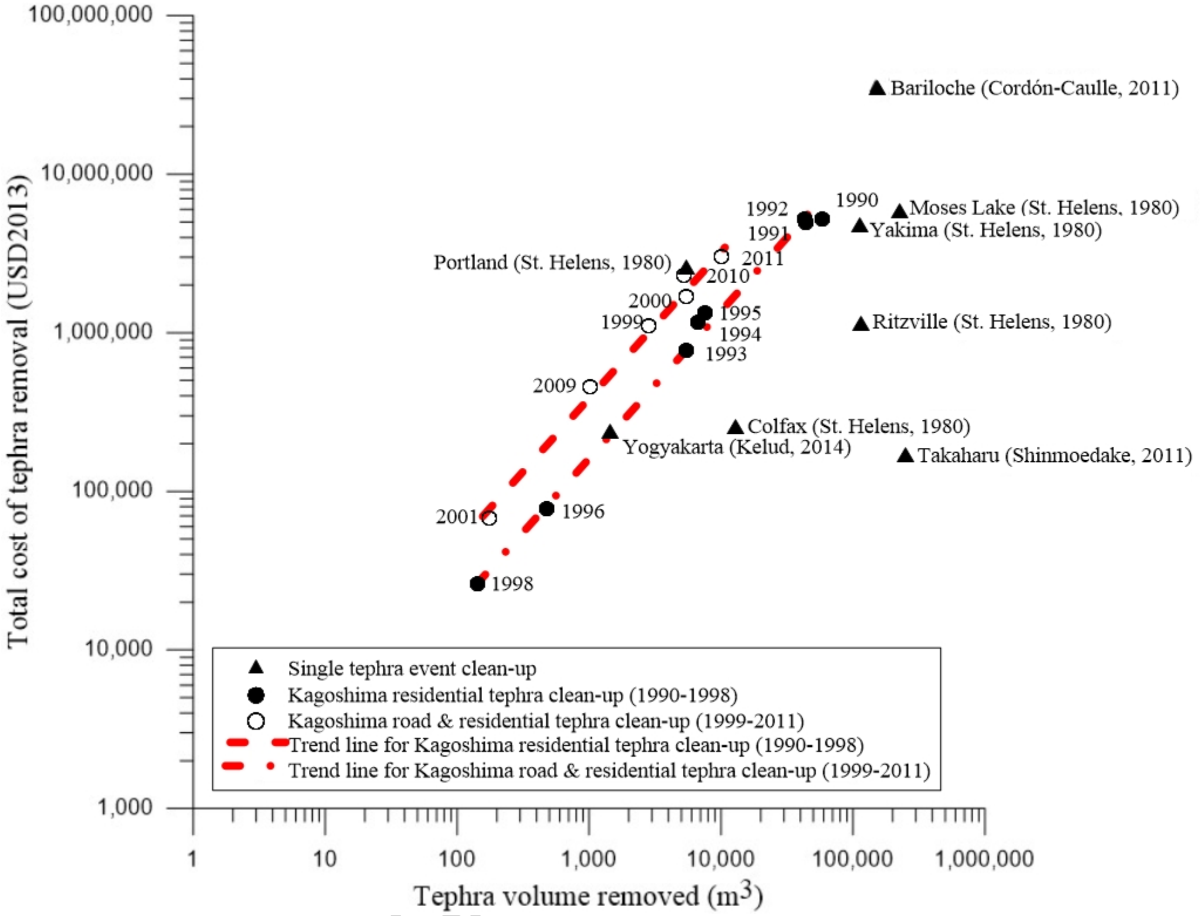
1,000
100
10
1
Clean-up operation duration (days)
Futaleufu (Chaiten, 2008)
Miyakonojo (Shinmoedake, 2011)
Heimaey (Eldfell, 1973)
Portland (St. Helens, 1980)
Bariloche (PCC, 2011)
Los Antiguous (Hudson, 1991)
Chile Chico (Hudson, 1991)
Anchorage (Spurr, 1992)
Guatamayla City (Pacaya, 2010)
Yogyakarta (Kelud, 2014)
Yakima (St. Helens, 1980)
10
100
1,000
10,000
100,000
1,000,000
Tephra accumulation (m3/km2)

Figure 2



10,000,000
1,000,000
100,000
10,000
1,000
Cost of removal (USD 2013)
1
10
100
1,000
10,000
100,000
Road Length (km)
Whitman County (St. Helens, 1980)
Adams County (St. Helens, 1980)
Yakima (St. Helens, 1980)
Portland (St. Helens, 1980)
2011
2010
2000
1999
2009
Guatemala City (Pacaya, 2010)
Takaharu (Shinmoedake, 2011)
2001
Othello (St. Helens, 1980)
Single tephra event clean-up
Kagoshima annual road tephra collection (1999-2011)
Trendline for Kagoshima data
Trendline for single tephra event clean-up data

Figure 3



100,000,000
10,000,000
1,000,000
100,000
10,000
1,000
Total cost of tephra removal (USD2013)
Bariloche (Cordón-Caulle, 2011)
1992
1990
Moses Lake (St. Helens, 1980)
1991
Yakima (St. Helens, 1980)
Portland (St. Helens, 1980)
2011
2010
2000
1995
1999
1994
Ritzville (St. Helens, 1980)
1993
2009
Colfax (St. Helens, 1980)
Yogyakarta (Kelud, 2014)
Takaharu (Shinmoedake, 2011)
2001
1996
1998
Single tephra event clean-up
Kagoshima residential tephra clean-up (1990-1998)
Kagoshima road & residential tephra clean-up (1999-2011)
Trend line for Kagoshima residential tephra clean-up (1990-1998)
Trend line for Kagoshima road & residential tephra clean-up (1999-2011)
1
10
100
1,000
10,000
100,000
1,000,000
Tephra volume removed (m3)

Figure 4

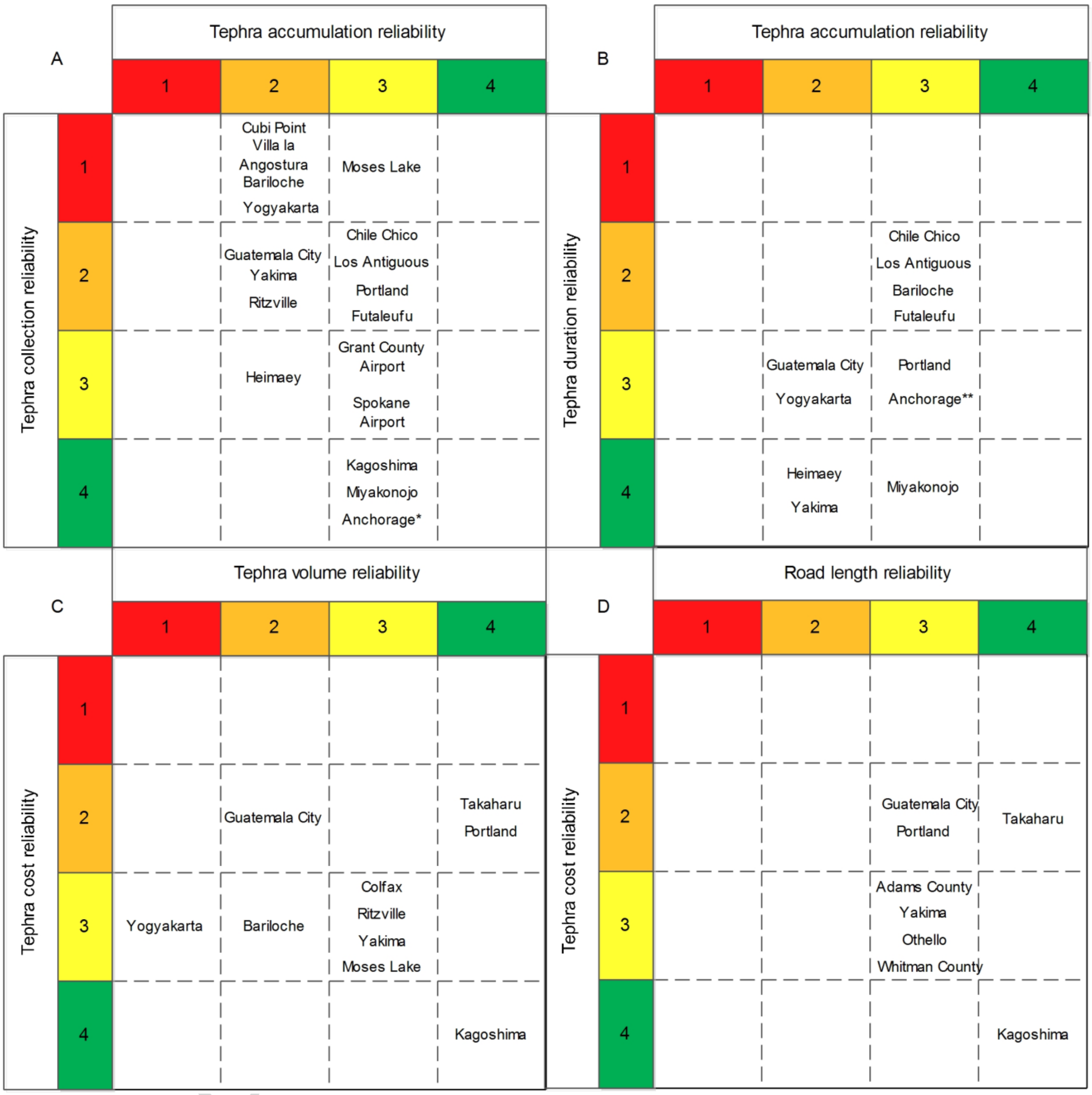

A
Tephra accumulation reliability
1
2
3
4
Tephra collection reliability
Cubi Point
Villa la Angostura
Bariloche
Yogyakarta
Moses Lake
Guatemala City
Yakima
Ritzville
Chile Chico
Los Antiguous
Portland
Futaleufu
Heimaey
Grant County Airport
Spokane Airport
Kagoshima
Miyakonojo
Anchorage*
B
Tephra accumulation reliability
Tephra duration reliability
Chile Chico
Los Antiguous
Bariloche
Futaleufu
Guatemala City
Yogyakarta
Portland
Anchorage**
Heimaey
Yakima
Miyakonojo
C
Tephra volume reliability
Tephra cost reliability
Guatemala City
Takaharu
Portland
Yogyakarta
Bariloche
Colfax
Ritzville
Yakima
Moses Lake
Kagoshima
D
Road length reliability
Tephra cost reliability
Guatemala City
Portland
Takaharu
Adams County
Yakima
Othello
Whitman County
Kagoshima

Figure 5

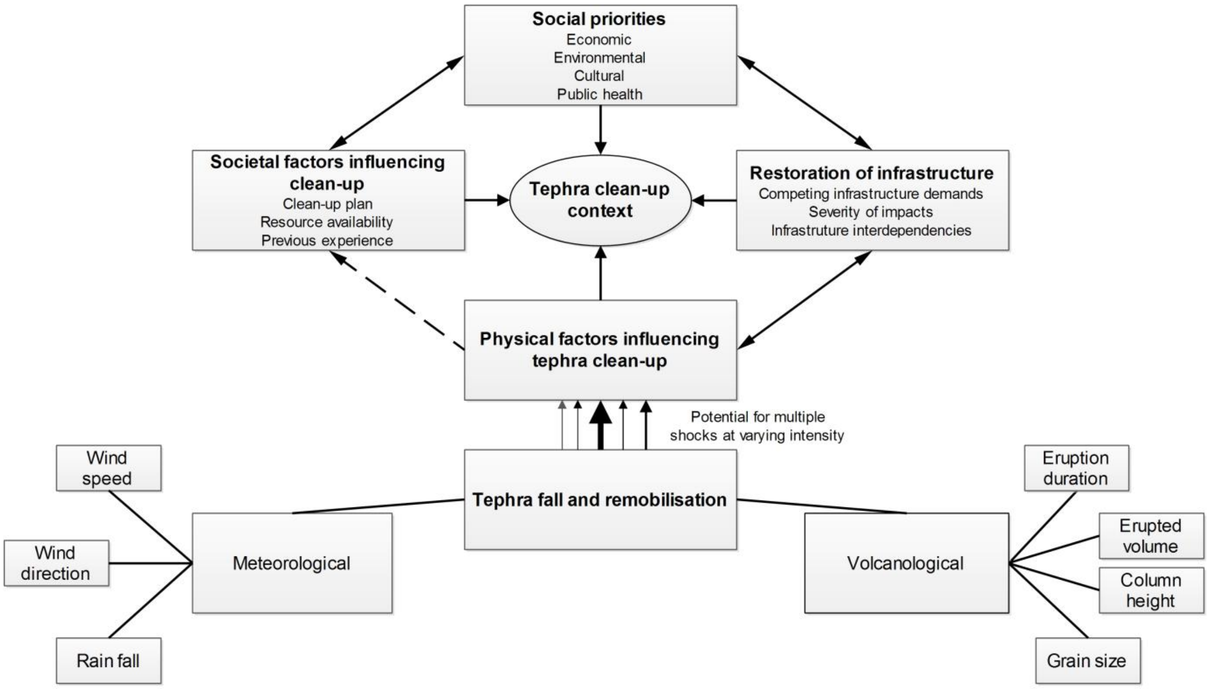
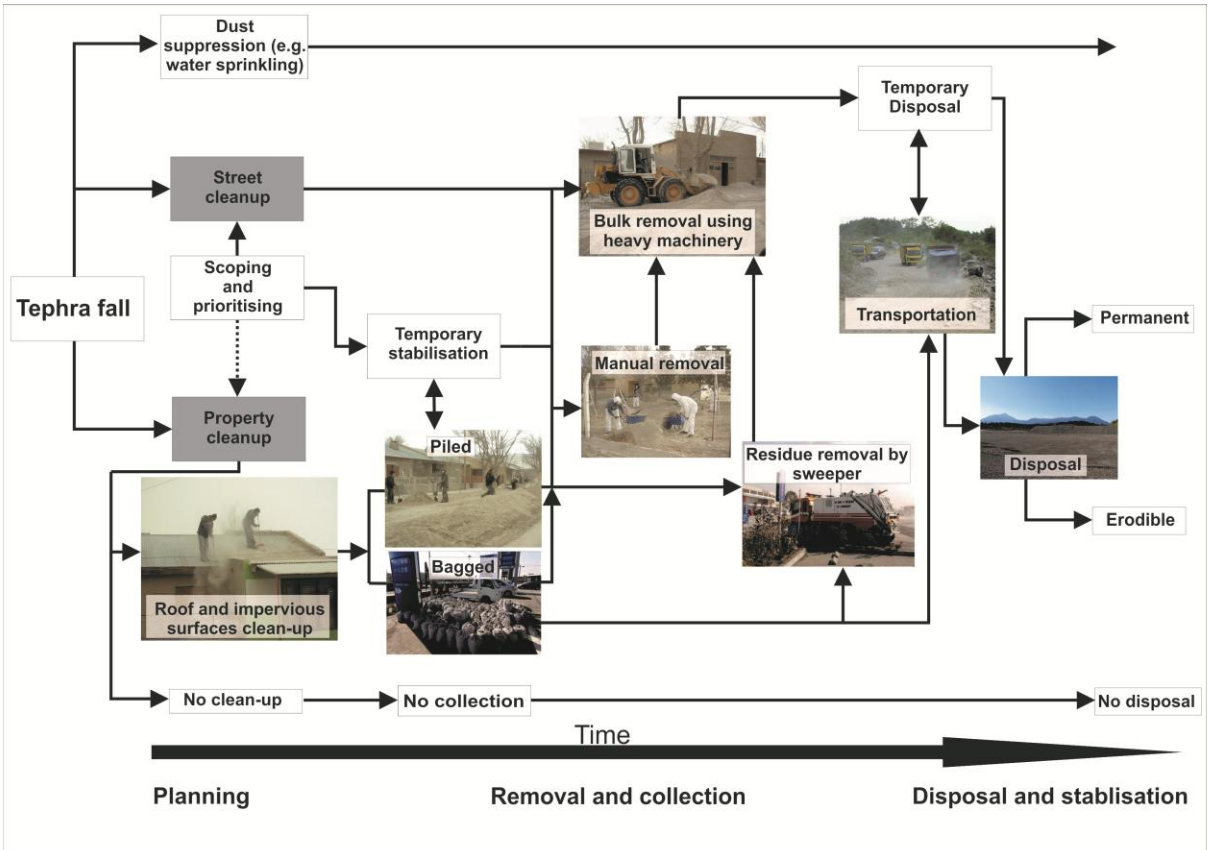

Social priorities
Economic
Environmental
Cultural
Public health
Societal factors influencing clean-up
Clean-up plan
Resource availability
Previous experience
Tephra clean-up context
Restoration of infrastructure
Competing infrastructure demands
Severity of impacts
Infrastruture interdependencies
Physical factors influencing tephra clean-up
Potential for multiple shocks at varying intensity
Tephra fall and remobilisation
Wind speed
Wind direction
Rain fall
Meteorological
Volcanological
Eruption duration
Erupted volume
Column height
Grain size

Figure 6



Dust suppression (e.g. water sprinkling)
Street cleanup
Tephra fall
Scoping and prioritising
Property cleanup
Temporary stabilisation
Piled
Bagged
Roof and impervious surfaces clean-up
Bulk removal using heavy machinery
Manual removal
Temporary Disposal
Transportation
Residue removal by sweeper
Disposal
Permanent
Erodible
No clean-up
No collection
No disposal
Time
Planning
Removal and collection
Disposal and stablisation

Figure 7

Figure 8

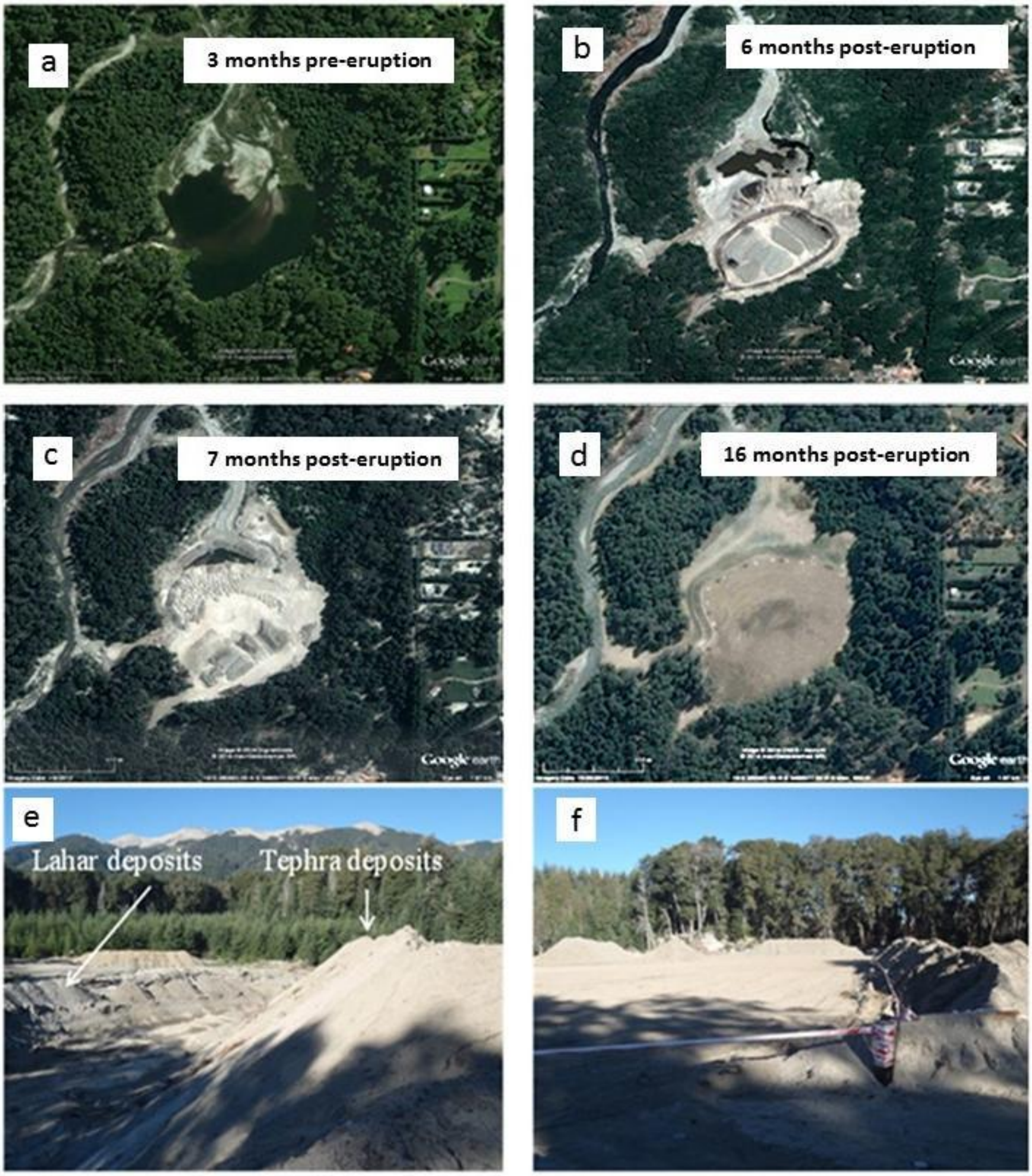

a
3 months pre-eruption
b
6 months post-eruption
c
7 months post-eruption
d
16 months post-eruption
e
Lahar deposits
Tephra deposits
f

Figure 9

Table 1: Potential tephra impacts within the urban environment in the absence of clean-up

	Potential Impact	Explanation	Cause of impact	References
Buildings	Structural damage	Roof and structural building component failure	Tephra loads exceeding the strength of roof material and/or support structure	Jenkins et al (2014)
	Non-structural damage	Roof corrosion	Prolonged contact with ash leachates	Oze et al (2014)
		Gutter failure	Tephra loads exceeding gutter strength	Jenkins et al (2014)
		Heating, ventilation, and air-conditioning shut down	Become clogged with tephra	Wilson et al (2012)
	Interior building contamination	Building contents	Ingress of tephra through cavities.	Wilson et al (2011)
Transport	Driving hazards	Reduced visibility	Tephra fall and remobilisation of tephra deposits	Wilson et al (2012)
		Reduced traction	Tephra deposition on roads	
		Obscured road markings and signage	Tephra deposition on roads and signage	
	Airport closures	Reduced traction on runway	Tephra deposition on runways	Guffanti et al (2009)
	Remobilisation	Movement of tephra from one location to another	Vehicle or aircraft movements cause tephra to remobilise	Blong (1984)
Waste water infrastructure	Reduced functionality	Blocked storm water drains	Tephra entering storm water drains	Wilson et al (2012)
	Damage	Abrasion on pipes		
Water supply	Reduced water quality	Change in turbidity and acidity	Tephra entering water supply network	Stewart et al (2006)
	Damage	Clogged filters, wear and tear on pumps		
Electricity	Reduced capacity	Short circuiting due to flashover	Tephra on lines leading to flashover	Wardman et al (2012b)
Public health	Physical	Respiratory, eye or skin irritations	Exposure to ashy environments	Horwell and Baxter (2006)
	Psychosocial	Anxiety, frustration, and depression	Constant reminder of disaster and perception of lack of recovery	Brown et al (2011); Sword-Daniels et al (2014)

Table 2: Information sources used for analysis. Within Information column, accumulation refers to sources that were used to determine tephra accumulation (m^3/km^2); collection refers to volume of tephra collected; methods refers to described clean-up methods, duration refers to the length of municipal clean-up operations, and disposal refers to methods of tephra disposal

Eruption	Locality	Information	References
Volcan Irazu (1963-1965)	San Jose, Costa Rica	Methods	Clark and Lee (1965)
Eldfell (1973)	Heimaey, Iceland	Accumulation[1]	Morgan (2000)
		Collection	Williams and Moore (1983); Morgan (2000)
		Methods	
		Disposal	
Mt. St. Helens (1980)	Yakima, USA	Accumulation	Blong (1984)
		Collection	Blong (1984); Zais (2001)
		Duration	
		Disposal	
	Ritzville, USA	Accumulation	McLucus (1980)
		Collection	Blong (1984)
		Methods	
	Portland, USA	Accumulation	Blong (1984)
		Collection	
		Duration	
		Methods	
	Moses Lake, USA	Accumulation	Blong (1984)
		Collection[2]	
	Grant county airport, USA	Accumulation	Casadevall (1993)
		Collection	
		Disposal	
	Grant County roads, USA	Disposal	Blong (1984)
	Spokane International Airport, USA	Accumulation	Schuster (1981)
		Collection	Casadevall (1993)
	Spokane County, USA	Disposal	Blong (1984)
	Adams County, USA	Disposal	McLucus (1980)
Mt. Hudson (1991)	Chile Chico	Accumulation	Naranjo et al. (1993)
		Collection[3]	Wilson et al (2009)
		Duration	Wilson et al. (2009)
		Methods	Wilson et al. (2009)
		Disposal	Wilson et al. (2009); Wilson et al. (2011)
	Los Antiguos	Accumulation	Naranjo et al. (1993)
		Collection[4]	Wilson et al. (2011)
		Duration	Wilson et al. (2009)
		Methods	Wilson et al. (2009); Wilson et al. (2011)
		Disposal	
	Perito Moreno	Disposal	Wilson et al. (2011)
Mt Pinatubo (1991)	Cubi Point Naval Base, Phillipines	Accumulation	Casadevall (1993)
		Collection[5]	
		Methods	
Mt. Spurr (1992)	Anchorage, USA	Duration	Johnston (1997)
		Methods	
		Disposal	
Mt Etna (2002)	Catania, Italy	Collection	Barnard (2004)
		Methods	
		Disposal	

Reventador (2002)	Quito, Ecuador	Methods	Leonard et al. (2005)
		Disposal	
Chaiten (2008)	Futaleufu, Chile	Accumulation	T.M. Wilson unpublished field notes
		Collection	
		Duration	
		Disposal	
Redoubt (2009)	Anchorage, USA	Accumulation	Wallace et al. (2013)
		Methods	T.M. Wilson unpublished field notes
Pacaya (2010)	Guatemala City, Guatemala	Accumulation	Wardman et al. (2012a)
		Collection	
		Duration	
		Methods	
Cordón-Caulle (2011)	Bariloche, Argentina	Accumulation	T.M. Wilson unpublished field notes
		Collection[6]	
		Duration	Wilson et al. (2013)
		Methods	
		Disposal	
	Villa la Angostura, Argentina	Accumulation	T.M. Wilson unpublished field notes
		Collection[7]	
		Methods	Wilson et al. (2013)
		Disposal	
	Jacobacci, Argentina	Disposal	Wilson et al. (2013)
Shinmoedake (2011)	Miyakonojo, Japan	Accumulation[8]	AIST, Geological Survey of Japan
	Miyakonojo, Japan	Removal	Magill et al. (2013); T.M. Wilson & C Magill unpublished field notes
	Miyakonojo, Japan	Methods	
	Miyakonojo, Takaharu, Takasake	Disposal	
Sakurajima (1955-present)	Kagoshima, Japan	Accumulation[9]	Kagoshima City (2013)
		Collection	
		Cost	
		Methods	Durand et al. (2001); Ishimine et al. (2012)
		Disposal	
Tongariro (2012)	Central North Island State Highways, New Zealand	Methods	G. Wilson, unpublished field notes
		Disposal	
Kelud (2014)	Yogyakarta, Indonesia	Accumulation	J.L. Hayes, unpublished field notes
		Collection	
		Methods	
		Disposal	

[1]Based on total estimated tephra volume

[2]Estimated from disposal piles

[3]Order of magnitude estimate

[4]Order of magnitude estimate

[5]Estimated from 25,000 dump truck loads carrying 6 m^3 per truck

[6]Estimated 250,000 dump truck loads carrying 6 m^3 per truck

[7]Estimated by 950 dump truck loads carrying 10 m^3 per truck

[8]Calculated from overall tonnage

[9]Annual g/m^2 at 22 observation points was converted to an average g/m^2. Then, assuming this value as an average across the entire city (547 km) and deposit density of 1.3 g/cm^3, was converted to m^3.

Table 3: Explanation of the criteria for assessing the reliability of information

Reliability of information				
Class	Accumulation (m^3/km^2)	Collection (m^3/km^2)	Duration	Cost
1	Unmeasured estimate from grey literature or a non-expert (e.g. locals living near volcano) with the given thickness range greater than 50% of the lower bound (e.g. 10-20 cm)	Estimate based on non-measured indirect information (e.g. number of truck loads, estimates from disposal sites) with no indication of spatial area of collection	Conflicting estimates of duration given from non-official sources with variance of more than 1 month	Partial costs estimated with no indication of components (e.g. equipment, disposal, maintenance, labourers); considered a minimum clean-up cost
2	Measurement from grey or peer reviewed literature with thickness range less than 50% of the lower bound (e.g. 10-13 cm); or total volume estimates from peer reviewed literature (e.g. total volume on Heimaey)	Estimate based on official figures from municipal reports/authorities with no indication of accurate spatial extent of collection (e.g. 'volume collected in villages proximal to volcano')	A duration range from an official source with varience of 1 month or less (e.g. Bariloche municipality estimate clean-up activities lasting 1-2 months)	Partial costs estimated with indication of components included (e.g. equipment hire or labour cost only); considered a minimum clean-up cost
3	Measurement from peer reviewed literature with tephra thickness ranges within 25% of the lower bound (e.g. 10-12 cm); or average of measurements taken at multiple locations (e.g. Kagoshima)	Estimate based on official figures from municipal reports/authorities with indication of spatial area of collection (e.g. 'volume collected in Yakima Central Business District')	An estimate of duration with an order of magnitude precision of 1 week (e.g. clean-up took 4-5 weeks); or start and end dates of 'major' clean-up activities stated	Total cost of clean-up given but no indication of individual breakdown of costs; considered a maximum cost
4	Measurement from peer reviewed literature with tephra thickness range within 25% of the lower bound (e.g. 10-12 cm) and an indication of when measurements were taken	Direct measurement of tephra (e.g. weighed at disposal sites) with an indication of spatial area of collection	Specific start and end points of clean-up activities, with clear indications regarding the distinction between municipal and individual clean-up activities	Full cost of clean-up with detailed breakdown of individual expenses; considered a maximum clean-up cost

Table 4: Summary of reported tephra clean-up processes and methodologies, shaded indicates methodology used (sorted by accumulation)

Location	Reported Clean-up duration	Thickness of in situ deposit (mm)	Accumulation (m^3/km^2)	Clean-up operation start point	Pre-collection		Residential collection		Urban collection			
					Roof clean	Stabilize tephra	Kerb side	Bagged	Graders	Manual	Sweepers	Vacuum
Kagoshima (Sakurajima, ongoing)	Goal of 3 days	Varies (1-5mm)	-	Immediate								
State Highways (Mt. Tongariro, 2011)	5-13 days	1	-	Immediate								
San Jose (Irazu, 1963-1965)	Not reported	~5	-	Not reported								
Portland (St. Helens, 1980)	10 weeks	1-5	$1.5x10^3$	Immediate								
Catania (Mt. Etna, 2002)	Not reported	1.6	$1.6x10^3$	Delayed								
Anchorage (Spurr, 1992)	6 weeks	3	$3x10^3$	Day after eruption								
Pullman (St. Helens, 1980)	Not reported	12	$1.3x10^4$	Not reported								
Spokane City (St. Helens, 1980)	Not reported	13-19	$1.6x10^4$	Not reported								
Miyakonojo (Shinmoedake, 2011)	Feb-Sept 2011	5-30	$1.75x10^4$	Not reported								
Yogyakarta (Kelud, 2014)	2 weeks	20	$2x10^4$	1 day after eruption								
Guatemala City (Pacaya, 2010)	3 weeks	20-30	$2.5x10^4$	Immediate								
Bariloche (Cordón-Caulle, 2011)	2 months	35	$3.5x10^4$	Not reported								
Jacobacci (Cordón-Caulle, 2011)	Not reported	50	$5.0x10^4$	Delayed 1 week								
Yakima (St. Helens, 1980)	7 days (24hr operation)	50-80	$7x10^4$	Immediate								
Ritzville (St. Helens, 1980)	Not reported	80-100	$9x10^4$	Two days after								
Chile Chico (Hudson, 1991)	30-60 days	100	$1x10^5$	Not reported								
Los Antiguos (Hudson, 1991)	1-2 months	100	$1x10^5$	Not reported								
Quito (Reventador, 2002)	Not reported	2-5	$2.34x10^5$	Not reported								

Cubi Point Naval Base (Pinatubo, 1991)	Not reporte d	150-200	$2.5x10^5$	Not reported								
Villa la Angustra (Cordón-Caulle, 2011)	Not reporte d	150	$2.86x10^5$	Not reported								
Heimaey (Eldfell, 1973)	April-October 1973	6-2,000	$2.5x10^6$	Delayed								

Table 5: Tephra properties influencing clean-up operations

Tephra property		Explanation
Grain size	> 2 mm	Lower potential for remobilisation
	< 2 mm	Higher potential for remobilisation
Mechanical strength	Low	Can be broken into smaller particles by crushing and shearing agents (e.g. vehicles), increasing potential for remobilisation
Moisture content	> 5%	Saturated and difficult to remove; when dry becomes cemented to surfaces
	1-5%	Binds particles together reducing the potential for remobilisation
	0%	Increased demand on water resources its use in preventing remobilisation
Abrasiveness	High	Damage to clean-up machinery (e.g. street sweepers) and surfaces (e.g. roofs)
Thickness	> 1 cm	Requires heavy machinery to remove bulk material
	< 1 cm	Requires street sweepers and manual labour to remove material

Table 6: Clean-up of surfaces at various accumulation levels (very low accumulation, Central North Island, New Zealand, image credit: Grant Wilson; Low accumulation Miyakonojo City Centre, Japan, image credit: Christina Magill; Medium accumulation Miyakonojo, Japan, image credit: Christina Magill; High accumulation, Jacobacci, Argentina image credit: Ailen Rodriguez)

Accumulation	Clean-up surfaces	Images
Very low (<500m^3/km^2)	No removal of tephra from properties, only minor clean-up (sweeping of roads). Removal of tephra from airport runways will be required.	
Low (500m^3/km^2 – 10,000m^3/km^2)	Coordinated clean-up of sealed roads in urban areas, and airports. Private properties can mostly cope without assistance. Assistance required for some community groups, such as the elderly.	
Medium (10,000m^3/km^2 – 50,000m^3/km^2)	Coordinated clean-up of all roads, and assistance with private property clean-up (e.g. bag distribution or roadside collection). Management of large volunteer work forces could be required.	
High (>50,000m^3/km^2)	Coordinated clean-up of all impervious surfaces and some recreational areas (e.g. parks). High demand for heavy earth moving machinery (e.g. loaders, graders).	

Table 7: Reported tephra disposal sites. T = towns/counties/road; A = airport, shaded indicates methodology used (sorted by volume collected)

Town	**Volume collected (m^3)**	**T/A**	**Existing waste disposal site**	**Disposal site specific for tephra**						**Extra information**
				Old quarry	**Water body**	**Secondary uses**	**Road side**	**Fields**	**General Landfill**	
Spokane county (St. Helens, 1980)	Not reported	T								Fallowed on rural fields
Adams County (St. Helens, 1980)	Not reported	T								Private landfills; roadside ditches
Othello (St. Helens, 1980)	Not reported	T								Abandoned landfill, and private pits and landfills
Spokane city (St. Helens, 1980)	Not reported	T								Two large municipal landfills mixed with normal refuse
Manila Int. Airport (Pinatubo, 1991)	Not reported	A								Edge of runways and inner fields
Perito Moreno (Hudson, 1991)	Not reported	T								Wasteland dumpsites
Guayaquil (Tungurahua, 1999-2010)	Not reported	T								Las Iguanas landfill site; Island off the coast
Takaharu (Shinmoedake, 2011)	Not reported	T								Existing landfill 2-3ha
Takasake (Shinmoedake, 2011)	Not reported	T								Old quarry
Anchorage (Spurr, 1992)	Not reported	T								City dumps, Grit on icy roads
Anchorage Int. Airport (Spurr, 1992)	Not reported	A								Fill for low lying areas
Catania (Etna, 2002)	Not reported	T								Side of road (rural); fill in landfills (City); some in sea
Quito (Reventador, 2002)	Not reported	T								Capping of existing landfill
Kagoshima (Sakurajima, ongoing)	Varied	T								Specific landfill sites in narrow valleys and waterfront land reclamation

State highways (Tongariro, 2012)	None	T								Mechanically broomed (sweeper truck) to side of the road
Yogyakarta (Kelud, 2014)	1,500	T								Filled in depressions at 4 villages located 5-10km from city
Colfax (Mt. St. Helens, 1980)	13,000	T								Three dumpsites – type not reported
Futaleufu (Chaiten, 2008)	30,000	T								Abandoned quarry with 4-5m of tephra
Grant County (St. Helens, 1980)	>38,000	T								Roadside ditches and 20 landfill sites
Grant County Airport (St. Helens, 1980)	45,000	A								Spread on fields at airport
Miyakonojo (Shinmodake, 2011)	46,000	T								Landfill and secondary uses such as bricks and sandbags
Villa la Angostura (Cordón-Caulle, 2011)	95,000	T								Filled in an old quarry which had turned into a lake
Yakima (St. Helens, 1980)	109,000	T								Horse track (25%); low wasteland for city park and sports fields (58%); Private sites (17%)
Ritzville (St. Helens, 1980)	115,000	T								Two temporary disposal sites (usually reserved for snow); area adjacent to airport runway; moved to abandoned basalt quarry
Bariloche (Cordón-Caulle, 2011)	150,000	T								Old quarry, lake
Moses Lake (St. Helens, 1980)	250,000	T								Initially dumped in wetlands then moved to over 10

										other dump sites on vacant lots
Cubi Naval Base (Pinatubo, 1991)	340,000	A								Edge of runway (for expansion) with residue spread on field
Chile Chico (Hudson, 1991)	500,000	T								Within valley south of city
Los Antiguous (Hudson, 1991)	500,000	T								Within valley south of city
Heimaey (Eldfell, 1973)	1,529,109	T								Land reclamation for airport; landfill for residential siting
Guatemala City (Pacaya, 2010)	11,350,000	T								Landfill sites at the edge of city

Table 8: Reported tephra stabilisation techniques. T = town/city/county; A = airport, shaded indicates methodology used (sorted by thickness)

Town	Thickness of in situ deposit (mm)	T/A	Permanent stabilisation			Chemical dust suppressant	Water	None	Notes
			Soil capped	Vegetated	Bagged				
Merrill Field Airport (Spurr, 1992)	3	A							
Anchorage International Airport (Spurr, 1992)	3	A							Soil capped
Quito (Reventador, 2002)	3	T							Unclear, but unlikely any was undertaken
Takasake (Shinmoedake, 2011)	5-30	T							Soil capped
Manila International Airport (Pinatubo, 1991)	10	A							Initially bagged, but this was discontinued and tephra was furrowed and sprayed with asphalt emulsion on fields.
Colfax (Mt. St. Helens, 1980)	13	T							Soil capped
Spokane city (St. Helens, 1980)	16	T							Sawdust and bagged. No stabilisation at disposal sites.
Perito Moreno (Hudson, 1991)	20	T							No stabilisation undertaken
Yogyakarta (Kelud, 2014)	20	T							Soil capped
Othello (St. Helens, 1980)	22	T							Top soil
Grant County Airport (St. Helens, 1980)	25	A							Grass growth
Grant County (St. Helens, 1980)	25	T							Rock salt on roads, no stabilisation at landfill sites
Jacobacci (Cordón-Caulle, 2011)	50	T							Building materials, plans to vegetate
Adams County (St. Helens, 1980)	60	T							Lignin sulphate on roads and ditches
Moses Lake (St. Helens, 1980)	60	T							1 inch of topsoil
Spokane county (St.	60	T							Mixed with 32% calcium

Helens, 1980)									chloride
Yakima (St. Helens, 1980)	70	T							Soil capped, irrigated and rye grass planted
Ritzville (St. Helens, 1980)	100	T							Top soil and grass
Chile Chico (Hudson, 1991)	100	T							Soil capped and grassed
Los Antiguous (Hudson, 1991)	100	T							Soil capped and grassed
Cubi Naval Base (Pinatubo, 1991)	200	A							Bulk tephra capped and vegetated. Residue swept to the infield and sprayed with asphalt emulsion
Heimaey (Eldfell, 1973)	300	T							Soil capped and vegetated (fertiliser and grass seed dropped from aircraft onto tephra)

Figure 1: Tephra fall accumulation and corresponding amount of tephra collected. Dashed/dotted line indicates 100% tephra collection. Single event tephra collection $R^2 = 0.75$, Kagoshima tephra collection $R^2 = 0.82$

Figure 2: Total tephra accumulation over urban area and duration of clean-up operation. Futaleufu clean-up duration here is the duration of primary clean-up operation. Note: Clean-up duration converted to days from qualitative estimates (e.g. about a month) assuming 30 days to a month. Where time ranges were given the maximum value was used (e.g. clean-up took 1-2 months = 60 days)

Figure 3: Total cost of clean-up compared to length of road requiring cleaning, Yakima, Othello, Adams County: McLucus (1980); Portland: Blong (1984). Takaharu: Magill et al. (2013). No Kagoshima clean-up for period 2002-2008. Kagoshima $R^2=0.81$, single tephra fall event $R^2=0.63$

Figure 4: Comparing the volume of tephra removed with cost estimates. Note Takaharu considers only tephra collected by individuals and does not include road and agricultural facilities clean-up. Both Kagoshima relationships $R^2 = 0.99$

Figure 5: Reliability of information sources for A) Figure 1, B) Figure 2, C) Figure 3, D) Figure 4. *Anchorage (2009), **Anchorage (1992)

Figure 6: Factors influencing tephra clean-up

Figure 7: Conceptual tephra clean-up process. Photo credits: Aileen Rodriguez, Thomas Wilson, Christina Magill, Tetsuya Okada and Josh Hayes

Figure 8: a) Manually piling tephra in street for heavy machinery to remove in Jacobacci Argentina (Cordón-Caulle, 2011) (Photo credit: Aileen Rodriguez), b) Bagged tephra in Miyakonojo City Centre, Japan (Shinmoedake, 2011) (Photo credit: Tetsuya Okada), c) Heavy machinery removing tephra in Jacobacci, Argentina (Photo credit: Aileen Rodriguez), d) Street sweeper in Miyakonojo City Centre, Japan (Photo credit: Christina Magill), e) Manual cleaning in Jacobacci, Argentina (Photo credit: Aileen Rodriguez)Two methods of tephra collection from properties are typically used: (1) residents and business owners pile tephra in designated locations (often 1-2m from kerb side) (Figure 7a), or (2) tephra is bagged by residents and businesses before collection (Figure 7b). Tephra removal and collection for private properties in Kagoshima is conducted by residents and small business owners who bag tephra and leave it at one of 6,400 collection points around the city (Ishinmine et al., 2012). In other areas and in situations where tephra accumulation is low (~1,000 m^3/km^2) residents or property owners may dispose of tephra either individually (e.g. in gardens) or, if available, use municipal collection services depending on circumstance and context. However, there has been confusion between residents and clean-up officials regarding how tephra will be collected. In Anchorage (Spurr – 1992), incorrect information given to residents resulted in tephra being disposed of with normal household waste, resulting in

damage to garbage trucks (Johnston, 1997).

Figure 9: Villa la Angostura, Argentina disposal site (Cordón-Caulle, 2011), a) Site on 18 March 2011, width of lake at widest point ~180m, b) site on 1 December 2011, c) site on 6 January 2012, d) site on 25 October 2013, e) photo of site March 2012 (photo credit: Thomas Wilson), f) photo of site March 2012 (photo credit: Thomas Wilson). Photos a-d from DigitalGlobe.

Highlights

- This paper reviews tephra clean-up operations from a variety of volcanic eruptions spanning over 50 years
- Tephra clean-up operations are expensive, time consuming, and resource intensive
- This study highlights the advantage of effective planning for tephra clean-up operations
- Results indicate the volume of tephra collected from urban areas is proportional to tephra accumulation