Modelling the impact of lifeline infrastructure failure during natural hazard events

By

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Cover photo: An erupting Sakurajima volcano backdrops the city of Kagoshima, Japan. Photo taken July 2013 by Emma Singh.

'Natural calamities strike at about the time when one forgets their terror'
– a Japanese proverb

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Abstract

In the case of natural hazard-caused disasters, direct impacts including building damage and loss of life are relatively well studied. Indirect disruption, on the other hand, including supply chain disruption and business interruption is harder to predict, quantify, visualise and insure. The need to better prepare for indirect disruption comes from the increasing cost and interruption it causes. A component of indirect disruption is the failure of lifelines such as power, communication, transportation and water; critical infrastructure and essential services that modern society relies on for everyday living.

The disruption of lifeline services during natural hazard events has the potential to impact populations by exacerbating the hazard itself and/or hindering the ability to respond to or recover from the event. Lifeline failure can also propagate outside the reach of the hazard footprint, causing disruption in regions not directly impacted by the event. In preparation for the true impacts of natural hazard events on society there is a need to better understand the exposure of lifeline infrastructure, the interconnectedness and behaviour of lifeline networks and to identify vulnerable populations that rely on their operation. Current research on lifeline networks focus efforts on the evaluation of network characteristics, their optimisation and robustness to random failure, or the consequences of targeted attacks. Limited research has been undertaken on the impacts of natural hazard events on these systems and the flow-on effects of failure for disaster response and recovery.

This thesis utilises mathematical graph theory tools alongside natural hazard modelling to analyse and quantify the extent of lifeline disruption during natural hazard events and the flow on effects of service failure. A future eruption of Mount Fuji in Japan is used as the major case study scenario to assess the usefulness of graph theory techniques in aiding disaster mitigation, emergency response and community recovery. In particular graph theory was used to assess the impacts of ash fall on the evacuation plans for Yamanashi Prefecture with regards to a future 1707 Hoei type eruption. It was found that:

- Ash induced road closures have the potential to affect current evacuation plans for Yamanashi Prefecture, particularly for those residents who are set to evacuate at or after the onset of a future eruption. Ash fall accumulation on roads, even after a few hours from the onset of an eruption, can inhibit road use, resulting in long detours or the inability for residents to be able to evacuate unassisted.

- After the cessation of an eruption, ash fall can impact the return of evacuees to their homes by either blocking roads or damaging buildings, affecting safety. Evacuees will have to wait for roads to be cleared of ash, and buildings to be assessed for damage, before they are able to return.
- In an eruption scenario where wind conditions are predominantly westerly the current plan for residents to evacuate to the north east of Yamanashi prefecture is not advisable. Assigned host locations in the northeast would be impacted by ash fall themselves; adding additional pressure on these communities and potentially resulting in further evacuations.

This scenario provided the opportunity to test graph theory techniques in natural hazard risk assessment and to demonstrate how graph theory can assist post event recovery in a real world context. Methods developed in this study can be used to further explore impacts of ash fall, or other volcanic phenomena, in other prefectures around Mount Fuji or other volcanoes throughout Japan. Moreover, these methods can be used to address the exposure and risk to lifelines from other natural hazard events or even to compare between them. The results of this thesis show that graph theory techniques, alongside Geographic Information Systems tools and hazard modelling, with an understanding of the use and vulnerability of particular lifelines, can help to envisage potential problems that could result from lifeline failure and aid in the process of recovery.

Not only is it important to make lifeline infrastructure more resilient to disruption from future natural hazard shocks, there is also a need to increase resilience by preparing communities to cope with service outages. For true shared responsibility to occur, local governments and communities need to be better informed and prepared so they can cope with the absence of lifelines during a disaster. Collaboration between all stakeholders is required to bridge information gaps and to create holistic disaster scenarios in order to provide more realistic and accurate assessments of future natural hazard impacts.

Declaration

I certify that the work in this thesis entitled *Modelling the impact of lifeline infrastructure failure during natural hazard events* has not been submitted previously, in whole or in part, for a degree at Macquarie University or any other university. To the best of my knowledge this thesis does not contain any material published or written by another person, except where acknowledged. I certify that this thesis is an original piece of research that is comprised of solely my own work. I also confirm that this project is being conducted in a manner that conforms in all respects with the *National Statement on Ethical Conduct in Human Research (2007)*, all other relevant pieces of legislation, codes and guidelines and the procedures set out in the original protocol (Macquarie University Ethics Committee approval reference number 5201400284, see approval letter in Appendix G).

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Preface

I was around thirteen when my fascination with Earth science began. My Aunty Anne was a geography teacher at a high school in Wellington. I would help her mark class assignments when we visited during the holidays. I was paid in Pebbles (the candy not the rock) and was not much older than the kids in her class. Looking back at it now I am not sure how I was allowed to critically assess other kids work? Anyway, putting my Aunt's work ethic aside (kidding! She was a great teacher), she once invited me along on one of her class trips to Rotorua, the smelly, hydrothermal-wonderland in the Bay of Plenty, New Zealand. I was a shy kid so being around a bunch of new people was daunting. Nonetheless I came out unscathed and with a newfound interest in the Earth beneath me.

In high school I took a wide range of classes including mathematics, science, geography and Art. Deciding what to do at university was difficult but in the end my fascination with the Earth's surface won and I enrolled at Massey University. Three years later I graduated with a Bachelor of Science, with a double major in Earth science and physical geography. Following this, a particular interest in volcanic hazards led me undertake a Master's degree with the Volcanic Risk Solutions Group at Massey University. My Master's thesis investigated the potential impacts of volcanic debris avalanches from Mount Ruapehu, New Zealand. Conducting my research on the rim of the Crater Lake, had its logistical issues but is still one of the best experiences of my studies so far.

In 2011, I moved to Sydney and found myself at Risk Frontiers, a natural hazards research centre, then based at Macquarie University. There my interest shifted from the physical processes of natural hazards to their impacts on people and the built environment. I worked as a research assistant and then as a risk scientist on various projects, and over a couple of years I was exposed to other areas of natural hazards such as social science, emergency management and policy. It became apparent how important interagency collaboration was for disaster mitigation and I enjoyed being part of a group that married academia and industry. However, I also saw how hard it was to implement research when some of the links in the chain are broken; how reports are written only to sit on shelves, how slow government can be at implementing change and how key terms come and go as the flavour of the month, mainly used to obtain funding.

In 2013 I was offered the opportunity to undertake a PhD. I was to address a gap in Risk Frontiers' expertise – indirect disruption from natural hazards. The impact of natural hazard events is often measured in fatalities and direct damage or loss; however, supply chain disruptions were being identified as becoming more important in the aftermath of recent events. I was presented with an open and undefined area to research, which I found hard to narrow down. However, there was one thing that stood out, which had the potential to affect both disaster response and recovery, and that was lifeline network disruption. Lifelines, such as power, transportation and communications, bind societies and economies and are relied on for all aspects of daily life. These complex systems exist silently in the background, until they fail - then chaos ensues.

The concept of lifelines as complex networks was new to me but I could see the importance of a better understanding of them and being able to predict and plan for their failure. The last project I worked on before undertaking my PhD involved the 2011 Illawarra South Coast flash flood event, New South Wales. Risk Frontiers was commissioned by the New South Wales State Emergency Services to better understand the actions of the residents of Shellharbour, Kiama and Jamberoo, before, during and after the event, and to understand how warnings and hazard information were perceived. Many of the impacts included the disruption of lifelines such as roads and communications. Roads were cut off by both flood waters and landslides, hindering residents from getting home or picking up children from school, and even prevented emergency services from conducting some rescue operations. A number of residents were also unable to access information or warnings at the time due to a lack of mobile phone reception and power outages. Through interviews and surveys, residents stated that the information they did receive was not specific enough and that if they knew which roads were cut off they would not have attempted to drive home through floodwaters. I could see how the incorporation of lifeline disruption into disaster planning and community engagement would help in cases like this and I was excited to research how to do this better in Australia.

Although lifeline infrastructure vulnerability and resilience is an area of interest for the Australian government and emergency managers, the information to truly assess either was difficult to come by. A number of representatives of the Australian lifeline sector and the Attorney Generals Department were approached about lifeline data accessibility. Although they were interested in the study, they either did not have the information to give, such as geolocations of assets or estimates of infrastructure vulnerabilities to natural hazard shocks, or were unable to do so due to security concerns and/or market sensitivities.

I therefore looked farther afield for data to create a realistic scenario to assess the usefulness of complex network modelling in a natural hazard context. This search led me to Mount Fuji, Japan, where I met with local prefecture governments, research centres and lifeline companies. These groups were willing to share information, helped to identify areas where more work was needed and allowed their emergency plans to be critically discussed. Through these meetings it became apparent that the impact of volcanic ash fall from a future eruption of Mount Fuji was yet to be fully addressed, in terms of both clean-up and disruption to emergency response operations. Using ash fall dispersal modelling outputs and graph theory techniques I aimed to assess the potential impact that ash fall could have on road infrastructure and how that in turn could impact current evacuation plans for Yamanashi Prefecture.

Once the information was gathered and translated, and the road data reformatted, network modelling could begin. Already simulated ash fall dispersal for the 1707 Hoei eruption, by my supervisor, Dr Christina Magill, was used as a potential future scenario. The scenario highlighted some problems with Yamanashi Prefecture's current evacuation plans, if such an event occurred again. Thick ash fall deposits could inhibit the use of roads, hindering evacuation and the subsequent return of residents. Some of the assigned host cities could also be impacted by ash fall; therefore evacuating residents to these locations may put extra pressure on these communities. Along with the results of this scenario I hope that Yamanashi Prefecture will utilise the methods outlined to test the feasibility of their evacuation plan in other scenarios. Methods developed in this thesis are also transferable to other eruptive scenarios, at other volcanoes throughout Japan. Moreover, the techniques used in this thesis can be used to address the exposure and risk to any lifeline from other natural hazard events or even to compare between them; when appropriate data are available. While security concerns must of course be addressed, when lifeline information is shared and utilised the impacts of natural hazard events on our built environment can be better prepared for. Which, when communicated with the public, may enable true 'shared responsibility' and 'resilience' to be obtained.

This thesis has been a huge learning curve for me, both academically and personally. There have been many highs and lows (as I trust most PhD students go through), but I can now look back and appreciate the journey, come to terms with bumps in the road and be proud of my achievements. I don't know whether to thank or curse my Aunty for potentially sending me down this path but either way I will get my own back as I post this thesis, with some candy, for her to read.

Chapter 1 Introduction

Lifelines are the critical infrastructure and systems crucial to the distribution and continuous flow of goods and services essential for human livelihoods, the functioning of society and economic prosperity. They include, but are not limited to: transportation, telecommunication and utilities, such as power and water. Transportation systems are used daily to move people to and from places of work and education, and goods between manufacturers, suppliers and customers. Telecommunication systems are used to connect people, conduct business, and perform financial transactions. Electricity and gas provide power to homes and industries, and water and sewage systems contribute to the public health of communities (Murray and Grubesic 2007). These lifelines have become so integrated into our modern society that they are commonly taken for granted; that is until something goes wrong. The failure of lifelines can range from being an inconvenience to being debilitating for a population both socially and economically (Davis 1999; Hawk 1999). Being without electricity or water for less than a few hours can generally be tolerated. However, prolonged disruption of such services can lead to major economic losses, deteriorating public health, and eventually population migration (Rose et al. 1997, Torres-Vera and Canas 2003, Brozovic et al. 2007, Rose and Oladosu 2008, Anderson and Bell 2012, Yates 2014). Power failure in Auckland, New Zealand (Leyland 1998); the drinking water quality crisis in Sydney, Australia (Clancy 2000); and gas outages in Victoria, Australia (Dawson and Brooks 1999), all in 1998, had media pointing out how easy it was for a modern building to convert into a third world slum when such services were lost (Hawk 1999).

A more recent example of lifeline failure occurred in December 2015, when Tasmania lost its electricity link to the mainland of Australia after the Basslink interconnector experienced a fault that impacted the electricity cable. At the time Tasmania relied on this source for 40% of its energy requirements. This combined with a severe hydropower shortage after record low rainfall presented Tasmania with the greatest energy security challenge in its history; the State resorted to diesel generators, significantly increasing power prices (Groom 2016a, Groom 2016b). Another example was seen in September 2017, when Auckland airport experienced a fuel shortage after a pipeline from Marsden Point oil refinery burst (NZ Herald 2017). Over 100 flights were cancelled and operating flights, which were only able to take 30% of the normal fuel load, had to stop in the Pacific or Australia to refuel (Radio New Zealand 2017). This was likely a great expense to businesses such as Air New Zealand and NZ Refining.

Lifeline infrastructure often consists of a large number of interconnected components, which span extensive geographic areas and, in some cases, multiple urban centres, states and international borders (Kinney et al. 2005, Guikema 2009). The concentration of mutually dependent lifeline infrastructure within urban centres results in complex and interconnected systems, creating feedback loops and complex topologies that can trigger and propagate disruptions in a variety of ways that are difficult to foresee (Rinaldi et al. 2001, McEvoy et al. 2012). Consequently, a fault in one lifeline can cascade and directly, or indirectly, affect other lifelines or services, with impacts felt not just locally but potentially nationally or even globally (McEvoy et al. 2012). Significant power failure, for example, can result in the disruption of telecommunication and transportation systems. Probably the most noted example of this was the Northeast Blackout in 2003 that impacted North-eastern United States and parts of Canada. This event not only cut power to over 50 million people but also disrupted internet communications. Banks, manufacturers, business services and education institutions were severely disrupted when they were taken offline for hours to days (Cowie et al. 2003, Murray and Grubesic 2007). The event cost an estimated 6 billion USD (Minkel 2008).

Lifelines can be disrupted by various shocks, including structural and technological failure, human error, targeted attack, and of interest in this thesis, natural hazard events (Murray 2013). A hazard can be defined as "*A dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage*". (UNISDR 2009, p 17). Natural hazards, in this thesis, concern hazards that arise from geological, meteorological, hydrological, and oceanic sources, such as earthquakes, floods and volcanic eruptions. Natural hazard prone areas, such as coastal zones and volcanic regions, have attracted large populations of people over time due to the presence of food sources, natural resources or fertile soils (Chester et al. 2001, Small and Naumann 2001, Klein et al. 2003). Today some of these settlements have grown into large cities, which continue to expand with urbanisation and natural population growth. The increasing demand for development can also see populations and infrastructure expanding into areas more exposed to natural hazards, such as flood plains, despite the risk (Huppert and Sparks 2006, Cutter and Finch 2008, Lall and Deichmann 2010). Risk here is defined as "*The combination of the probability of an event and its negative consequences*". (UNISDR 2009, p 25). The continual and growing presence of populations and infrastructure within natural hazard prone areas, combined with a changing climate, has the potential to intensify the exposure and vulnerability of lifelines to natural hazard shocks (Wu et al. 2002, Van Aalst 2006). Based on the definitions stated in UNISDR (2009): exposure is the presence of people, property and systems within natural hazard zones that have the potential to be subjected to losses, and vulnerability is the susceptibility of a population, system or asset to damage or loss from a natural hazard, based on various physical, social, economic and environmental characteristics and circumstances.

The increases in density of infrastructure and people exposed to natural hazards (Comerio 2000, United Nations 2015, United Nations 2016), along with an increased reliance on lifeline services and technology (Crucitti et al. 2004, Lund and Benediktsson 2011, Rougier et al. 2013), heightens the potential for loss and disruption during, and after, future natural hazard events. The cost of indirect disruption from lifeline failure has the potential to match, if not surpass, the cost of direct damage from natural hazard events (Comerio 2000, Menoni 2001, Brozovic et al. 2007, Rose et al. 2007, Tatano and Tsuchiya 2008). Ultimately, future lifeline failure of varying degrees of seriousness may simply have to be expected (Hawk 1999). To mitigate the cost and disruption from lifeline failure it is necessary to better understand how lifelines and their functionality might be impacted when subjected to disruption from natural hazards, and the social and economic implications of such failure. This includes a better understanding of the exposure of critical infrastructure to natural hazards, their vulnerability to disruption from future events and the impact of their failure on emergency response and disaster recovery.

1.1 Compounding impacts from lifeline infrastructure failure during natural hazard events

The often large footprint of natural hazard events has the potential to cause simultaneous failure of multiple lifeline components, across one or more networks (Erjongmanee et al. 2008). For example: storms can bring down powerlines with strong winds or fallen trees, while simultaneously cutting off transportation routes with flood water (Chang et al. 2007, King et al. 2016); earthquakes can destroy multiple lifelines, such as pipes and roads, through ground shaking or liquefaction (Menoni 2001, Giovinazzi et al. 2011, O'Rourke et al. 2012, Lanzano et al. 2014); and only millimetres of ash fall from volcanic eruptions can disrupt most lifeline services (Blong 1984, Jenkins et al. 2014, Wilson et al. 2014).

The 2016 7.8 magnitude Kaikōura earthquake in New Zealand triggered thousands of landslides, which destroyed and/or blocked roads and railways at many places in the eastern part of the South Island (Kaiser et al. 2017), including both north and south access to Kaikōura Township (GNS Science 2016). This completely isolated the Kaikōura community, which strongly relies on tourism for its economy, and impacted the movement of people and freight throughout New Zealand by stopping an estimated 4,000-5,000 vehicles daily (New Zealand Treasury 2016, Meduna 2017). In the month after the earthquake, visitor numbers to Kaikōura dropped by 80%, meaning the town missed their busy summer season (NZ Herald 2016, Meduna 2017). For the rural community the loss of road access made everyday tasks such as school attendance, doctor visits and seeing a vet challenging. It also hindered recovery as clean-up equipment was difficult to obtain (Meduna 2017). Interestingly, Meduna (2017) found that the impact to tourism was not all negative; thanks to the coastal uplift that occurred during the earthquake, longer-term coastal erosion and foreshore problems were solved.

In 2016, the state of South Australia was hit by a severe storm that knocked over 22 electricity transmission poles and damaged a number of electricity generation facilities. This resulted in a state-wide power outage, leaving 1.67 million South Australian residents without electricity for nearly 12 hours, disrupting businesses and affecting other lifelines operations such as communication and transportation (King et al. 2016, Lucas 2017). South Australia Water lost power to its pumping stations causing some properties to be without water and unable to clear sewage (Burns et al. 2017). Other disruptions outlined in Burns et al. (2017) included: train and tram services being stopped for safety reasons, traffic light outages in Adelaide CBD; long delays in security screening at Adelaide airport; and the disruption of cell phone networks and triple-0 services in some areas. Due to loss of power to mobile phone based stations and infrastructure, some Optus customers were without voice or data services in Port Lincoln, Port Pirie and Eyre Peninsula (Singtel Optus Pty Limited 2016). The State-wide blackout caused large disruptions for copper mines, steelmakers, the lead smelter, and forced most businesses to close overnight; total business losses were expected to have reached hundreds of millions of dollars (Reuters 2016, Burns et al. 2017).

The failure of lifelines during natural hazard events has the potential to affect populations by exacerbating the impacts of the event itself and/or hindering the ability to respond to or recover (Menoni 2001, Chang and Chamberlin 2004, Brozovic et al. 2007, Tatano and Tsuchiya 2008, EERI 2011, McEvoy et al. 2012, Tamaki and Tatano 2014, Yamamoto and Nakada 2015). Loss of power during a heatwave, for example, can leave a population without services relied upon to cope with prolonged high temperatures such as fans, refrigeration and air-conditioning (Miller et al. 2008, Reeves et al. 2010, Coates et al. 2014). The loss of these aids can be life threatening for those most vulnerable to heatwaves, such as the elderly and ill, potentially increasing the rate of heat related deaths and illnesses, and putting additional pressure on emergency and health services (Reeves et al. 2010, Broome and Smith 2012) (see Chapter 2 for a more extensive review of the 2009 south-eastern Australian heatwave).

Lifeline failure can also propagate outside the reach of the hazard footprint, causing disruption in regions not directly impacted by the event. An example of this is the 2010 Eyjafjallajökull eruption in Iceland. Although not impacted by eruption products on the ground, the United Kingdom and parts of Europe were severely affected by the week long closure of airspace due to volcanic ash in the atmosphere (Budd et al. 2011, Ellertsdottir 2014). Over this seven-day period more than 100,000 flights in, out and around Europe were cancelled, stranding over 10 million passengers (IATA 2010, Budd et al. 2011). This disruption cost the airline industry an estimated 1.7 billion USD in lost revenue (IATA 2010). Other industries around the globe were also impacted, particularly those dependant on flights to transport goods and people. Flower and fruit growers in Africa were especially hard hit, with fresh products due to be air-freighted to Europe being left to rot, resulting in the loss of millions of dollars in exports (Budd et al. 2011, Ellertsdottir 2014). Without the reliance on air travel and transport, the eruption may not have been experienced in this region at all (see Chapter 2 for a more in-depth review of this event).

A further complication of natural hazards is the potential for events to be prolonged; i.e. have an extended duration (a week or more), or consist of a series of events that occur in succession (Blong et al. 2017). Natural hazards can be associated with secondary hazards, which can occur simultaneously or subsequently. Earthquakes, for example, are often associated with liquefaction, landslides, fires, tsunami and aftershocks (EERI 2011, Daniell et al. 2017). An excellent example is the 2011 Tohoku earthquake, which was quickly followed by a devastating tsunami and nuclear disaster. The 9.0 magnitude quake and near 40 metre tsunami resulted in the death or disapparence of over 24,000 people (Mimura et al. 2011). The impacts to the Fukushima Nuclear Power Plant resulted the evacuation of around 60,000 people who lived within 20-30 km of the plant (Matanle 2011). Another natural hazard that has the potential to be prolonged is volcanic eruption. Volcanic eruptions are not only associated with a range of phenomena, such as lava flows, lahars, pyroclastic density currents and ash fall (Jenkins et al. 2014, Wilson et al. 2014), but can also be sustained for weeks, months or even years (Siebert et al. 2011, Sword-Daniels et al. 2014). Sakurajima volcano in South Kyushu, Japan, has been erupting almost constantly since 1955 and regularily impacts the city of Kagoshima with volcanic ash.

A prolonged natural hazard event can affect a region for an extended period, causing vast and on-going disruptions to lifeline services vital for disaster response and community recovery. The quake-stricken Canterbury region of New Zealand endured thousands of disruptive aftershocks that continued for a number of years following the initial 7.1 magnitude earthquake in September 2010 (Bannister and Gledhill 2012). Aftershocks contributed to delays in repair and rebuilding and caused significant additional damage, with larger events being associated with shaking damage, rock falls and liquefaction (King et al. 2014, Potter et al. 2015). The 6.2 magnitude aftershock on February 2011, occurring close to the city of Christchurch, caused catastrophic damage and resulted in 185 deaths (Cubrinovski et al. 2011, Potter et al. 2015). The disruption to lifelines from the 2011 aftershock was the largest New Zealand had experienced in over 80 years with water, wastewater and power systems impacted by shaking and liquefaction (Giovinazzi et al. 2011, O'Rourke et al. 2012). Bridges over the Avon River were damaged due to liquefaction and lateral spreading (Giovinazzi et al. 2011, Yamada et al. 2011). Rock falls and slope failures in the hill suburbs damaged power, water and sewage infrastructure, and the ongoing risk of further rock falls threatened the road between Christchurch city, Red Cliffs and Sumner (Giovinazzi et al. 2011).

The compounding impacts of lifeline failure can be hard to foresee and in turn mitigate. However, past experiences highlight that lifeline failure during a disaster can be costly, especially when populations are ill-prepared. In preparation for the true impacts of future natural hazard events, we need to include lifelines in disaster preparedness, response and recovery plans (Solano 2010). Infrastructure failure has been addressed by a number of organisations, such as the insurance industry, businesses and governments, who have put in place frameworks and strategies to assess and mitigate risk (Galey et al. 2002, Haueter 2013, Lloyds 2013, Asia Insurance Review 2014, McKinnon 2014, Pielke 2015, World Economic Forum 2017). However, the risk of lifeline disruption is often addressed in isolation, with lifelines neglected in natural hazard risk assessments and disaster management plans (Jensen et al. 2015, Newman et al. 2017). Communities need to be aware that lifelines can fail, what to expect when they do and what actions they can take to ensure they are able to cope. However, it is not always been possible to share information on lifeline vulnerabilities within civil emergency planning due to the classified or commercially sensitive nature of some information (Commonwealth of Australia 2010, UK Cabinet Office 2011).

Local governments are often responsible for disaster response and resilience decisions, and can directly influence disaster risk reduction through appropriate land-use planning, building codes and infrastructure design; and through providing natural hazard maps and information to residents (Klinenberg 2015, King et al. 2016). However, this level of government is also often the most constrained due to a lack of funding, resources and often inherits poor past planning decisions (King et al. 2016). Although there has been a call for shared responsibility between all stakeholders, Davies et al. (2015) and Box et al. (2016) point out that where many disaster strategies fall short is in the inclusion of community members, and in the outlining of their responsibilities (an extensive review of the current inclusion of lifelines in disaster planning can be found in Chapter 2).

Not only is it important to make lifeline infrastructure more resilient to disruption from natural hazard shocks, there is also a need to increase resilience by preparing communities to better cope with service outages. To do this we need to better understand the interconnectedness and behaviour of lifeline networks, to identify vulnerable populations that rely on their operation and to create holistic disaster scenarios that involve the collaboration of all stakeholders.

1.2 Lifeline network modelling

Understanding the vulnerabilities of essential lifeline networks is key to supporting response during and recovery following natural hazard events. Chang and Chamberlin (2004) found that incorporating assessments of lifeline outages with those of traditional natural hazard impacts, such as building damage, provided a more realistic and accurate measure of how strengthening lifeline systems can improve disaster resilience compared to modelling lifeline outages in isolation. Most methods for assessing the vulnerability of critical infrastructure have involved mathematical modelling approaches, such as graph and network theories, which use graph representations to determine infrastructure topologies and interconnections (Solano 2010, Murray 2013). Other methods for assessing lifeline disruption include: probabilistic approaches, logic principles and cost minimisation (Lewis 2006), qualitative assessments (Haimes and Longstaff 2002, Baker 2005) and expert judgement (Cooke and Goossens 2004, Egan 2007, Ezell 2007, Parks and Rogers 2008) (Solano 2010, Ouyang 2014). However, most of these methods incorporate aspects of graph theory in their approaches (Solano 2010).

Graph theory is the study of network representations in which vertices (nodes) and edges (connections) describe the building blocks of complex systems (Van Steen 2010) (see Figure 3.1). Its foundations go back to the mathematician Euler, who, in 1735, proved that it was impossible to take a walk through the medieval town of Königsberg, Russia, and visit each part of town by crossing each of its seven bridges only once (Barabási 2002). In recent decades, applications of graph theory have been facilitated by automated data acquisition, increases in computing resources and the desire to understand complex real-world networks (Albert and

Barabási 2002). These networks include the World Wide Web (Albert et al. 1999; Broder et al. 2000; Dourisboure et al. 2007), the Internet (Faloutsos et al. 1999, Pastor-Satorras and Vespignani 2007) and social networks (Newman et al. 2002, Kossinets and Watts 2006, Kumar et al. 2010, Klausen 2015) (See Chapter 3 for a more in depth explanation of graph theory methodologies).

The simplified nature of graph theory allows the architecture of networks to be observed and reveals the laws that govern network evolution (Barabási, 2002). Various software packages with pre-created algorithms (i.e. *Mathematica* (© 2015 Wolfram Research, Inc., https://www.wolfram.com/mathematica/); *igraph* (© 2003 – 2015 The igraph core team. http://igraph.org/); *Gephi* (© 2008 – 2012 Gephi contributors. https://gephi.org/)) are readily available to solve a range of queries relating to network structure, robustness and processes; characteristics that are not always apparent when observing a pictorial illustration of the network (Newman 2010). Research aims in the area of graph theory have progressed from describing network topology to understanding the mechanisms that shape network evolution (Barabasi, 2002). 'Real-world' networks have ceased to be modelled as static random graphs and are now seen as dynamic systems, which change constantly through the addition (or loss) of nodes and connections (Barabasi, 2002). A random graph is a graph in which properties such as the number of vertices and edges are determined randomly, where the evolution of a 'real-world' network has been found to be governed by generic organising principles. 'Real-world' networks have been used to study a range of very different systems (e.g. social, biological and computational) (Albert and Barabasi, 2002). Topology (network structure) is not the only factor controlling a network's susceptibility or resilience to failure. Cascading failure can occur when neighbouring nodes do not have the capacity to take on loads or responsibilities from failed nodes. Failure of this kind is more likely to be devastating to a network if failure starts at a highly connected node (Barabasi, 2002). Network modelling must therefore not only take into account a network's topology but also its dynamic properties (i.e. growth, preferential attachment, flow, weight and direction). The most recent advancements in graph theory endeavour to understand cascading failures (Buldyrev et al. 2010, Cupac et al. 2013, Fang et al. 2014, Koç et al. 2014, Shuang et al. 2014), weighted networks (De Montis et al. 2005, Soh et al. 2010) and directed flow through networks (Albert and Barabasi, 2002, Barabasi, 2002).

One expanding area of graph theory is in examining critical infrastructure systems (Matisziw et al. 2009, Murray and Grubesic 2012), including power grids (Albert et al. 2004, Crucitti et al. 2004, Kinney et al. 2005, Holmgren 2006, Correa-Henao et al. 2013, Iešmantas and Alzbutas

2014, Koç et al. 2014, Moradkhani et al. 2014, Pagani and Aiello 2014), transportation networks (Angeloudis and Fisk 2006, Derrible and Kennedy 2010, Sullivan et al. 2010, Zhang and Virrantaus 2010, Chan et al. 2011, Snelder et al. 2012, Cardillo et al. 2013, Voumard et al. 2013, Verma et al. 2014), and water infrastructure (Shuang et al. 2014, Beh et al. 2017). Koc et al. (2014) used graph theory and complex network measures along with the characteristics of an electric power grid to assess the impact of topology on cascading failures, which enabled them to create a more accurate metric for grid robustness. Verma et al. (2014) used graph theory measures to map the structure of the World Airline Network (WAN) and to identify consequences of its topology. They found that the WAN was organised into two different classes of clusters: a highly resilient and strongly connected core and fragile star-like periphery. This means that long distance travel is robust to disruption but the removal of short connections can isolate remote locations that have limited connections.

Most research into lifeline infrastructure using graph theory tools has focused on network topology (Sen et al. 2003, Seaton and Hackett 2004, Chan et al. 2011), and robustness to random failure and attack (Angeloudis and Fisk 2006, Holmgren 2006, Berche et al. 2009, Cardillo et al. 2013, Duan and Lu 2013, Berezin et al. 2015, Faramondi et al. 2018). However, like the evolution of graph theory research on the whole, research involving lifelines has begun to investigate flow through lifeline networks, including cascading lifeline failure and flow through weighted networks (Albert et al. 2004, Crucitti et al. 2004, Kinney et al. 2005, De-Los-Santos et al. 2012, Koç et al. 2014). When combined with other tools, network modelling has great potential for assessing the effects of lifeline disruption when a real disaster occurs. Geographic information systems (GIS) are commonly used alongside graph theory and complex network techniques to help display more realistic geographic representations of lifeline networks (Solano 2010, Newman et al. 2017). This is important when assessing lifeline behaviour due to natural hazard shocks because of the spatial nature of both components. Bono and Gutiérrez (2011) combined simple graph theory concepts with GIS tools to assess how urban space accessibility decreased when road networks were damaged or blocked with debris as a result of the 2010 Haiti earthquake. They found that this method was effective in showing isolated regions of Port Au Prince that might not have been recognised using GIS alone. Although further improvements to the methodology were recommended, Bono and Gutiérrez (2011) stated that the combination of approaches helped to make sense of the disruption that the Haiti earthquake caused, both socially and economically (Chapter 3 further explores this area of work, integrating graph theory with natural hazard footprints).

Graph theory allows the investigation of lifeline networks at a low computational cost due to the use of analytical calculations (Ouyang 2014). However, when applied to real-world natural hazard cases, graph theory alone is incomplete in providing a realistic and accurate assessment of impacts. Graph theory techniques are useful for identifying critical components important to the functioning of networks and for providing optimal flow paths, but can misinterpret network behaviour in the real world without additional supporting information to appropriately weight network connections (Eusgeld et al. 2009, Hines et al. 2010). Additional input data can also be difficult to access, specifically information describing infrastructure component characteristics (Ouyang 2014). However, there is great potential for graph theory techniques to add value in the disaster management space when combined with other tools – such as natural hazard modelling and GIS – and to be integrated into holistic scenarios that incorporate inputs from all stakeholders (Thacker et al. 2017).

1.3 Thesis aim and objectives

The aim of this thesis is to create a better understanding of the impacts of lifeline failure during natural hazard events through the use of graph theory.

Specific objectives include:

- Identifying current gaps in emergency management and disaster mitigation with regards to shocks to lifeline infrastructure from natural hazards, and the flow on effects of lifeline failure.
- Assessing the usefulness of mathematical graph theory tools in aiding disaster mitigation, emergency response and community recovery.
- Utilising graph theory techniques in a real-world scenario to analyse and quantify the extent of lifeline disruption and the effects of service failure during a natural hazard event.

1.4 Thesis structure, outputs and contributions

This thesis is divided into five chapters. Each chapter expands on the specific issues identified in this introductory chapter and provides a distinct contribution to the aim of the thesis. Chapter 2 provides additional background information. Chapter 3 provides preliminary methods and results, pertinent to the Tokyo Subway case study it addresses. Chapter 4 provides further method development and results to an additional case study on road transport disruption during a future eruption at Mount Fuji. Together Chapters 2-4 address the three objectives above, and Chapter 5 provides a discussion tying the research outputs together and identifies potential areas for future work.

1.4.1 Chapter 2. Compounding impacts of lifeline failure and the inclusion of lifeline disruption in current disaster plans

Chapter 2 takes a closer look at the 2009 south-eastern Australian heatwave and the 2010 Eyjafjallajökull eruption in Iceland to investigate how lifeline failure can exacerbate the impacts of natural hazard events. Following on from the learnings of these events, this chapter reviews the current inclusion of lifelines in natural hazard risk assessments and disaster planning, and explores how this could be improved to better prepare for lifeline disruption during natural hazard events. This chapter addresses the first objective of the thesis and is the first step towards a better understanding of the compounding effects of loss of critical infrastructure services on disaster response and recovery.

A variation of Chapter 2 was submitted as a chapter to the book titled '*The demography of disasters*'. The submitted chapter is entitled: '*Disruption from disaster or disasters from disruption? Compounding impacts from lifeline infrastructure failure during natural hazard events*'. The book chapter is currently with the book editors for final review.

I solely authored this chapter and the submitted manuscript; however, acknowledgement is given to Dr Christina Magill, and the book editors, Dr Deanne Bird, Dr Dávid Karácsonyi and Dr Andrew Taylor for their reviews of the content and helpful comments.

1.4.2 Chapter 3. Applying graph theory to assess lifeline network disruption during disasters: an example using the Tokyo Subway

Chapter 3 addresses the second thesis objective by assessing the applicability of graph theory techniques to help interpret lifeline failure in a disaster. In particular, the Tokyo Subway network is subjected to a hypothetical flood inundation scenario to test the usefulness of graph theory techniques in a natural hazard context. The impact that this shock has on the subway network's capacity, with respect to the movement of people, is analysed using mathematical graph theory and GIS tools. Although the scenario explored here is imagined, it is suitable for explanatory and demonstration purposes.

Chapter 3 was summarised and published as an article in the Asia Pacific Fire magazine: Emma Singh (2017). Can graph theory techniques help with emergency response? *Asia Pacific Fire.*

MDM Publishing Ltd. April 2017. http://apfmag.mdmpublishing.com/can-graph-theory-techniques-help-with-emergency-response/. This article can be found in Appendix D

This work was also presented as a poster at the 2016 Australasian Fire Authorities Council (AFAC) conference: Emma Singh (2016). Disruption of critical infrastructure during natural disasters. *AFAC16 (Bushfire and Natural Hazards CRC, 2016), Brisbane, Australia, August 2016*. This poster can be found in Appendix E

I carried out all analysis and writing of this chapter and resulting research outputs. The original concept of using graph theory was developed jointly by Dr Felipe Dimer de Oliveira and Prof John McAneney. I acknowledge Dr Felipe Dimer de Oliveira and Pranil Singh for their coding assistance and Dr Tetsuya Okada for his help with sourcing and translating Japanese data. Both Dr Christina Magill and Dr Jennifer Rowland provided extensive reviews on the structure of this chapter.

1.4.3 Chapter 4. Exposure of roads to volcanic ash from a future eruption from Mount Fuji, Japan: Implications for evacuation and clean-up

Chapter 4 takes the methodologies described and refined in chapter 3 and applies them to a real world scenario in order to quantify the extent of lifeline disruption and the effects of service failure during a natural hazard event, fulfilling the third objective.

To generate realistic representations of complex lifeline systems, modelling of lifeline impacts needs to include social, organisational and environmental variables alongside engineering components (Solano 2010). With limited publically available data on lifeline infrastructure, any approach to lifeline modelling requires collaboration with infrastructure sectors to bridge the information gap (Buxton 2013, Eleutério et al. 2013). However, building these relationships can take time and sector representatives are not always able to engage.

A scenario based on a future eruption of Mount Fuji, Japan, was utilised primarily because of the availability of information and the willingness of prefecture governments, research centres and lifeline companies to identify gaps in their emergency plans where graph theory techniques could be of assistance. Site visits and interviews with various stakeholders highlighted that the impacts of volcanic ash fall from a future eruption of Mount Fuji were yet to be fully addressed, in terms of both clean-up and disruption to emergency response operations.

Using ash fall dispersal modelling, GIS and graph theory techniques this chapter assesses the potential impacts that ash fall could have on road infrastructure and how this in turn could impact emergency response and recovery. In particular these techniques are used to assess the impact that ash induced road closures might have on current evacuation plans for Yamanashi Prefecture.

Preliminary modelling for this chapter was presented at the BNHCRC Showcase in Adelaide in July 2017, and AFAC17 conference in Sydney in September 2017: Emma Singh (2017). Disruption of critical infrastructure during natural disasters. *AFAC17 (Bushfire and Natural Hazards CRC, 2017), Sydney, Australia, September 2017*. This poster can be found in Appendix E.

An oral presentation was also given at the 2017 IAVCEI (International Association of Volcanology ad Chemistry of the Earth's Interior) conference in Portland, Oregon, United States in August 2017.

Network analysis and the writing of this chapter were done by myself. I acknowledge Dr Tetsuya Okada for accompanying me on fieldwork in Japan, for interpreting interviews and for helping source and translate information. I would like to acknowledge Dr Christina Magill for supplying the ash fall dispersal modelling results and for reviewing the chapter structure. Dr Kae Tsunematsu is acknowledged for taking the time to discuss the proposed eruption scenario. Yamanashi and Shizuoka Prefecture Governments are also acknowledging for their time and information. Dr James O'Brien and Dr Mingzhu Wang helped with formatting road data and provided GIS support.

1.4.4 Chapter 5. Discussion

Chapter 5 provides a summary of and critical discussion on the findings of each chapter and reviews the success of the thesis aim and objectives. This chapter further discusses the implications and contributions of this research to disaster management, and highlights the limitations of the methods used and areas of future research that may improve this area of work going forward.

1.4.5 Additional outputs

A number of other research outputs were produced during my candidature, which although did not contribute directly to the final thesis, helped to shape the direction of my research.

- The first was the conference paper: Phillips et al. (2013a). Experience, attitudes and behaviour. Residents in response to warnings during the March 2011 flash flooding in

Shellharbour, Kiama and Jamberoo, NSW. *AFAC13 (Bushfire and Natural Hazards CRC, 2013), Melbourne, Australia, September 2013*. This can be found in Appendix A. The paper summaries a report from the last project I managed before starting my PhD: Phillips et al. (2013b). An integrated research assessment of the physical and social aspects of the March 2011 flash flooding in Shellharbour, Kiama and Bega Valley, NSW. *A report for the New South Wales State Emergency Services*. This project brought to my attention the impact that lifeline failure can have on emergency response during natural hazard events and highlighted the current lack of incorporation of lifeline disruption in disaster planning and community engagement. Note that publications before 2016 use my maiden name 'Phillips'.

- The second was a Risk Frontiers Briefing Note on the 2014 Darwin blackout. This was a timely example of how vulnerable critical infrastructure and services can be and how much society relies on these services for everyday living, the economy and emergency response. This article can be found in Appendix F.
- The third was a conference paper: Phillips et al. (2015). Disruption of critical infrastructure during prolonged natural disasters. *AFAC14 (Bushfire and Natural Hazards CRC, 2014), Wellington, New Zealand, September 2014*. This work was done at the start of my PhD and was a preliminary case study for my thesis that could not progress due to end user and information constraints. This paper can be found in Appendix B.
- The forth was a magazine article: Phillips (2015). Volcanic eruptions and disruptions. *Actuaries Digital*. https://www.actuaries.digital/2015/10/08/volcanic-eruptions-and-disruptions/. This article summarises preliminary literature reviews on indirect disruption, contingent business interruption, gaps in insurance cover for pear-shaped events and the disruptive potential of large volcanic eruptions. This article can be found in Appendix C.

These chapters and research outputs, although addressing individual objectives or thought pieces, link together to address the overall thesis aim of creating a better understanding of the impacts of lifeline failure during natural hazard events through the use of graph theory.

Chapter 2 Compounding impacts of lifeline failure and the inclusion of lifeline disruption in current disaster plans

2.1 Chapter overview

Lifelines, such as transportation, communication, power and water, have become so integrated into our modern and globalised world that they are commonly taken for granted. That is, until their services are disrupted. The failure of lifeline services during natural hazard events has the potential to impact populations by exacerbating the hazard itself and/or hindering the ability to respond to or recover from the event. Lifeline failure can also propagate outside the reach of the hazard footprint, causing disruption in regions not directly impacted by the event. Understanding the potential flow on effects from lifeline failure during natural hazard events is vital for future disaster mitigation, response and recovery. The 2009 south-eastern Australia heatwave and the 2010 Eyjafjallajökull eruption in Iceland are drawn on to highlight and discuss the vulnerability of lifelines to disruption from natural hazard shocks and the compounding impacts of lifeline failure during natural hazard events.

2.2 Key findings

The outcomes of both case study events were influenced by unpreparedness. For south-eastern Australia it was the magnitude of the event itself. For the United Kingdom/Europe it was a scenario deemed unlikely and previously ignored. Both events became the much needed wakeup call to spark major reviews of management plans and policies and highlighted the need for the inclusion of lifelines into disaster preparedness, response and recovery plans. The findings from these case studies led to a discussion and further review to identify the extent to which lifelines are currently included in natural hazard risk reduction; where improvement is needed; and barriers to this. It was found that although some countries have endeavoured to include lifelines into disaster management plans there were still a number of barriers that limited the extent of this inclusion, namely:

- inadequate community education and engagement about lifeline failure in a disaster
- limitations of local government to strengthen lifeline infrastructure and mitigate service failure
- inaccessibility of sensitive lifeline information
- a lack of holistic disaster scenarios

2.3 Introduction

To better prepare for future natural hazard events there is a need to understand how lifelines and their functionality might be impacted when subjected to natural hazard shocks. Lifeline infrastructure vulnerabilities also need to be considered alongside social dimensions to take into account the ability of populations to adapt to or cope with service failure. To further explore the compounding effects of lifeline disruption during natural hazard events this chapter looks at two case study examples in detail: the 2009 south-eastern Australia heatwave and the closure of European airspace during the 2010 Eyjafjallajökull volcanic eruption in Iceland. The chapter concludes with a discussion on what was learnt from these events and what needs to be done to further include lifeline disruption into disaster management plans.

2.4 Case study 1: The 2009 south-eastern Australia heatwave

2.4.1 Hazard

Heatwaves are episodes of extreme hot weather and are known to cause serious health, social and economic problems (McInnes and Ibrahim 2013, Wong 2016). During a heatwave hot days are followed by hot nights resulting in little to no relief from high temperatures. This can put a strain on medical facilities, support services, electricity supply and transport infrastructure (Reeves et al. 2010). Prolonged periods of high temperatures pose significant health risks, particularly for the ill, elderly or very young (Wong 2016). Although not as dramatic as other natural hazards, such as wild fires and major storms, heatwaves can cause great loss of life. The 2003 European heatwave, for example, resulted in extensive loss of life with more than 40,000 heat-related deaths (García-Herrera et al. 2010). In Australia heatwaves have been the most significant natural hazard in terms of lives lost, with the exception of disease epidemics, causing more than 4,000 deaths over the past 200 years (McInnes and Ibrahim 2013, Coates et al. 2014).

Heatwaves also put a strain on lifeline infrastructure. In particular, extreme hot weather can cause an increase in demand for electricity systems as residents turn to air conditioning and electric fans to keep cool (Miller et al. 2008). On top of this, high temperatures can impact electricity infrastructure directly. Most problems occur when underground transmission lines overheat and short out, or when overheated above ground power lines that have stretched and sagged, come into contact with trees and short to the ground (Palecki et al. 2001). To keep systems from overheating and to avoid complete electricity outage, there has to be a reduction in the total amount of energy produced and, in turn, distributed to end-users (McEvoy et al. 2012). To mitigate overheating and reduce the likelihood of potential fires produced from electrical system faults, the enforcement of rolling blackouts can occur (Strengers 2008, Broome and Smith 2012).

Extreme temperatures experienced during heatwave events can also directly impact transportation infrastructure by buckling rail lines and melting roads (Palecki et al. 2001, Zuo et al. 2015). Indirectly, transportation systems such as public transport and traffic signals, which rely on power to operate, can be impacted by the loss of electricity (Rinaldi et al. 2001). The health of public transport employees and passengers may also be affected by extreme temperatures (Reeves et al. 2010, McEvoy et al. 2012).

2.4.2 Event overview

In 2009 south-eastern Australia experienced its most extreme heatwave on record. The states of Victoria and South Australia were exposed to severe, extensive and prolonged heat across two weeks in January and February. These conditions were caused by the stalling of a hot air mass over south-eastern Australia due to slow-changing synoptic conditions, with sea and bay breezes providing only little relief in coastal areas (Reeves et al. 2010, McEvoy et al. 2012). During this period new daily maximum temperatures were observed for Adelaide (45.7°C) and Melbourne (46.4°C) (Reeves et al. 2010), the state capital cities for South Australia and Victoria respectively. Adelaide experienced eight consecutive days over 40°C and Melbourne had three days over 43°C, 12-15°C above the seasonal average (Reeves et al. 2010, McEvoy et al. 2012). The Victorian town of Hopetoun experienced a record high of 48.88°C (McInnes and Ibrahim 2013).

The extreme heat experienced during the 2009 heatwave resulted in a dramatic increase in mortality and morbidity. The persistent high temperatures resulted in increased cases of heat-related illness and exacerbated chronic conditions. There was an increase in emergency ambulance dispatches and presentations of heat-related conditions at emergency departments (Reeves et al. 2010, Lindstrom et al. 2013). The extreme heat resulted in an estimated 374 excess deaths in Victoria and between 50 and 150 excess deaths in South Australia (Reeves et al. 2010, McInnes and Ibrahim 2013).

On 29 and 30 January Melbourne experienced rolling blackouts due to a combination of failures that occurred throughout the system. Supply was impacted when the Basslink connection between Tasmania and Victoria was shut down due to heat related problems and generators were unable to supply additional power. Transformer faults resulted in outages of major transmission lines and supply loads were restricted in the western metropolitan area. Additional faults occurred in up to 50 local voltage transformers. Load shedding was finally required to protect the security of the electricity network, further restricting supply (Reeves et al. 2010, McEvoy et al. 2012). Cumulative system faults, aging infrastructure and a rapid increase in demand (breaking Victoria's load record by 7%), primarily from use of air-conditioning, all contributed to the system's vulnerability to the heatwave (Reeves et al. 2010, McEvoy et al. 2012). Rolling blackouts resulted in over 500,000 residents being without power on the night of the 30 January. The outages occurred for 1-2 hours but the ripple effects lasted up to two days (McEvoy et al. 2012).

Transportation systems suffered minor to moderate disruptions during the heatwave, with rail being the most affected by the high temperatures. During the initial heatwave peak (27-30 January) more than a third of train services were cancelled in Melbourne and 7% in Adelaide (Reeves et al. 2010, McEvoy et al. 2012). There were nearly 30 instances of reported track buckling in Melbourne, which slowed down or disrupted services and increased maintenance and repair expenses for the rail transport industry (McEvoy et al. 2012). In addition, half of the train fleet were older in style with air-conditioning units not designed to operate above 34.5 °C. Air-conditioning failure was the main cause for service cancellations due to industrial action taken by train drivers (Reeves et al. 2010, McEvoy et al. 2012).

2.4.3 Flow on affects from lifeline disruption

In addition to the direct impact of heat on lifelines there were also knock-on effects from their disruption. Electricity outages, for example, resulted in the indirect disruption of other lifelines. Rolling blackouts on 30 January impaired traffic signals at 124 intersections in Melbourne and resulted in the cancellation of city loop train services, stranding a large number of inner city commuters (Reeves et al. 2010). Reeves et al. (2010) also found that lifeline failures had an impact on the economy with power outages and transport disruption resulting in an estimated financial loss of AUD800m.

However, the biggest compounding impact of lifeline disruption during a heatwave is the impact of electricity outages on community well-being. The loss of power during a heatwave means a loss of telephone, television and radio communications, non-operation of electric garage doors, and disruption of water distribution systems (Broome and Smith 2012). One of the largest impacts on health is the loss of air-conditioning and refrigeration. Both are key aids in reducing exposure to extreme heat, particularly vital for those most at risk, such as the elderly and ill. Moreover, with an increase in medical recuperative care being carried out at home rather than hospital, rolling blackouts could have serious repercussions and can potentially be life-threatening (McEvoy et al. 2012).

2.4.4 Learnings

The 2009 heatwave was characterised by a substantial increase in health service demand and disruptions to electricity supplies and public transport systems. Governments, councils, utility providers, hospitals, emergency response organisations and the community were largely underprepared for an event of this magnitude, with the extreme conditions not anticipated in seasonal forecasts (Reeves et al. 2010).

Following the 2009 heatwave event, both South Australia and Victoria moved from a reactive and response-driven approach to a focus on mitigation and risk reduction. Health and emergency services developed strategies to identify and manage vulnerable groups (Reeves et al. 2010). Vulnerabilities and lack of redundancy in lifelines, such as transport and power, were highlighted. Attitudinal, socioeconomic, behavioural and financial barriers to improve resilience in future heatwave events were also identified. Specifically, the increase in population vulnerability to heat-related mortality due to an aging population and an increase in obesity in adults was highlighted (Petkova et al. 2014). It was also identified that there was an increase in the expectation and dependence on emergency services for warnings and timely advice (Reeves et al. 2010). It must be noted, that the unfortunate occurrence of the Black Saturday bushfires during the second phase of the heatwave overshadowed the impacts of the heatwave itself, hindering the publicity of the huge health impacts of heatwaves, lifeline vulnerabilities to extreme heat and post event reflection.

Although many stakeholders took steps to assure future risks were adequately managed, they have appeared to have done so in isolation (McEvoy et al. 2012). Due to the integrated nature of the urban system there is a need for all stakeholders to take on a 'whole system' approach. McEvoy et al. (2012) concluded that sectoral segmentation and the lack of holistic urban infrastructure management are major barriers to improving urban resilience to future heatwave events.

There is still much to be done to increase resilience and adaptation capacity to extreme heat within Australia. The 2009 event showed that heatwaves can have significant impacts on vulnerable lifeline infrastructure with flow on effects to health. Heat-sensitive infrastructure such as the electricity network and rail transport will continue to be vulnerable to extreme heat events, compounding impacts of events. A warming climate may make heatwaves more likely (Meehl and Tebaldi 2004, Revi et al. 2014), putting more pressure on expanding urban areas (McInnes and Ibrahim 2013). Expanding urbanisation and high-density housing will also exacerbate the situation through heat island effects (Coates et al. 2014, Petkova et al. 2014, Wong 2016). Furthermore, populations are increasingly living and working in climate controlled environments, relying on air-conditioning to reduce heat stress, therefore isolating people from a changing climate and limiting their ability to acclimatise (Reeves et al. 2010, Coates et al. 2014). This further increases dependence on air-conditioning, whose operation cannot be guaranteed during a heatwave.

Publications on health impacts from heatwaves generally dominate the literature and this was also the case for the 2009 heatwave (Bi et al. 2011, Broome and Smith 2012, Zhang et al. 2013b). As well as health impacts, lifeline failure during heatwaves can also impact emergency response and business productivity (Reeves et al. 2010). However, little information was found on impacts to these other sectors during this event leading to a potential underestimation of the true impacts of lifeline failure in this case.

2.5 Case study 2: The 2010 Eyjafjallajökull volcanic eruption in Iceland

2.5.1 Hazard

The impact of volcanic eruptions can be widespread and may persist over many weeks or months (Siebert et al. 2011, Sword-Daniels et al. 2014). Multiple volcanic hazards can occur simultaneously or consecutively, causing impacts over various distances and time scales (Blong 1984, Seibert et al. 1987, Wilson et al., 2014). Lateral forces, vertical loads, burial and exposure to high temperatures from lava flows, lahars, pyroclastic density currents and tephra falls can immediately damage buildings and infrastructure (Johnston et al. 2000, Self 2006, Wilson et al. 2007, Wilson et al. 2013, Jenkins et al., 2014, Wilson et al. 2014). Volcanic ash in particular can spread far and wide; it is hard, highly abrasive, corrosive and conductive; and only millimetres are needed to disrupt most essential lifeline services (Blong 1984, Barsotti et al. 2010, Wilson et al. 2011, Wilson et al. 2012, Magill et al. 2013, Jenkins et al. 2014). Volcanic ash is the material produced by explosive eruptions and is made up of tiny fragments of rock and glass (Wilson et al. 2012). Tephra is the collective term for all material ejected explosively in an eruption, including larger blocks and bombs, where ash refers to the material of 2 mm or less. Ash can easily infiltrate openings, clog air-filtration systems and abrade surfaces (Jenkins et al. 2014). Airline operations may also be affected by ash falling on airports, or if volcanic ash is erupted high enough into the atmosphere it can become a risk to flying aircraft (Casadevall 1994, Jenkins et al. 2015, Webley 2015).

The risk volcanic ash poses for modern aviation was brought to attention in 1982 when a British Airways flight flew through high concentrations of volcanic ash produced by an eruption at Mount Galunggung in west Java. The Boeing 747 lost power to all four engines and dropped over 12,000 feet before restoring power and making an emergency landing in Jakarta (Lund and Benediktsson 2011, Ellertsdottir 2014). The 1989 Redoubt eruption in Alaska, and 1991 Mount Pinatubo eruption in the Philippines, also affected aircraft that came in contact with ash clouds, including engine failure and extensive damage to engines and windshields (Przedpelski and Casadevall 1994, Casadevall et al. 1996, O'Regan 2011, Webley 2015). With the conclusion that volcanic ash can cause jet engine failure, great financial loss and potentially loss of life, a 'no threshold' guideline was, at the time of the Eyjafjallajökull event, universally adopted and no-fly zones were implemented whenever volcanic ash was detectable in airspace (O'Regan 2011, Ellertsdottir 2014).

2.5.2 Event overview

On 20 March 2010 fire-fountain activity started along a fissure at Fimmvörðuhálsi, an ice free area between Eyjafjallajökull and Mýrdalsjökull volcanic vents in the southern region of Iceland, and ended on 13 April, leading many to believe that this was the end of the eruption (Donovan and Oppenheimer 2011). However, on 14 April, the eruption resumed, this time at the summit of Eyjafjallajökull. The interaction of ice and melt water with a more viscous batch of magma resulted in a more explosive eruption (Donovan and Oppenheimer 2011), sending ash up to 10 km in the atmosphere (Carlsen et al. 2012, Stevenson et al. 2012).

Ash fell to the south of the volcano impacting rural communities around the south of the island, resulting in the evacuation of 800 people and causing impacts to agriculture and local tourism (Adey et al. 2011, Donovan and Oppenheimer 2011, Bird and Gísladóttir 2012). The eruption was also accompanied by a number of glacial outburst floods, which impacted roads and farmland. Volcanic eruptions and their associated hazards are a fact of life for Iceland. The communities impacted by ash from Eyjafjallajökull in 2010 had just previously participated in an exercise in preparation for a larger eruption at Katla, and, as a result, residents were generally well prepared and self-reliant (Bird and Gísladóttir 2012). Those most vulnerable to the direct impacts of ash were those isolated from official information or emergency services and those with underlying lung conditions (Bird and Gísladóttir 2012, Carlsen et al. 2012). Road closures from outburst floods, which could result in the isolation of communities or hinder evacuation, did not seem to exacerbate conditions for those directly impacted by the ash in this case. Overall the flood damaged roads were quickly repaired and the ash, although causing stress and discomfort, was not reported to harm or injure any people. The majority of Iceland to the north of the volcano was relatively unaffected by the ash, Reykjavik in particular saw limited impacts despite being less than 150 km away from the volcano and the airports there stayed open (Lund and Benediktsson 2011). The most significant impact was caused by the ash that remained in the atmosphere. This airborne ash was rapidly blown to the south and east towards mainland Europe and caused the largest shutdown of European airspace since WWII (Budd et al. 2011, Ellertsdottir 2014).

As the ash cloud from Iceland made its way across Europe, the European Aviation Authorities progressively closed sectors of airspace due to fears for public safety (Ellertsdottir 2014). The airspace over Scotland and Norway was the first to close on the evening of 14 April. Irish, Dutch, Belgian and Swedish airspace also saw restrictions as the ash spread further south and east. By 18 April, airspace over Ireland, Ukraine, and Canary Islands was also closed (Budd et al. 2011). Flight restrictions were lifted on 21 April with close to normal air traffic resuming the next day (Ellertsdottir 2014). Over the seven-day period more than 100,000 flights in, out and around Europe were cancelled, stranding over 10 million passengers (Budd et al. 2011, IATA 2010). The worst affected places were the United Kingdom, Ireland and Finland, who experienced a 90% decrease in air traffic (Ellertsdottir 2014). Maximum closure of airspace occurred on 18 April, grounding just under 30 per cent of the world's scheduled flight capacity, overall costing the airline industry approximately 1.7 billion USD in lost revenue (IATA 2010). This loss could not typically be claimed under the airlines' business interruption insurance since there was no 'material damage' (O'Regan 2011). It was reported that aviation risked being sent into bankruptcy if the closure had lasted much longer (Ellertsdottir 2014).

2.5.3 Flow on affects from lifeline disruption

The European airspace is one of the busiest in the world, used by 150 airlines, which make 9.5 million flights every year across 150,000 air routes (O'Regan 2011). The airspace and aircraft that occupy it are part of a large interconnected network that provides private, military and economic mobility. The complex network of flight paths, airways and control zones, navigated by flight crew, air traffic control, collision avoidance software and controlled by strict international regulations, is largely unseen by passengers (Budd et al. 2011). It is a system often taken for granted until flights are delayed, diverted or cancelled.

The closure of the European airspace in 2010 impacted a wide range of people and businesses and uncovered a vast dependence on global air travel. European, African and Asian economies were also affected as air freighted imports and exports were halted. Shortages of imported flowers, fruits and electronic hardware were reported in the immediate days after airspace closure. Pharmaceutical, automotive, and transport and delivery companies were also impacted. The hardest hit were those supply chains that relied on air freight for just-in-time deliveries and exporters of perishable goods. Where some products and parts could be delivered later, perishable goods could not. Flower and fruit growers in Africa were especially hard hit, with fresh products due to be air-freighted to Europe being left to rot, resulting in the loss of millions of dollars in exports (Budd et al. 2011, Ellertsdottir 2014).

2.5.4 Learnings

With around 60 volcanic eruptions occurring world-wide every year, volcanic ash or the potential for its eruption, causes airspace restrictions almost on a daily basis (Donovan and Oppenheimer 2011). Iceland, in particular, produces around 20 eruptions per century, many involving significant explosive activity (Langmann et al. 2012). Tephra from numerous eruptions from Icelandic volcanoes over the past 7,000 years has also been documented to have reached Europe (Swindles et al. 2011, Stevenson et al. 2012). The 2010 eruption at Eyjafjallajökull itself was not an extraordinary event. However, the disruption it caused, to an industry that should have been prepared for its occurrence, was.

Although the risk of volcanic ash was recognised by scientists, operational meteorological institutes and aviation authorities, it was considered a relatively low risk due to its low probability of occurrence and therefore had not penetrated into policy (Adey et al. 2011, Donovan and Oppenheimer 2011). Because of this, the relatively small eruption of 2010 required a hasty and extreme response, which resulted in the reactive formation of advisory committees and meetings throughout Europe (Bonadonna and Folch 2011a, Bonadonna and Folch 2011b, Donovan and Oppenheimer 2011, Bonadonna et al. 2012).

The heavy reliance on the airline industry for world trade and transportation resulted in the 'no-threshold' guideline, which was in place at the time of the 2010 eruption, being questioned. Decision makers were caught between public safety concerns and the demanding need for global mobility (Lund and Benediktsson 2011). The complete closure of European airspace was seen as an overreaction and a review of the procedures was demanded. However, what constituted a safe concentration of volcanic ash was highly contested among international safety regulators, airlines, aircraft engineers and manufactures (Budd et al. 2011, Ellertsdottir 2014). As a result, major airlines, including Lufthansa, KLM and British Airways, performed a series of test flights and determined that 2,000 micrograms of ash per cubic metre was an accepted threshold through which aircraft could fly (Budd et al. 2011, O'Regan 2011).

The 2010 eruption was exacerbated by the lack of data detailing ash tolerance of aircraft and engines and the inability of international safety regulators, airlines, aircraft engineers and manufactures to agree on a 'safe' concentration of atmospheric ash (Budd et al. 2011). Budd et al. (2011) also highlighted that national policies were not aligned with other countries where volcanoes affect air travel, such as the United States. Had the creation of advisory groups occurred before the eruption, and not as a reactive scramble, preparations could have been made both politically and financially and safe ash thresholds may have been already determined (Donovan and Oppenheimer 2011). This event highlighted the dependency on global mobility and the need to recognise that natural hazards and their impacts are not always confined to geographical or political boarders. Globalisation turned an ordinary geological event into near world-wide chaos.

2.6 Discussion

The failure of lifeline networks during natural hazard events has the potential to impact populations by exacerbating the hazard itself and/or hindering the ability to respond to or recover from the event. The 2009 heatwave caused moderate disruption to transportation services. Although transport was not vital in mitigating heat exposure, the loss of train services impacted public transport users by disrupting their access to work, home or loved ones, and had the potential to increase stress. With public transport often being an affordable form of transport, the loss of operation largely impacted the mobility of social groups such as students, the elderly and poor (Rodrigue 2017). The 2009 heatwave also resulted in periodic loss of electricity, which in turn caused loss of air conditioning and refrigeration, key aids that people rely on to cope with prolonged high temperatures, especially those most vulnerable to heatwaves. An individual's ability to respond to a heatwave depends on both the degree of exposure to the heat hazard and their adaptive capacity, which is influenced by social, economic and biophysical factors and their access to resources, technology, information, and infrastructure (García-Herrera et al. 2010, Reeves et al. 2010, Coates et al. 2014, Wong 2016). Elderly, urban, marginalised and socially isolated residents were identified as the most vulnerable groups during the 2009 heatwave, often lacking the capacity to avoid or reduce exposure to the heat hazard (Reeves et al. 2010). Losing aids such as air conditioning, electric fans and refrigeration on top of this would intensify peoples' experience of the heat event, potentially increasing the rate of heat related deaths and illnesses, and putting more pressure on already stretched emergency and health services. Access to electricity on high heat days is so important to population health and safety that Broome and Smith (2012) calculated that being without power, and therefore air conditioning, would increase the risk of those susceptible of dying from heat-related illness by 50%, especially the elderly and those in remote rural communities. These authors estimated that if electricity was cut for an entire day in Victoria during the 2009 heatwave, 28 additional deaths could have occurred. If the heatwave event lasted any longer, conditions could have pushed the heat sensitive power system into a complete shutdown or resulted in the implementation of longer rolling blackouts to avoid total failure. Moreover, with an increase in medical recuperative care being carried out at home rather than hospital, it becomes difficult to plan rolling blackouts effectively in order to avoid loss of human life (Reeves et al. 2010).

Reeves et al. (2010) concluded in their report on the impacts and adaptation response of infrastructure and communities to heatwaves, that extreme heat should be given the same prominence as high-impact natural hazards such as bushfires or flooding with regards to impacts on lifeline infrastructure. The report highlighted how vulnerable lifelines, specifically electricity and transportation systems, can be to heat stress and how significant the impacts of lifeline failure, both direct and indirect, can be for people and the urban system. Therefore, they concluded that the urban system as a whole, including lifelines, needs to be considered in future risk assessments and mitigation measures.

Lifeline failure can also propagate outside the reach of the hazard footprint, causing disruption in regions not directly impacted by the event. During the 2010 eruption of Eyjafjallajökull, the area to the south of the volcano was impacted most severely by glacial outburst floods, lightning and volcanic ash (Bird and Gísladóttir 2012). Sections of roadways were washed away in the floods; however, this did not appear to impact the population greatly with regards to evacuations or return access to farms, which was needed to attend to stock. The largest consequences of this event reached far beyond Iceland. Although not impacted by eruption products on the ground, the United Kingdom and Europe were severely affected by the closure of airspace due to atmospheric ash. If it was not for the existence and reliance on air travel the eruption may not have been felt in this region at all. Air travel has increased the mobility of people and business; it is relied upon by manufacturers to join spatially disaggregated operations, and enables time sensitive and perishable freight to be carried over long distances in a short time (Bowen and Leinbach 2006, Pedersen 2001, Button and Yuan 2013, Mukkala and Tervo 2013, Rodrigue et al. 2017). The decrease in the cost of air travel over time has also been crucial to the growth of tourism (Rodrigue et al. 2017). The cessation of air travel over a large area like the United Kingdom and Europe would, therefore, reduce global mobility, impeding economic activities and social connections, which would ultimately impact on development. Reducing transportation to land and sea, which is generally confined by geographic barriers, would dramatically increase travel times, disrupt supply chains and even result in the isolation of some populations or economies. It was fortunate that the 2010 eruption was relatively short in duration. Eruptions at Eyjafjallajökull have the potential to last for months to years. Eyjafjallajökull volcano has erupted three times in the last 1,100 years with the most recent, in the 19th century, lasting more than a year (Gertisser 2010). Aviation companies could have easily faced bankruptcy if the 2010 eruption continued for a greater length of time and with similar no-fly enforcements (Ellertsdottir 2014).

The outcomes of both these case study events were influenced by unpreparedness. For south-eastern Australia it was the magnitude of the event itself. South-eastern Australia has suffered from heatwave events previously (e.g. 1908 and 1939) but the heatwave of 2009 was extraordinarily extensive, long-lasting and severe compared to those previous (Chhetri et al. 2012). For the United Kingdom/Europe it was a scenario deemed unlikely and previously ignored. An eruption impacting the United Kingdom or Europe was considered relatively low risk due to its low probability of occurrence and therefore there was no clear policy or planning for such an event. Both events became the much needed wakeup call to spark major reviews of management plans and policies. Implementation of various recommendations has since proven to be beneficial, improving the management of future events. The impacts of two subsequent events, the 2011 Grímsvötn eruption and 2014 heatwave are discussed below.

The 2010 Eyjafjallajökull eruption was an expensive lesson to learn but, undoubtedly, it better prepared the airline industry and global business for future volcanic eruptions. This was highlighted in 2011 when another Icelandic volcano, Grímsvötn, began to erupt. At its peak, the eruption column reached a height of 20 km, compared to ~10 km during Eyjafjallajökull's eruption, and produced nearly twice as much volcanic ash (Stevenson 2012). Although the 2011 eruption of Grímsvötn was nearly 100 times larger in magnitude than that of Eyjafjallajökull's in 2010, it did not have the same impact. Yes, the situation was different, with different eruption parameters and weather conditions; however, it was namely new rules around safe ash concentrations that meant disruption in Europe was relatively minor, with just 900 out of 90,000 scheduled flights cancelled during the first three days of the eruption compared to 42,600 flights cancelled in in the first three days in 2010 (European Commission 2011, Parker 2015).

In January 2014 south-eastern Australia was again hit by a heatwave. Although maximum temperatures were not as high as those experienced during January 2009, mean temperatures were higher and the heatwave peak lasted for longer (4 days in 2014 compared to 3 days in 2009) (Department of Health 2014). The 2014 heatwave resulted in an estimated 167 excess deaths in Victoria, compared to the 374 in 2009. The decrease in estimated excess mortality was contributed to the implementation of Victoria's heatwave plan (Department of Health 2014). Since 2014, a section on being prepared for electricity failure has also been included in the 'How to cope and stay safe in extreme heat' brochures (Victoria State Government 2015). Although it is unknown at this stage what impact these measures had had on the public's preparedness. The transportation sector made several steps to adapt to extreme heat events by: upgrading rail infrastructure to prevent track buckling; creating better heat policies for drivers, and providing easier access to cold water and ice; and creating better contingency plans, including providing stand-by replacement services (Chhetri et al. 2012). The 2014 heatwave resulted in minor disruption to Melbourne's public transport as trains operated at reduced speeds (Mullett and McEvoy 2014). The electricity sector also fared better in 2014 with the system avoiding load shedding during the highest temperature period. Only small local distribution outages were experienced due to distribution equipment failure; however, periods of low reserves were of concern and AEMO (2014) discussed that any fault with an interconnector or major generator could have changed the outcome and resulted in load shedding. The system's ability to cope in 2014 was in part attributed to the contribution of embedded solar PV generation, namely in South Australia, which helped to support the peak usage period (AEMO 2014).

The improvements made in each case study are commendable. However, particularly in the case of south-eastern Australia, there still seems to be a disjointed approach to hazard mitigation with minimal sector cross-over. In their report on Australia's response and adaptation to major weather events, Chhetri et al. (2012) found that individual post event actions usually result only in small improvements in overall resilience. To improve urban-wide resilience to natural hazard events, there is a need to improve communication, information sharing, collaboration and coordination between all sectors. The fragmented nature of critical infrastructure sectors, such as transportation and electricity, and the spanning of lifeline infrastructure across local or state government borders can make the development of coordinated policies and planning frameworks a challenge; hindering a structured response to natural hazard shocks. It is hard to prepare society for the compounding impacts of lifeline failure that are often hard to foresee, however, we can no longer prepare for the future just by looking to the past. The case studies in this chapter show how costly it is to be caught unprepared.

2.6.1 Current inclusion of lifeline failure in global risk assessments

The case study events in this chapter revealed a lack of disaster planning with respect to lifeline infrastructure and highlighted a need for the inclusion of lifelines into disaster preparedness, response and recovery plans. This section seeks to identify: how lifeline failure risk is perceived globally; the extent to which lifeline failure is currently included in natural hazard risk reduction; where improvement is needed; and current barriers to this.

Global systems such as finance, supply chains, energy and the Internet have become more complex and interdependent, and their level of resilience determines global stability. Strengthening system resilience requires collective actions through the cooperation of businesses, governments and civil society (Jenson et al. 2015). Lifeline disruption, on its own, is ranked as a prominent risk in a number of global lists. Towers Watson, a risk management and human resource consultancy firm, ranked infrastructure failure as 15 in their top 15 extreme risks (Hodgson et al. 2013, Pielke 2015). Lloyd's third biennial Risk Index, which assesses corporate risk priorities and attitudes among businesses globally, ranks critical infrastructure failure and supply chain failure as the 22nd and 23rd risks (Lloyds 2013). The World Economic Forum

Global Risks Report for 2017 acknowledged changes in lifeline vulnerability as the world moves into the future. In the age of the 4th Industrial Revolution, where digital technology has cut the cost of connectivity and created a ‘systems-of-systems’, there are huge opportunities for innovation but also complex risks (World Economic Forum 2017). However, the failure of critical infrastructure has not appeared in the top 5 of this list in terms or likelihood or impact in the past 10 years; although infrastructure failure is also seen as a potential impact from other highly ranked risk such as major natural hazard-caused disasters, cyber-attacks and war (World Economic Forum 2018).

Supply chains managers have also become aware that ‘good business practice’, aimed at saving costs and increasing productivity, has made systems more vulnerable leading to business disruption. In particular, manufacturing companies are outsourcing parts of their original activities or entering complex partnerships with external and offshore organisations to lower production and labour costs, and diversify their supply base (Galey et al. 2002, McKinnon 2014). In fact, almost every manufacturing organisation, production plant or retail business is dependent on products from outside sources and on a global customer base, creating a complex web and an interdependence between factories, warehouses, freight systems and retailers around the world (Galey et al. 2002, McKinnon 2014). The consequence of this is that business risk management systems lack full supply chain transparency due to unavailability of data (Miller Insurance 2012, Ladbury 2014). The resulting vulnerability suggests there needs to be a change in focus from efficiency to risk mitigation and resilience (McKinnon 2014). Lifeline infrastructure disruption has, in part, been included in supply chain risk management approaches with both the 2012 Deloittes framework for managing global supply chains (Deloittes 2012) and the 2013 World Economic Forum (World Economic Forum 2013) listing lifeline disruption as a component of risk mitigation; particularly transportation, which is one of the most important lifelines that link supply chains (McKinnon 2014).

The insurance industry is another sector that acknowledges the risks of lifeline and supply chain disruption; however, these risks have been a challenge for the industry, which requires risk to be knowable, quantifiable and statistically important (Pielke 2015). Insurers and reinsurers are key risk takers and ultimately act as shock absorbers in today’s increasingly interconnected and volatile world. Throughout its evolution, the insurance industry has been exposed to a number of challenges including large catastrophes and financial crises (Guatteri et al. 2005, Haueter 2013). Although it has had its setbacks, the sector has managed to adapt and grow with technological advancements and information sharing.

Recent events have made the insurance industry review its capacity and polices. The terrorist attack on the World Trade Centre in 2001 resulted in thousands of casualties and billions of dollars in property damage. It also opened the industry's eyes to the possible size of losses and the interconnectivity and accumulation of seemingly unrelated risks – e.g. decline in recreational air travel caused by behavioural change following the event (Bonham et al. 2006, Kozak et al. 2007, Haueter 2013). The 2011 Thailand floods and 2011 Tohoku earthquake, tsunami and nuclear disaster highlighted the enormous accumulation potential of supply chain disruptions and showed insurers and reinsurers how exposed they were to contingent business interruption (Greeley 2012, Asia Insurance Review 2014). The realisation that lifeline and supply chain failures can rapidly lead to enormous financial losses has prompted the industry to change their approach to include indirect disruption. However, the demand for and struggle to obtain greater supply chain transparency continues. Utility providers generally understand their own systems well but are often in the dark about the vulnerabilities of other lifeline systems they themselves rely on (Davis and Bardet 2011, Tyler and Moench 2012, World Economic Forum 2017). However, essential information needed to evaluate risk is currently not fully available, often due to a lack of cooperation between providers or inability to obtain the required data. Problems are worsened by the complexity of modern supply chains and global systems, and that networks often cross national or state boundaries where business cultures, regulations and management styles differ (Asia Insurance Review 2014, McKinnon 2014, World Economic Forum 2017).

Lifeline management requires the sharing of information among network operators, the adoption of common principles and a holistic approach (World Economic Forum 2017). However, the fragmented nature of lifeline infrastructure governance is a barrier to lifeline resilience. This is seen in the United States where the cellular industry has not been regulated, with no federal laws on minimum requirements for backup power, on providers sharing networks, or on providers dropping roaming charges in an emergency when access to information is vital (Klinenberg 2015). Taking a national-level approach to support infrastructure growth and resilience, but also leaving room for competition and innovation, can be a difficult balance; however, the United Kingdom, Australia and New Zealand have recognised this need and formed sectors such as the National Infrastructure Commission (https://www.nic.org.uk/), Infrastructure Australia (http://infrastructureaustralia.gov.au/) and the National Infrastructure Unit (http://www.infrastructure.govt.nz/), respectively (World Economic Forum 2017).

It can be seen that infrastructure failure is being addressed by a number of industries, and that frameworks are being put in place to help companies and governments create risk and resilience strategies; however, each potential shock – be it lifeline network disruption, an economic crisis, or war – is often addressed in isolation, when in fact multiple events and outcomes can occur simultaneously. In preparation for the true impacts of future natural hazard events on modern society there is a need to incorporate lifeline disruption alongside building damage and social impacts. We should therefore consider to what extent lifelines are currently included in natural hazard assessments and mitigation practices.

2.6.2 Lifeline failure in emergency management and disaster risk strategies

Throughout history, experience with and repeated exposure to natural hazards has forced populations to better manage disaster risk. Over time, and in spite of natural hazard risk being exacerbated by increases in population, urbanisation and global wealth, little progress has been made in engineering, policy and public education to decrease economic loss and loss of life (Davies et al. 2015, Pielke 2015, Kelman 2017). The International Decade for Natural Disaster Reduction (1990-1999), in particular, saw an intergovernmental commitment, through the United Nations, to improve disaster risk management (Aitsi-Selmi et al. 2016). Subsequently, disasters such as the 2004 Indian Ocean Tsunami persuaded the international community to take further action on disasters, expanding disaster management beyond response to include preparedness and recovery, resulting in the creation of the Hyogo Framework for Action (HFA) 2001-2015 (https://www.unisdr.org/we/coordinate/hfa) (Aitsi-Selmi et al. 2016). Post 2015 came the Sendai Framework for Disaster Risk Reduction 2015-2030, an agreement that states that disaster risk reduction is not only a primary role of the State but also a responsibility that should be shared with all stakeholders including local government and the private sector (https://www.unisdr.org/we/coordinate/sendai-framework).

The current challenge for disaster risk reduction is in incorporating indirect and cascading failure, such as the disruption of lifelines (Jensen et al. 2015). In their review of natural hazard decision support systems from around the world, Newman et al. (2017) found that lifelines was one of the areas that was generally neglected in determination of risk criteria. Most criteria were based on economic indicators, which mainly stemmed from direct losses from natural hazards. However, there have been some countries and regions that have realised the importance of improving lifeline resilience in order to reduce vulnerability to natural hazards.

The Netherlands is a model example when it comes to upgrading lifeline infrastructure to withstand disruption from natural hazard events. Klinenberg (2015) describes how, after the 1953 storm surge that devastated Rotterdam, a national project – Delta Works – called for the building of dams, seawalls and barriers, which are currently being upgraded. The Netherlands has also used smart designs to improve other lifeline services resulting in fast Internet and a resilient power grid. Klinenberg (2015) compares The Netherlands' power grid to that of the United States; where The Netherlands' power lines are underground and in a circular grid design, to be more resilient to failures, lines in the United States mainly run across wooden poles and are generally distributed in a hub and spoke network, leaving lines exposed to falling trees and the network vulnerable to failures. Other regions may not be able to easily replicate the particular measures that The Netherlands have put in place to ensure lifeline resilience against natural elements; however, they can follow their example by having foresight and determination (Klinenberg 2015).

The United Kingdom (UK) is another positive example, with the Cabinet Office releasing a guide to improving the resilience of critical infrastructure and essential services from natural hazard risks (UK Cabinet Office 2011). The vulnerability of the UK's national infrastructure and essential services to disruption from natural hazards was highlighted by events such as the 2010 eruption of Eyjafjallajökull volcano and prolonged periods of extreme cold weather in January and December 2010 (UK Cabinet Office 2011). The guide was developed to support infrastructure owners and operators, government departments industry groups, and emergency responders to work together to improve the resilience of critical infrastructure and essential services by sharing best practice and advice.

New Zealand too provides a number of examples. In the first, the city of Auckland, New Zealand, undertook a comprehensive project to assess the vulnerability of Auckland's critical infrastructure to earthquake, volcano, tsunami and cyclone hazards. The Auckland Engineering Lifelines Project stage 1 final report (Auckland Regional Council 1999) was published in 1999 and has since been superseded by subsequent critical infrastructure projects and reports (http://www.aelg.org.nz/document-library/critical-infrastructure-reports/) undertaken by the Auckland Lifelines Group. This group aims to enhance the connectivity of lifeline utility organisations across agency and sector boundaries in order to improve infrastructure resilience.

In the second example, this time in Canterbury, previous improvement to the resilience of lifelines to natural hazards shocks proved beneficial during the 2010 and 2011 earthquakes in Canterbury, New Zealand. In their review of the performance of lifelines during these events, Fenwick (2012) concluded that infrastructure damage would have been greater and recovery slower if the Christchurch Engineering Lifelines Group had not taken previous mitigation steps to protect lifelines from earthquakes hazards. These steps included Orion's electricity distribution seismic strengthening programme that commenced in 1996 and was estimated to have saved 60-65 million NZD in direct asset replacement and repair costs. This and other lifeline mitigation work was based on recommendations from the Risk and Realities project report (Lamb 1997) and is a good example of what collaborative work can achieve (Fenwick 2012). Fenwick (2012) stated that Canterbury was fortunate that many individuals and organisations were able and willing to put in the time and effort to contribute to the project, as it can be difficult to coordinate such initiatives when organisations do not have the ability or willingness to work on issues that are deemed high-impact and low probability. This example shows that improving lifeline infrastructure has the potential to reduce losses and impacts on communities in a disaster.

The third and most recent example is a multi-hazard scenario of an Auckland Volcanic Field eruption, which included in-depth analysis on the impact of lifelines such as electricity services and transportation systems (Deligne et al. 2017, Blake et al. 2017b). This project included input from scientists, emergency managers and lifeline sectors. This example shows what can be achieve with collaboration.

2.6.2.1 Current barriers to preparedness of lifeline failure during disasters

Collaboration across sectors, such as government, emergency services, lifeline operators and the insurance industry, is needed in disaster planning to enable information sharing and joint contingency planning. When it comes to mitigating against and preparing for lifeline failure during natural hazard events; however, there are still a number of barriers that inhibit inclusion into disaster plans. Namely: inadequate community education and engagement about lifeline failure in a disaster, limitations of local government to strengthen lifeline infrastructure and mitigate service failure, inaccessibility of sensitive lifeline information, and a lack of holistic disaster scenarios.

Community engagement:

Where many disaster strategies fall short is in outlining the responsibilities of the general public and the inclusion of community members in the creation of disaster plans (Davies et al. 2015 and Box et al. 2016). Box et al. (2016) states that although the Australian National Strategy for Disaster Resilience (Attorney General's Department 2009) called for and described the importance of shared responsibility for all stakeholders, including local community members, there is still a gap with how this would actually work in practice. Where community was mentioned in the National Strategy it was generally with a passing comment ensuring information is passed down, portraying the view that the general public are simply recipients of information. The problem with this is that not all communities have the same ability to understand or interpret the information (Box et al. 2016). In their paper on shared responsibility and social vulnerability during the 2011 Brisbane floods in Queensland Australia, Box et al. (2016) found that residents' feedback often centred on how councils and emergency services could improve and that residents felt that more information should be available. This gave the impression that residents saw governments and emergency services as solely responsible for flood protection. The same was found following severe flash flooding in March 2011 along the Illawarra South Coast region in New South Wales. Survey and interview responses in Phillips et al. (2013b) showed that some residents waited until the SES door knocked and told them in person to evacuate before doing so. Even when residents were presented with flood information and warnings it was deemed not specific enough or ignored due to experience bias. Residents appeared to have a lack of understanding of the capability of emergency services and their ability to gather and send information in a timely manner (Phillips et al. 2013b).

Lack of community involvement and therefore lack of community knowledge can hinder resilience to natural hazard events. Box et al. (2016) found that the construction of the Wivenhoe Dam before the 2011 Brisbane floods led residents to believe that flooding could henceforth not occur. Residents both misunderstood the role of the dam and the terminology used to describe flood magnitudes and recurrence. A concentration on preventative measures, such as this example, can give communities a false sense of protection from hazard events (King et al. 2016). Vulnerable infrastructure and communities create disasters, and communities become vulnerable when they lack the knowledge, capability, social ties, support and funding to cope with natural hazard events (King and MacGregor 2000, Cutter et al. 2003, Haynes et al. 2008, Box et al. 2016, Kelman 2017). Aitsi-Selmi et al. (2016) recommends that social sciences need to play a greater role in disaster response and recovery in order to help understand behaviour and decision-making.

Despite their vulnerabilities, Box et al. (2016) points out that communities are often willing to help each other in times of need, which demonstrates a pre-existing desire to work together. This desire needs to be tapped into following an event through the involvement of community members in rebuilding and preparing for future events. Reducing risk and vulnerabilities to natural hazards requires the participation of communities in all stages – prevention, preparedness, response and recovery. The involvement of community in disaster risk reduction can help overcome denial, evasion and inaction and result in the reduction of damage and loss through the collective protection of homes, work places and lives (Paton and Johnston 2001, Pearce 2003, Gaillard and Mercer 2013, Sanderson and Sharma 2016). A community's vulnerability to natural hazards is not solely based on their exposure but also on the resources they have to cope and recover (Klinenberg 2015, Box et al. 2016, Pearce 2003). Resilience doesn't just come from mitigating damage from disasters but also strengthening social connections and wellbeing within communities (Paton and Johnston 2001, Pearce 2003, Klinenberg 2015).

In protecting lifelines from natural hazards most investment has gone into upgrading lifeline infrastructure; however, even the best mitigation efforts to improve infrastructure resilience cannot avoid future failure (McKinnon 2014, Klinenberg 2015). Communities need to understand that lifelines can fail, what to expect when they do and what actions they can take to ensure they are able to cope without services. Communities need to be aware of the abilities and limitations of emergency services during a disaster and know that there is a possibility they might have to fend for themselves for a period of time (Box et al. 2016). Therefore they also need to know what actions to take during a disaster and not just be aware of the risks.

Limitations of local governments:

Local governments need to avoid development in hazard prone areas such as floodplains, coastal zones and bushland, which can put communities and infrastructure at risk (Klinenberg 2015, Maier et al. 2017). The need for land-use planning to better align with emergency management and disaster mitigation systems was identified as a priority in the Hyogo Framework for Action (HFA) 2005-2015, which details the work required from different sectors and actors to reduce disaster losses (King et al. 2016). This includes the protection of infrastructure, reduction of risk through post-disaster reconstruction and allocation of safe land (King et al. 2016). Local governments can directly influence disaster risk reduction through: zoning, including development control and stricter building codes; appropriate urban settlement and infrastructure design; and by providing maps and hazard information to residents (Klinenberg 2015, King et al. 2016). However, poor results can occur when planning is primarily geared toward facilitating development without taking into account disaster risk reduction (King et al. 2016). In the HFA midterm review, it was found that unsatisfactory progress had been made due to poor urban and local governance (King et al. 2016); potentially because local government is the most constrained. Davies et al. (2015) states that a potential barrier to community resilience is the inability of local governments to support local level disaster risk reduction due to a lack of funding and resources. There is often a variation in local governments' ability to collect hazard information and a lack of data sharing across local government areas (Box et al. 2016). King et al. (2016) adds that while land-use planning is within the role of local government, the ability to support disaster resilience is not only constrained by the lack of resources but also that local governments often inherit past planning decisions. It is difficult to reduce risk with land-use planning when communities are already established in hazard prone areas. It is also up to voters to select policies that will help decrease vulnerabilities. Voting for lower taxes and less government support for marginalised people, consequently results in an increase in disaster vulnerability (Klinenberg 2015, Kelman 2017).

Jensen et al. (2015) suggested that if national levels of governance provide a better link between global and local levels, local governments would be able to govern and develop solutions for complex local issues without being confined to limited capacities and/or investments. These authors go on to say that one key way to better equip local governments is through the diffusion of education and flow of information. Further, national governments not only need to better understand the interconnectedness of lifeline systems and what impact the failure of such infrastructure, locally or abroad, can have, but they also need to invest in and upgrade vital infrastructure (McKinnon 2014, Klinenberg 2015). Lifeline upgrades also need to consider the potential impacts of disruption on the community as a whole, not just costs and benefits to utility providers (Chang and Chamberlin 2004).

Information sharing:

The Sendai Framework for Disaster Risk Reduction 2015-2030 calls for an 'all-of-society' and 'all-of-State institution' approach to reduce disaster risks and highlights the imperative role that local governments and communities play in reducing community vulnerability and improving resilience (https://www.unisdr.org/we/coordinate/sendai-framework). However, without adequate information on lifeline vulnerabilities local governments and communities cannot fully prepare for service disruption. Evidence from the 2007 floods in the United Kingdom showed that a lack of awareness regarding the consequences of loss of critical infrastructure compromised the response to the event (UK Cabinet Office 2011). It was therefore concluded that thinking needs to change from 'need to know' to 'need to share' (UK Cabinet Office 2011).

The United Kingdom's guide on improving the resilience of critical infrastructure and essential services from natural hazard risks states that:

"*To improve resilience to natural hazards, organisations need the following information about the risks:*

- *knowledge of the likelihood, and frequency, of natural hazards of greatest concern and the linkage between different natural hazards (for example, how heavy snowfall can lead to flooding);*
- *knowledge of the likely primary impacts of different kinds of natural hazards on infrastructure operations and operators;*
- *knowledge of the secondary impacts of hazards including those caused by disruption to other infrastructure operations and key supply chains; and*
- *understanding of the vulnerability of the organisation to these risks, their primary impacts, and to secondary impacts including through dependencies on other infrastructure and essential service providers*" (UK Cabinet Office 2011, p22).

But the guide also goes on to explain that, in some cases, critical national infrastructure has not been able to be shared for civil emergency planning due to the classified or commercially sensitive nature of some information, although it was hoped that the guide would help improve this.

The Australian Government established a national Critical Infrastructure Resilience Strategy for Australia (Commonwealth of Australia 2010). This Strategy provides a foundation for which governments, and owners and operators of critical infrastructure, can prepare for, and respond to, a range of significant disruptive events. The Critical Infrastructure Resilience Strategy Policy Statement specifically stated:

"*The Australian Government will continue to work closely with The Trusted Information Sharing Network (TISN) groups, international partners, government agencies and academia to examine strategic issues and trends affecting critical infrastructure, and will facilitate cross-sectional collaboration and information sharing on these issues, including through exercises and workshops*" (Commonwealth of Australia 2015 page 12).

However, the TISN, which provides a secure, non-competitive environment, has a deed that prohibits confidential and sensitive information from being shared beyond this group (Commonwealth of Australia 2018), challenging the statement above.

Not providing information that might help support decision makers prepare for the impacts of natural hazard events in the future is inexcusable (Pielke 2015). To better inform both communities and land-use decisions, there is a need for comprehensive hazard mapping and the sharing of this information to empower residents and industry (King et al. 2016). Information on the consequences of loss or disruption of critical infrastructure is also vital for effective emergency response; not only to better understand the impact on the public, but also on services essential during response operations, such as communication between emergency services, water to fight fires and electricity to pump away flood waters (UK Cabinet Office 2011). However, the development, maintenance and dissemination of these data are both time consuming and resource intensive (King et al. 2016). Therefore more support is needed to make data that have been collated become open access. Also, a standardised approach to tools, maps and data would make natural hazard information more accessible to decision makers and general community members (Aitsi-Selmi et al. 2016).

Adapting to changes in the disaster landscape:

Pielke (2015) describes three types of catastrophes: the familiar, the emergent and the extraordinary. The familiar are the hazards we have information on and experience with, such as earthquakes in Japan and hurricanes in the United States. The challenge with these hazards is not with the collection of knowledge but with the application of that knowledge and, unfortunately, best practices are not always put in place. In 2005, Hurricane Katrina resulted in more than 1,000 deaths and 80 billion USD in losses in the United States despite the event occurring in a region known to be prone to extreme hurricanes, and in a country that has the resources and experience to better mitigate against such events (Burby 2006, U.S. House of Representatives 2006, Pielke 2015). Looking at the impacts of Hurricane Harvey in 2017, Kelman (2017) highlights that although the finger was pointed at climate change and/or the hurricane's characteristics it was namely unpreparedness that was the biggest factor for the magnitude of consequences. The author notes that the real issues were that Texas allowed development on floodplains and along the coast; it concreted over green spaces, increasing rain runoff; and that social inequalities are prevalent across the state. Ignoring the shortcomings in disaster mitigation and shifting the blame to nature hinders the communities' ability to adapt to events in the future (Kelman 2017). Events themselves do not cause disasters, vulnerabilities do (Smith 2006, Steinberg 2006, Pelling 2012, Kelman 2017).

Emergent catastrophes such as cascading supply chain failures or epidemics have arisen from the complex and interconnected systems prevalent in today's modern world. Mitigation of emergent catastrophes requires a different approach, in comparison to familiar and more localised hazards due to their unpredictable nature and widespread impacts. Because of this, there is a need to be able to deal with issues as they emerge. A good example of cooperative and successful response to an emergent hazard was the 2014 Ebola response in West Africa, which required the capabilities from a number of organisations (Jenson et al. 2015, Pielke 2015). However, not all disaster plans are currently built to account for emergent hazards. There is a propensity to research and work on areas we already know a lot about and avoid areas where there is great uncertainty (Pielke 2015). A potential downfall of disaster plans is when they are based on known, past events. However, the past is not always a blueprint for the future (Woo 2011, Sanderson and Sharma 2016). Newman et al. (2017) states that only relying on past experience can significantly bias peoples' estimates of future event impacts.

Although lifelines are mentioned in a number of risk ratings (Hodgson et al. 2013, Lloyds 2013, Pielke 2015, World Economic Forum 2017) and national disaster plans (Auckland Regional Council 1999, UK Cabinet Office 2011, Fenwick 2012, Klinenberg 2015), true mitigation of lifeline failure seems to only be implemented after an unforeseen/underestimated event, or a series of events not previously predicted. The 2010 Eyjafjallajökull eruption and subsequent European airspace closure being one example. Although in this case steps were made to mitigate similar scenarios in the future, there is a tendency to only learn from the past and not be prepared for unknown events that could occur in the future.

Newman et al. (2017) found that current decision support systems for disaster risk reduction have limited consideration for future changes to risk, including testing the impact of different risk-reduction options. Mitigation for one natural hazard could increase or alter the risk from another; for example, mitigating for flood risk by revegetating catchments may increase bushfire risk. Other factors that could alter future event impacts are a changing climate and an increase in exposure due to increasing populations and infrastructure development. A change in these factors can result in a 'once in 100-year flood loss' becoming a 'once in 20-year flood loss' over time; therefore, this change needs to be accounted for (McKinnon 2014).

Dealing with emerging threats requires the development of strategies to deal with the unknown (Woo 2011, Marzocchi et al. 2012, Smet et al. 2012, Pielke 2015). It is difficult to make decisions on risk reduction, with the aim to reduce future exposure and vulnerability, when the future state is unknown (Maier et al. 2017). Therefore there is a need to step away from trying to predict the future and instead increase resilience to whatever happens (Harford 2016, Davies et al. 2015, Sanderson and Sharma 2016).

Extraordinary catastrophes are those that may not be foreseeable or, if they can be foreseen, there is nothing that we can do to prepare for, e.g. a large solar storm or asteroid impact (Pielke 2015). These events are not within the scope of this present study.

2.6.2.2 The way forward

To improve and better guide disaster mitigation, emergency response and community recovery for future natural hazard events, disaster management should be approached holistically, and include potential impacts to lifelines. To be resilient to disruption in this globalised world, we also need to look beyond our backyards and acknowledge that lifelines can often span large geographic areas, with the ripple effects of disruption able to flow beyond regional and national borders. Not only is it important to make lifeline infrastructure more resilient to disruption from future shocks, we also need to increase resilience by preparing communities to better cope with service outages.

Although the threats of tomorrow may not be known, this should not inhibit our preparation for the future. Collectively discussing how unlikely catastrophes might be dealt with will ultimately help with the development of strategies to cope with unknown threats when they do present themselves (Jensen et al. 2015, Pielke 2015, Sanderson and Sharma 2016). To reduce impacts of future disasters multi-hazard and multi-disciplinary approaches need to be developed, and disaster risk management needs to be holistic with knowledge shared and coproduced with all sectors involved (Davies et al. 2015, Aitsi-Selmi et al. 2016).

At the heart of disaster management are disaster scenarios (Woo 2011). Scenarios are created to address specific questions related to the consequences of a particular event occurring. A deterministic scenario looks at one particular outcome, whereas a probabilistic scenario looks at a distribution of all possible outcomes. Probabilistic risk models and quantitative risk assessments are important tools currently used by government and insurance sectors to plan for future events and their impacts; however, not all probabilistic scenarios capture statistically infrequent or unforeseen events, or local level impacts (Davies et al. 2015, Pielke 2015). Therefore, in addition, the development of deterministic scenarios is needed to complement existing probabilistic risk assessment (Davies et al. 2015, Pielke 2015, Sanderson and Sharma 2016). This is particularly true when dealing with emergent hazards, which requires looking at the possible, not the probable. The benefit of developing various scenarios instead of trying to forecast the future is that it can bring different sectors and perspectives together (Fenwick 2012, Harford 2016). Disaster scenarios can help us face up to uncomfortable prospects, build relationships between various sectors of the community, recognise interconnections not previously identified, and even lead to contradicting outcomes that highlight that the future is unknown (Davies et al. 2015, Klinenberg 2015, Harford 2016). Scenarios have been used as planning tools by the military throughout history (Sanderson and Sharma 2016). Ultimately scenarios let us look at 'when' not 'if'. Asking 'when' enables deeper thought about potential consequences and adaptive capacities for future events (Sanderson and Sharma 2016). However, the quality of a scenario is controlled by the capacity of each participating sector and the available knowledge (Woo 2011, Sanderson and Sharma 2016).

Scenarios are often developed and explored through scenario modelling. A disaster scenario is comprised of the severity and spatial footprint of a hazard event, the exposure of human and economic assets to the hazard, and the vulnerability of these assets to damage and harm; from which loss and damage estimates can be calculated (Woo 2011). Decision support systems can help visualise risk reduction strategies and test the impacts of their implementation on different scenarios, providing quantitative evidence for decision making (Newman et al. 2017). Maier et al. (2017) modelled five varying possible hazard scenarios for Adelaide, Australia, to explore the impacts of the implementation of different risk-reduction strategies. To create these scenarios they used the likelihood of natural hazard events occurring in certain locations (such as floods or bushfires); mapped the exposure to those hazards at these locations (including people, buildings, industry, agriculture and lifelines); and assessed the vulnerability of those exposed. The scenarios were developed to investigate community resilience, and Maier et al. (2017) worked with policy makers to develop the five different scenarios. The scenarios were modelled in a decision support system and risk was expressed in terms of average annual loss per 100 m x 100 m grid, this enabled the authors to compare potential impacts from different hazards in each mapped area. Modelling a variety of scenarios allowed the authors to explore the outcomes of policy decisions on future natural hazard risk. However, this method only allows the user to see exposure and vulnerability to future natural hazard events and not the impact of failure on services such as lifelines, and the flow on effects of service failure.

In order to include the impacts to lifeline infrastructure and the flow on effects of service failure there is a need to also incorporate lifeline network modelling. Buxton (2013) compared lifeline interdependency modelling techniques used by The Critical Infrastructure Protection Modelling and Analysis (CIPMA) group within the Australian Attorney-General's Department and The Simulation Modelling Analysis Research and Teaching (SMART) research group at the University of Wollongong, Australia, with techniques used by GNS Sciences in New Zealand. It was found that modelling variations, which ranged from matrices, Bayesian belief networks and economic impact models, occurred due to differences in the groups' purposes and aims; however, there were similar problems regarding the shortage of lifeline information, especially data on interdependencies. The review found that with sparse information at various scales, it was difficult to map from a detailed to high level as lifeline dependencies change with scale. Buxton (2013) also stated that any approach to lifeline modelling benefits from close relationships with infrastructure sectors, as this helps to bridge the information gap; however, it was acknowledged that collaborations take time. Solano (2010) also suggests that human/infrastructure interactions also need to be simulated; however, notes that this will increase computational time. Adding many components to a modelled scenario will also add large uncertainties.

The high occurrence probability of familiar and emergent natural hazard events means that social and economic consequences need to be researched alongside the hazards themselves (Pielke 2015). To generate more realistic representations of complex lifeline systems, future work on modelling lifeline impacts needs to include social, organisational and environmental variables alongside engineering components (Solano 2010). FEMA's HAZUS loss estimation software (https://www.fema.gov/hazus) has progressed to account for multiple sources of loss and business level impacts; however, the indirect disruption from lifeline failure – both social and economic - is not well accounted for yet (Chang and Chamberlin 2004).

In preparation for the true impacts of future natural hazard events on modern society there is a need to better understand the exposure of lifeline infrastructure, the interconnectedness and behaviour of lifeline networks and to identify vulnerable populations that rely on their operation. Chang and Chamberlin (2004) found that incorporating lifeline outages with traditional natural hazard impacts, such as building damage, provided a more realistic and accurate assessment of how mitigating lifeline systems can improve disaster resilience, than modelling lifeline outages in isolation. Understanding the vulnerabilities of essential lifeline networks is key to supporting response during and recovery following a disaster. With the technological advancements and growth of interconnected systems during the 4th Industrial Revolution, The World Economic Forum (2017) recommends the development of modelling exercises, not only to expose vulnerabilities in infrastructure systems but also to build technical capabilities and standards for stress testing and information sharing. The impact of natural hazard events on lifeline network infrastructure needs to be included in risk assessment and scenario development. The next chapter explores graph theory techniques to model lifeline disruption in a natural hazard context.

Chapter 3 Applying graph theory to assess lifeline network disruption during natural hazard events: an example using the Tokyo Subway

3.1 Chapter overview

Understanding the vulnerabilities of essential lifeline networks is key to supporting response during and recovery following a disaster. On the whole, current research efforts on lifeline networks focus on evaluation of network characteristics, their optimisation and robustness to random failure or the consequences of targeted attacks. Limited research has been undertaken on the impact of natural hazard events on these systems and the flow-on effects from failure. This chapter explores how mathematical graph theory tools can be used to analyse and predict service disruption during network failure caused by a spatially-distributed disaster footprint. I subjected the Tokyo Subway network to a hypothetical inundation scenario and removed stations and tracks that coincide with the inundation footprint. The network was weighted with travel times to determine the extent and magnitude of the simulated disruption. The impact this disruption had on the network's capacity in respect to the movement of people was analysed using mathematical graph theory tools. Comprehensive explanations of common network terms and measures can be found in the supplementary section 3.7.

3.2 Key findings

This hypothetical inundation scenario resulted in 26% of the network being deemed non-operational, potentially impacting over 5 million daily passengers. The majority of impacted stations were periphery stations to the northeast leaving the remaining central hub of the network relatively unaffected with only minor detours needed. It was these outer branches of single track lines that were found to be the most vulnerable sections of the subway system. Failures on these branches cannot be bypassed, resulting in the isolation of entire lines. Compared with random failures or attacks, natural hazard shocks are more likely to affect a larger area, and therefore potentially a higher number of network components. This exercise demonstrates that, with understanding of a networks use, graph theory measures can be useful tools for interpreting network failure, including: identifying critical components; measuring transport disruption; and determining detours where available. Additionally, these techniques can be applied to any natural hazard scenario and/or infrastructure network and have the potential to be used in disaster response and management.

3.3 Introduction

Lifeline infrastructure – transportation networks, communication systems and utilities – are essential for maintaining a modern society's socioeconomic activities and in responding to and recovering from disasters. Lifeline networks are vulnerable to disruption from numerous shocks, including structural and technological failure, human error, targeted attack or natural hazards. Moreover, lifeline networks are commonly interconnected and dependent upon one another: for example, power is needed for the proper operation of traffic signals, telecommunication systems and water pumping stations; and transportation networks are crucial for the movement of fuels and materials. This coupled feature of critical lifelines can potentially turn a single failure into a cascading disaster event (Menoni 2001, Moon and Lee 2012).

Most methods for assessing the vulnerability of critical infrastructure have involved mathematical modelling approaches, such as graph and network theories, which use graph representations to determine infrastructure topologies and interconnections (Solano 2010, Murray 2013). Other methods for assessing lifeline disruption include: probabilistic approaches, logic principles and cost minimisation (Lewis 2006), qualitative assessments (Haimes and Longstaff 2002, Baker 2005) and expert judgement (Cooke and Goossens 2004, Egan 2007, Ezell 2007, Parks and Rogers 2008) (Solano 2010, Ouyang 2014). However, most of these methods incorporate aspects of graph theory in their approaches (Solano 2010). Using the Tokyo Subway system, Japan, as an example, this chapter explores how mathematical graph theory tools can be used to analyse and predict service disruption during a spatially-distributed disaster event.

Graph theory is the study of systems and networks through graphical representations. Vertices and edges are used to represent the building blocks of networks and other interactions (Figure 3.1) (Van Steen 2010). The simplified nature of graph theory allows the architecture of networks to be observed and reveals the laws that govern network evolution (Barabási 2002). Pre-created algorithms are readily available to solve a range of queries relating to network structure, robustness and processes; characteristics that are not always readily apparent when observing a pictorial illustration of the network (Newman 2010).

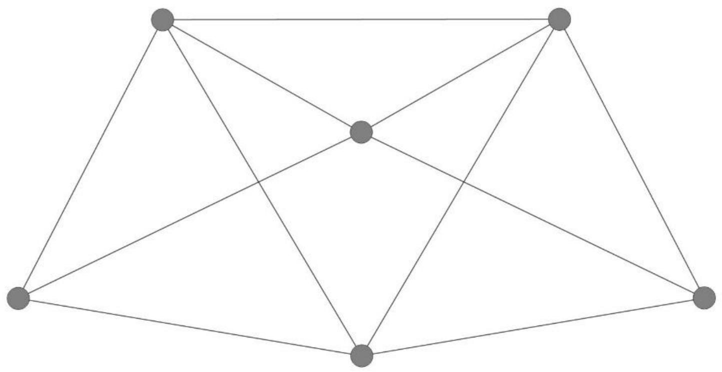


Figure 3.1: Example of a graph with six vertices and eleven edges.

A network represented by a graph *G* will have a collection of vertices *V(G)* and edges *E(G)*. A graph can be expressed as an *adjacency matrix*, a square matrix whose rows and columns correspond to the vertices of a graph and whose elements give the numbers of edges from vertex v_i to vertex v_j; a list of connected vertices (*edge list*); or a graphical representation containing vertices and edges (Figure 3.2). Graphs can be directed or undirected, meaning connections between vertices can go in one direction or both (Figure 3.3). The graph components (vertices and edges) can also be weighted to represent cost, capacity, distance and/or time.

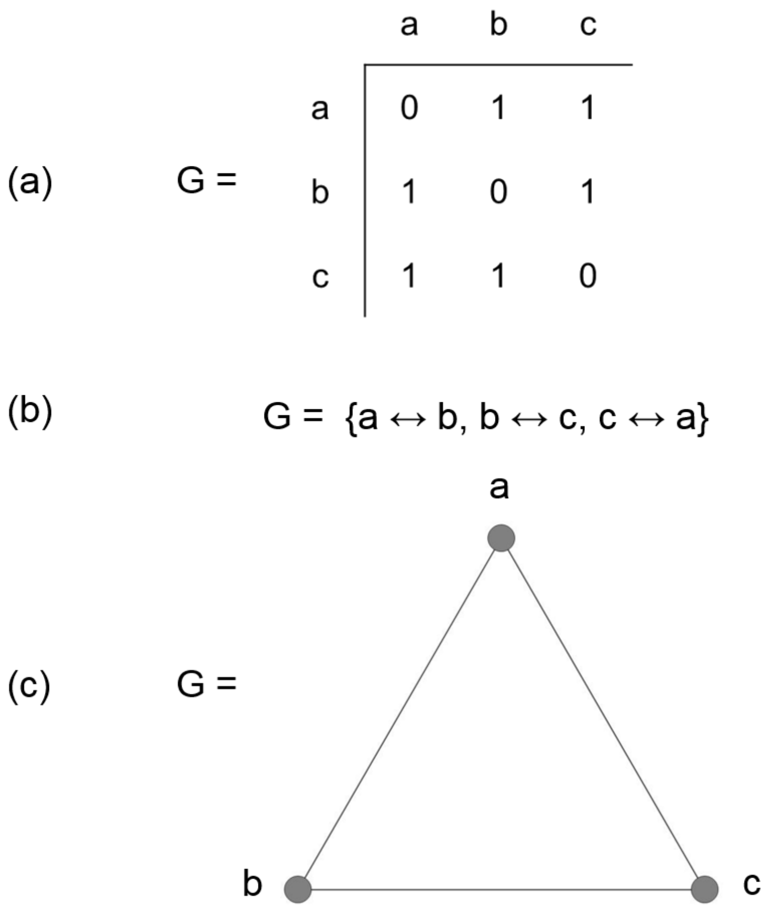


Figure 3.2: Various representations of a graph G: (a) Square matrix containing the number of edges connecting adjacent vertices: for example, in column 1 row 2, the number 1 shows that vertex **a** and **b** are connected by one edge, and the diagonal elements are zero showing that the vertices have no edges (or loops) connecting to themselves; (b) A list of adjacent vertices connected by an edge. In this case G is undirected, meaning connections go both ways, and adjacent edges only have to be stated once, i.e. since a ↔ b is specified, b ↔ a does not need to be; and (c) Graphical representation of G using dots (vertices) and lines (edges).

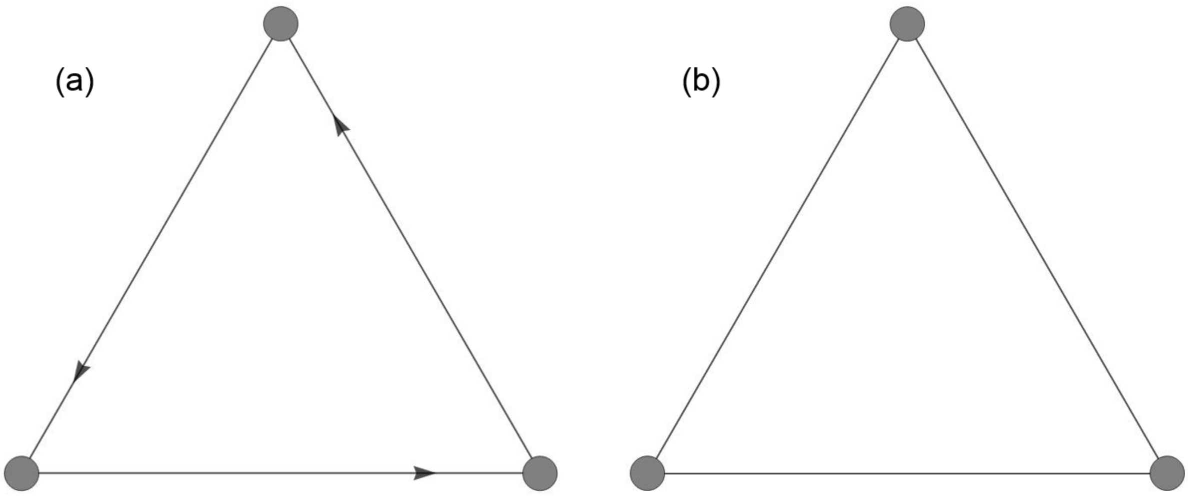


Figure 3.3: Graph (a) represents a directed network and graph (b) an undirected network.

Graph theory measures the complexity and efficiency of networks by identifying common network characteristics such as path lengths, clustering, degree of connectedness and a variety of centrality measures. If all vertices are accessible to all other vertices via a *path* along connecting edges, the network is said to be *connected*; if not, the graph becomes *fragmented*; in other words, the network reduces to several independent and connected components, or *subgraphs*. Further explanation of network measures used in this study can be found in the supplementary material section 3.7.1.

Numerous studies have applied graph theory to road (Erath et al. 2009, Bono and Gutierrez 2011, Chan et al. 2011, Duan and Lu 2013), rail (Sen et al. 2003, Seaton and Hackett 2004, Angeloudis and Fisk 2006, Lee et al. 2008, Chopra et al. 2016) and air (Cardillo et al. 2013, Verma, 2014) transportation networks on varied spatial scales to better understand network structure and behaviour such as: network evolution and form (Erath et al. 2007, Chan et al. 2011), how network structure can affect robustness (Lee et al. 2008, Berche et al. 2009, Verma 2014) and resilience to failure (Cardillo et al. 2013). This chapter continues to explore the potential of graph theory tools to assess the impact of natural hazard events using, by way of example, the Tokyo Subway network.

As roads have become more congested, rail transit systems (i.e. subways and metros) have become especially important for public transportation in urban and suburban environments. With over 30 million people, Greater Tokyo is the world's largest metropolitan area. Tokyo is Japan's epicentre for rail, ground and air transportation and its public transport system comprises an extensive train and subway network, with secondary bus, monorail, ferry and tram services. The Tokyo rail system transports tens of millions of people each year (Hirooka 2000); with the

Tokyo Subway network (including Tokyo Metro and Toei subway) a vital part of this rail network, cessation of its operation would have significant impacts on people and businesses.

This chapter combines graph theory concepts with Geographic Information Systems (GIS) to assess the use of these tools in a disaster context. In this case the Tokyo Subway system is subjected to a hypothetical flood inundation scenario. While the scenario explored here is imagined, it is suitable for explanatory purposes.

3.3.1 Application to subway networks

Graph theory has been used to study a number of subway networks across the world. Like all lifeline networks, subway systems can be disrupted by maintenance, failure or attack. The extent of fragmentation of a network after vertex or edge failure is conditional on its structure. Subway networks are generally highly connected, meaning there are numerous ways to travel between two stations; but have low maximum vertex degrees – the number of edges adjacent to a vertex or the number of lines or track connections to a station. The high connectivity of subway networks makes them relatively robust, with a large number of components needing to fail before network fragmentation occurs (Angeloudis and Fisk 2006). These authors explain that subway networks tend to evolve through the addition of chains – numerous connected stations forming a line, contrary to other networks that grow through the addition of single vertices. If there is preferential attachment of these new chains to existing transfer stations (a station shared by more than one line) ‘hub’ stations may be created. As these hubs acquire more connections their vertex degree increases and paths between stations become dependent on them. This increases the maximum vertex degree of the network and therefore potentially decreases robustness if these hubs were to fail for some reason. If these hubs cannot be bypassed in the event of their failure a section of the network could be disrupted and potentially cut off (De-Los-Santos et al. 2012, Sun et al. 2015).

Much of the graph theory literature concerning subways and metro systems has focused on topology, congestion, robustness to failure or transport optimisation (Sen et al. 2003, Seaton and Hackett 2004, Angeloudis and Fisk 2006, Derrible and Kennedy 2010, Derrible and Kennedy 2011, Raveau et al. 2011, Roth et al. 2012, Zhang et al. 2013a, Sun et al. 2015). Only a few studies have attempted to quantify the impact a failure would have on network capacity and flow. Majima et al. (2007) utilised graph theory to evaluate a theoretical waterbus service in Tokyo in order to elevate congestion and increase robustness in the public transport system, including the Tokyo Subway. Although Majima et al. (2007) included path distance when determining flow, they suggested that future work could also weight the network by passenger numbers. De-Los-Santos et al. (2012) looked at robustness of the Madrid rail transit system by introducing a number of indices relative to the overall travel time of the network when links failed. In looking at the impact for its users, this study went beyond network failure but did not quantify the total number of passengers likely to be impacted by the disruption. Chopra et al. (2016) developed an approach to quantitatively assess the impact of network structure, spatial distribution of network components and intra-urban passenger movements on the resilience of the London metro system. Although the authors mention that the random failures they modelled could represent natural disasters, or other disruptive events such as track failure or maintenance, they did not utilise a disaster footprint to represent this hazard or to create an understanding of the spatial relationship between the network and the hazard. In what follows we build on previous efforts by applying graph theory techniques to evaluate changes to the connectedness of the Tokyo Subway system when impacted by a hypothetical flooding scenario.

3.4 Methodology

3.4.1 Tokyo Subway

The Tokyo Subway (including Tokyo Metro and Toei Subway) services an average of 8.7 million passengers daily (Bureau of Transportation Tokyo Metropolitan Government 2012, Tokyo Metro Co. Ltd. 2015). The Tokyo subway has a low maximum vertex degree at transfer stations by virtue of having many transfer stations outside the city core, contributing to the degree of robustness of this large system (Derrible and Kennedy 2010). Despite its reputed reliability and punctuality, the Tokyo subway is still susceptible to failure and disruption, such as the sarin attack in 1995 (Okumura et al. 1998, Pangi 2002, Tokuda et al. 2006) and congestion during peak commuting hours (Hibino et al. 2005, Tomoeda et al. 2009). The subway is also located in a region susceptible to various natural perils including earthquake, tsunami, volcanic eruption and typhoon.

The Tokyo Subway representation (Figure 3.4) has a total of 214 vertices (stations) and 273 edges (track connections and walking transfers), and is considered to be an undirected network. In collating information for this graph, the locations of vertices (stations) were specified by latitude and longitude coordinates. The edges were plotted as straight lines between stations and thus may depart from the true path of the physical tracks; however, for our purposes these inaccuracies are immaterial.

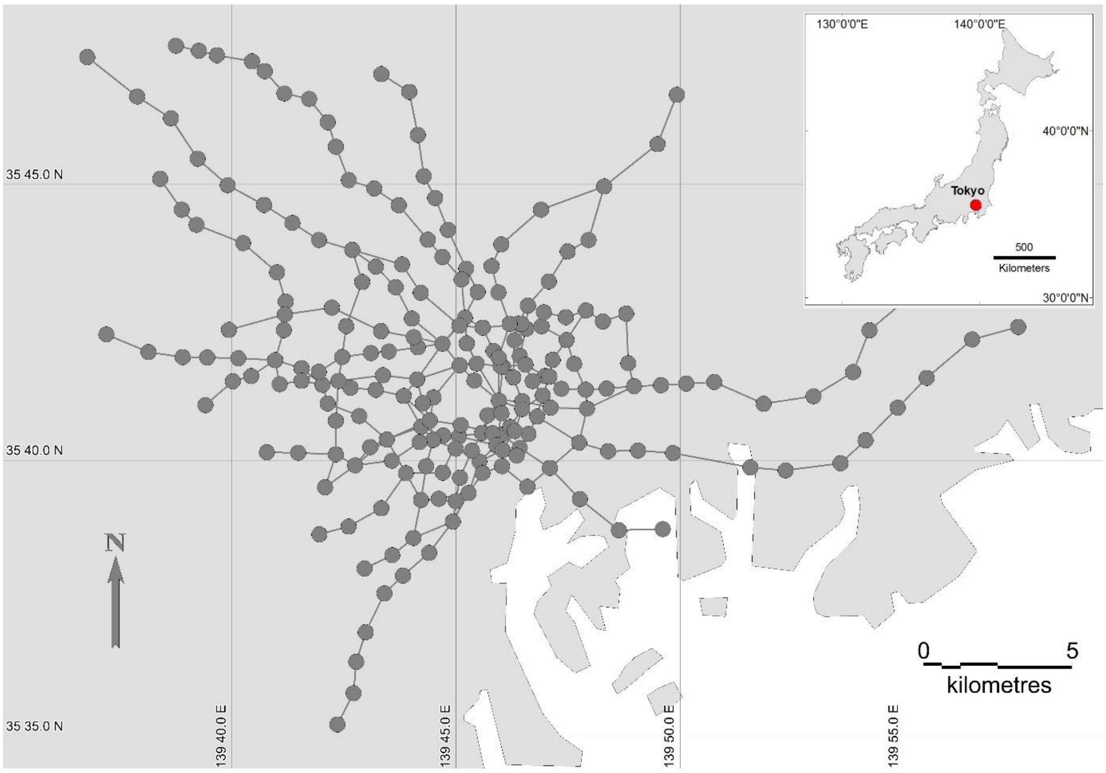


Figure 3.4: Location and graphical representation of the Tokyo Subway network. The dark grey dots are stations and the lines between mark how the stations are connected. The light grey background represents land while white represents sea.

3.4.2 Inundation scenario

A hypothetical hazard scenario was constructed from Alex Tingle's global-sea-level-rise flood map (http://flood.firetree.net/) and was utilised to gauge the network's behaviour to a natural hazard shock (Figure 3.5). The hazard footprint was based on the estimated inundation from a 7-metre rise in sea level. While inundation from rising sea levels will occur only very slowly, and likely not to this extent, inundation from other peril events such as riverine flooding and storm surge associated with typhoons is plausible as the area is generally low lying and prone to flooding (Okada et al. 2011; Tokyo Metropolitan Government 2016). The inundation footprint was overlaid onto the subway representation to determine the location points of network failure. All network elements that fell within the hazard footprint were assumed to have failed; vertices that "failed" and the edges attached to these vertices were deleted from the network. Neither the depth of inundation nor the probability of service failure were considered.

The extent of network disruption was analysed using existing graph theory-based algorithms in Mathematica 10.1 (© 2015 Wolfram Research, Inc., https://www.wolfram.com/mathematica/).

Basic operational network characteristics were measured and then re-assessed after vertex and edge deletion to determine the extent of network disruption.

Figure 3.5: Graphical representation of the Tokyo Subway. The hypothetical inundation hazard footprint (http://flood.firetree.net/) is indicated by the grey area ■ and the network components that coincide with the footprint are highlighted in white ○.

3.4.3 Data acquisition and processing

Network data including lines, distances between adjacent stations and daily average passenger numbers for 2013 for the Tokyo Metro and Toei Subway stations were sourced from Tokyo Metro Co. Ltd and the Tokyo Metropolitan Bureau of Transportation. Coordinates (latitude and longitude) for each station were obtained using the Wikimedia tool, GeoHack. Travel time between each adjacent station was obtained through Google Map data 2016 and rounded to the nearest whole minute. These and other data sources are listed in Table 3.1.

The raw data from Tokyo Metro Co., Ltd and the Tokyo Metropolitan Bureau of Transportation provided edge lists with respect to metro lines rather than physical tracks. The data were reformatted to avoid duplication where stations belonged to more than one metro line. Loops –

where more than one edge connects two particular adjacent stations – were deleted so that the network remained undirected.

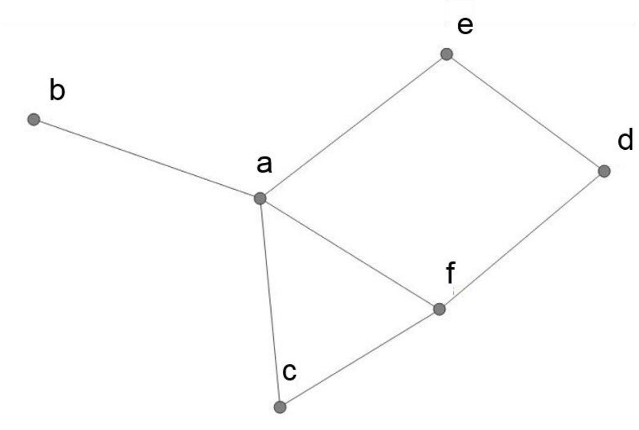
Table 3.1: Acquired data and source.

Data	Source
- **Tokyo Metro line identification** - **Distances between adjacent stations (km)** - **Daily average passenger number per station (for 2013)**	Tokyo Metro Co., Ltd http://www.tokyometro.jp/index.html
- **Toei Subway line identification** - **Distances between adjacent stations (km)** - **Daily average passenger number per station (for 2013)**	Tokyo Metropolitan Bureau of Transportation http://www.kotsu.metro.tokyo.jp/
- **Travel time between adjacent stations (min)**	Google Maps 2016 https://maps.google.com.au/
- **Station coordinates (latitude, longitude)**	Wikimedia tool GeoHack https://tools.wmflabs.org/geohack/
- **Estimated extent of inundation (at 7 m global sea level rise)**	Alex Tingle http://flood.firetree.net/

Travel distance (km) and time (minutes) were assigned as attributes (weights) to the edges and geo-locations (latitude, longitude) were assigned as attributes to vertices. Thirteen connections between stations are walking transfers, with no rail track connection. Although these are physically shorter paths, the pedestrian transfer makes for longer travel duration. To account for this, time was used in the calculation of shortest paths rather than distance. Ultimately these walking transfers were included in the system to retain the *traversability* of the network.

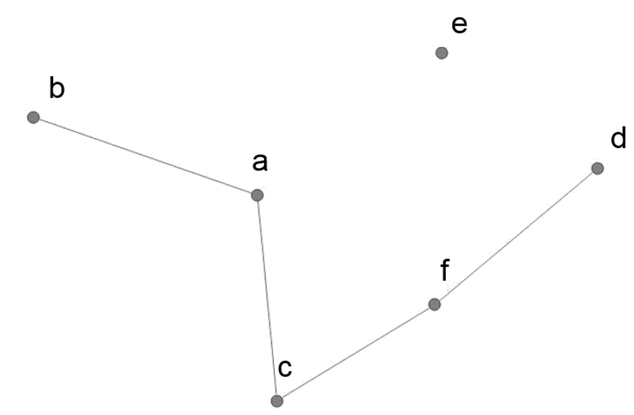
3.4.4 Component failure and alternative paths

If the track connecting two stations fails for whatever reason, and that failure cannot be bypassed, adjacent stations become unreachable, with the potential to isolate whole portions of the network. We identified how the closure of stations and tracks coinciding with the hazard footprint would impact subway system usability using inbuilt algorithms (for list see http://reference.wolfram.com/language/), and by comparing the graph distance matrix (square matrix describing distances between vertices) of the original network with the graph distance matrix describing the network after component deletion. Figures 3.6, 3.7 and 3.8 demonstrate the approach using a simple network.



	a	b	c	d	e	f
a	0	1	1	2	1	1
b	1	0	2	3	2	2
c	1	2	0	2	2	1
d	2	3	2	0	1	1
e	1	2	2	1	0	2
f	1	2	1	1	2	0

Figure 3.6: Geographical (left) and distance matrix (right) representations of example graph, with edge weight equal to 1.



	a	b	c	d	e	f
a	0	1	1	3	∞	2
b	1	0	2	4	∞	3
c	1	2	0	2	∞	1
d	3	4	2	0	∞	1
e	∞	∞	∞	∞	∞	∞
f	2	3	1	1	∞	0

Figure 3.7: Geographical (left) and distance matrix (right) representations of example graph after the deletion of three edges. Note ∞ denotes there is no longer a path between two vertices.

	a	b	c	d	e	f
a	0	1	1	3	∞	2
b	1	0	2	4	∞	3
c	1	2	0	2	∞	1
d	3	4	2	0	∞	1
e	∞	∞	∞	∞	∞	∞
f	2	3	1	1	∞	0

−

	a	b	c	d	e	f
a	0	1	1	2	1	1
b	1	0	2	3	2	2
c	1	2	0	2	2	1
d	2	3	2	0	1	1
e	1	2	2	1	0	2
f	1	2	1	1	2	0

=

	a	b	c	d	e	f
a	0	0	0	**1**	∞	**1**
b	0	0	0	**1**	∞	**1**
c	0	0	0	0	∞	0
d	**1**	**1**	0	0	∞	0
e	∞	∞	∞	∞	∞	∞
f	**1**	**1**	0	0	∞	0

Figure 3.8: Difference in distances between vertices after edge deletion achieved by subtracting the first graph distance matrix (Figure 3.6) from the second (Figure 3.7). Note ∞ denotes there is no longer a path between two vertices.

Figure 3.8 shows that the paths a – f, a – d, b – d, and b – f all increased by one length. Vertex e is now inaccessible with no edges connected it to any other vertex. This same method was applied to the larger Tokyo Subway network; increases in shortest path between stations, and stations no longer accessible following inundation, were identified with results presented in the next section.

3.5 Results

3.5.1 Usability of the damaged subway network

The hypothetical inundation scenario impacts the north and east of the Tokyo Subway network, fragmenting the network into three disconnected networks or *subgraphs* (Figure 3.9). All network components intersecting the hazard footprint were deemed non-operational and thus deleted from the network. The cessation of operation of 56 stations and 73 track connections resulted in 11 stations being isolated from the rest of the network and an increase in travel time for many routes throughout the remaining subway system (Table 3.2).

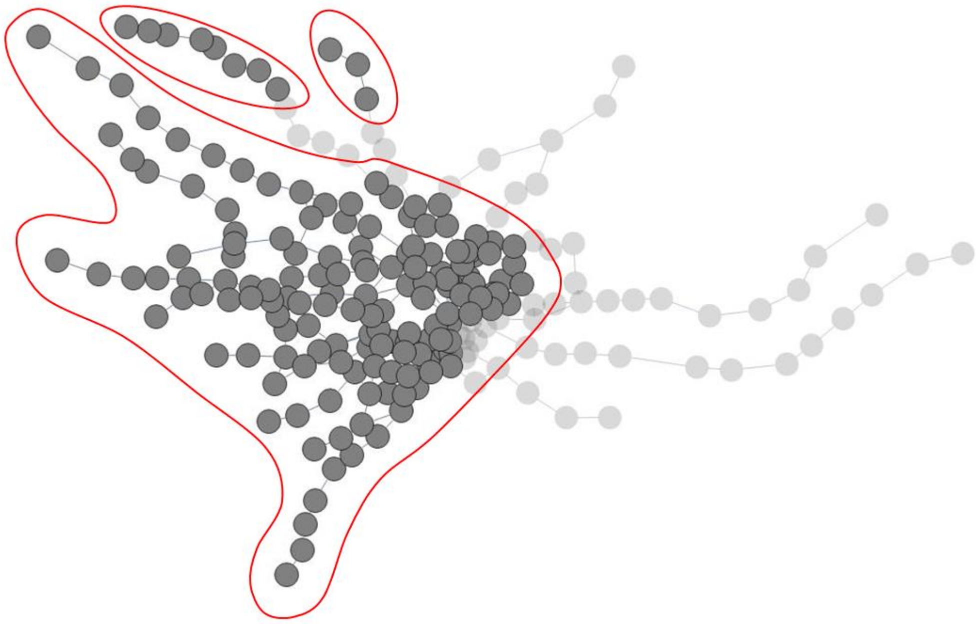


Figure 3.9: Fragmentation of the subway network into three subgraphs after component deletion.

Table 3.2: Impact of the theoretical inundation scenario on the Tokyo Subway network.

Impact	Count	% of network
Stations inundated	56	26
Track connections inundated	73	27
Shortest paths terminated	24,058	52
Shortest paths extended (by travel time)	1,734	4
Shortest paths unchanged	20,004	44
Number of daily average passengers impacted	5,186,095	27
Number of daily average passengers isolated from remaining operational section of network	298,751	2

Considering this scenario, over 5 million daily passengers across 9 of the 23 Special Wards of the Tokyo Metropolitan Prefecture (Chuo, Koto, Edogawa, Sumida, Taito, Arakawa, Adachi, Kita and Itabashi) would be impacted. Passengers wanting to leave from or travel to the 56 non-operational stations would have to find alternative transport, if available. This scenario could also isolate or hinder over 290,000 passengers leaving or travelling to the 11 stations that form the two smaller subgraphs cut off from the remaining operational section of the network. Only 44% of the subway system's shortest paths (with regards to travel time) remained unchanged, with 52% of the shortest paths no longer possible and 4% having to be extended (with a maximum time increase of 13 minutes and average increase of 2.6 minutes). In other words, passengers taking these routes would need to take an alternative path, or detour, increasing the travel time, or not travel at all. A maximum travel time increase of 13 minutes is a small disruption for those still able to use the network but the number of passengers affected is large so this metric alone does not do full justice to the ensuring disruption.

Of the stations still operating, passengers travelling from Ningyōchō Station would be impacted the most by this scenario in terms of increased travel time to their destinations (Figure 3.10). From 213 possible destinations from Ningyōchō Station, 111 took longer to reach and 67 (including deleted stations) were rendered inaccessible, leaving only 16.5% of shortest paths functioning as normal.

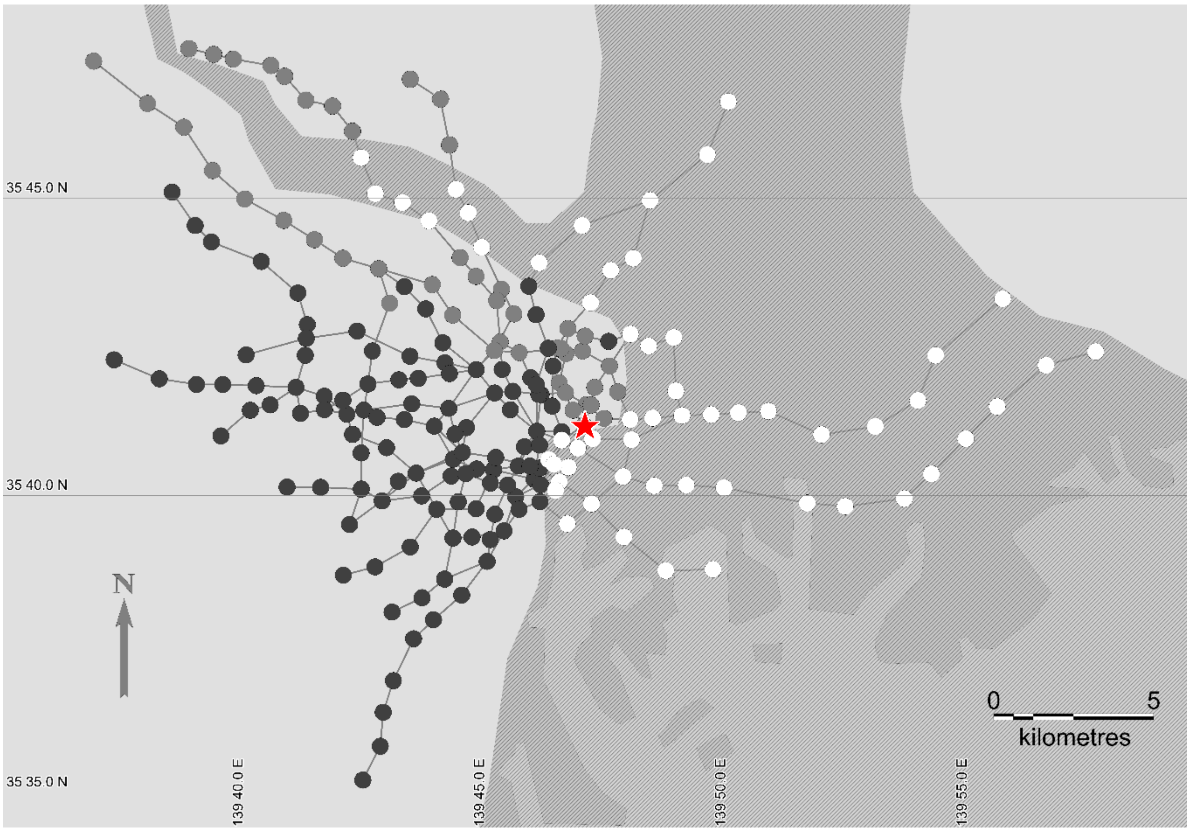


Figure 3.10: The change in shortest paths from Ningyōchō Station ★ to all other stations. White stations ○ are no longer accessible, black stations ● take longer to reach and grey stations ● are unchanged. The grey area ■ represents the area of inundation.

The largest increase in travel time across the network was by 13 minutes between Tsukijishijō and Ningyōchō Stations, and Tsukijishijō and Ryōgoku Stations (Figure 3.11). We were unable to determine the number of passengers that usually took these particular paths from the passenger data available.

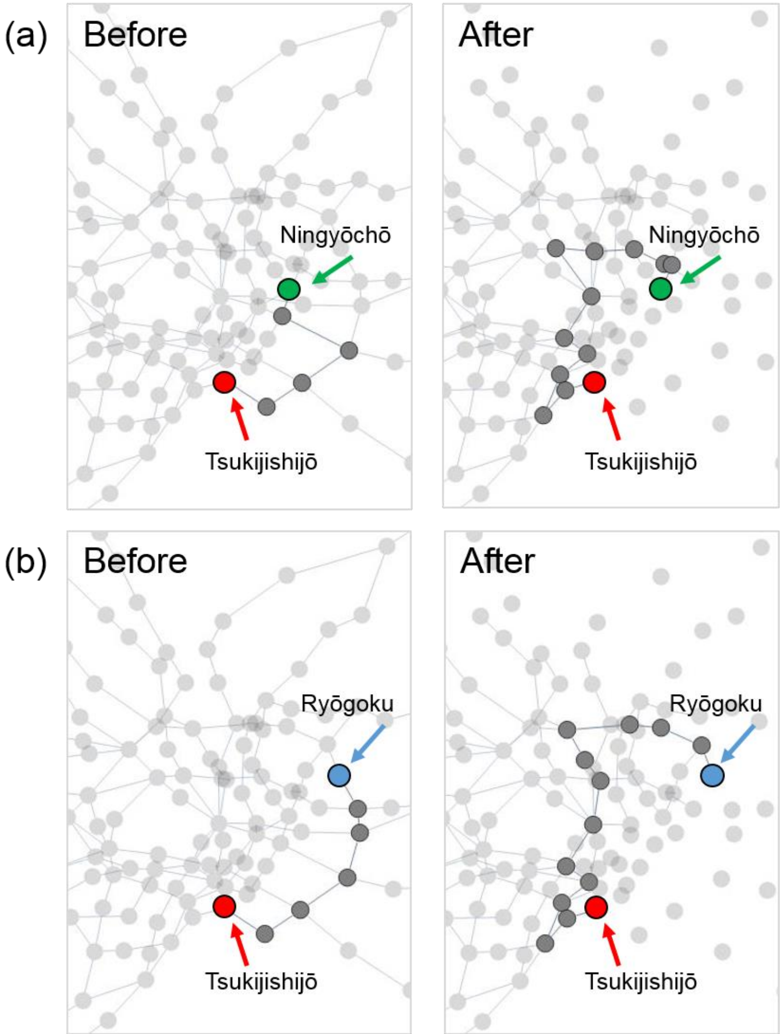


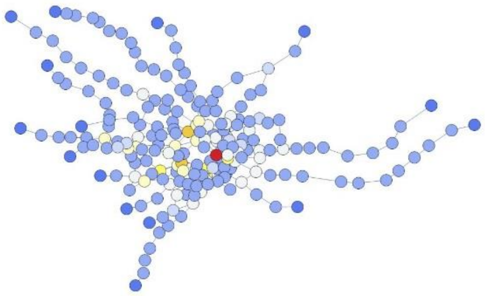
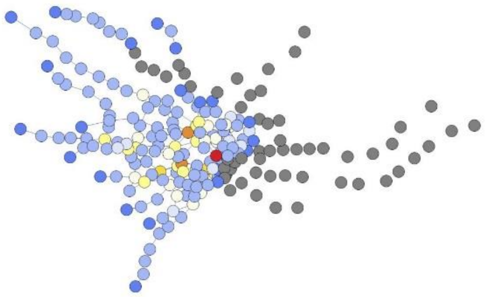
Figure 3.11: Change in shortest path between: **a** Tsukijishijō and Ningyōchō stations and **b** Tsukijishijō and Ryōgoku stations after inundated stations and connections were deleted. Note the loss of connections between stations coloured light grey in the after images.

3.5.2 Station position and importance measures

The position and importance of each station with regards to common graph theory measures (degree, closeness, betweenness and eigenvector centralities) before and after the disruption were compared (Tables 3.3-6). These common network metrics employed to describe station importance are defined formally in section 3.7.1 (supplementary material).

Table 3.3 shows only a small difference between the largest degree centralities. Degree centralities measure the number of edges a vertex has. The average degree centrality and the distribution of the scores also remained very similar, which indicates that the most connected stations in the network remained the most connected following inundation.

Table 3.3: Station degree centrality before and after deletion of inundated components.

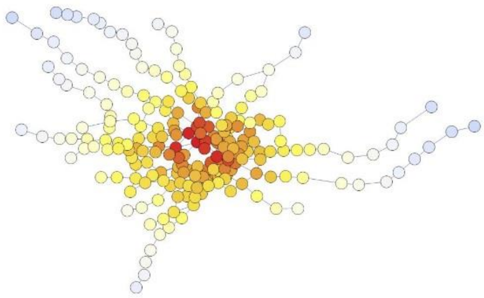
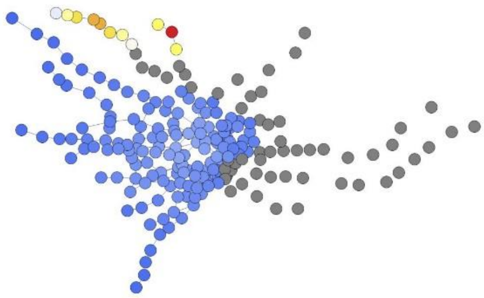
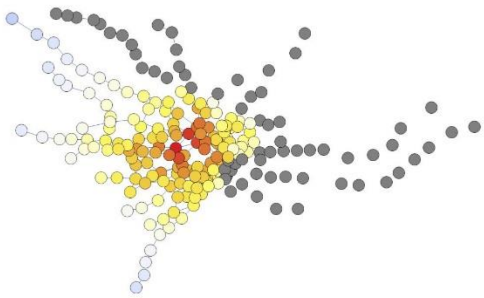
Highest ranked stations	**Degree centrality scores***	**Distribution of degree centrality scores****
Original subway network		
Ōtemachi	9	
Nagatachō	7	
Iidabashi	7	
Damaged subway network		
Ōtemachi	8	
Nagatachō	7	
Iidabashi	7	

* Number of connections a station has, also known as the vertex degree (see section 3.7.1).

** Warmer colours indicate high scores, cooler colours indicate low scores and grey shows deleted stations.

Closeness centralities measure the ease of reaching all other stations from a particular station. The two smaller subgraphs heavily skewed the closeness centrality scores of the damaged network (Table 3.4). Therefore, we compared the closeness centralities of only the largest subgraph. When compared to their original ranking, 73.5% of the stations in the largest subgraph were ranked higher with regards to closeness. This is due to the high proportion of deleted stations that are periphery stations, making the damaged network closer overall. With regards to centrality measures, 24.5% of stations were ranked lower due to the 'centre' of the network shifting, in this case towards the west. Three stations' closeness centralities were unchanged.

Table 3.4: Station closeness centrality before and after deletion of inundated components.

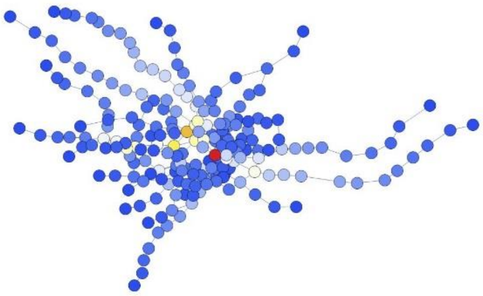
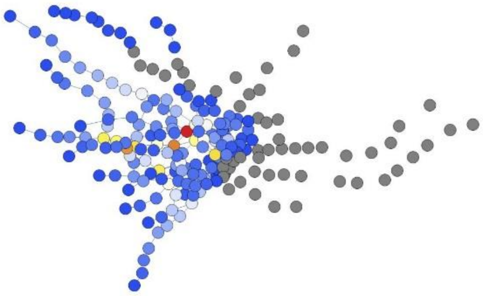
Highest ranked stations	Closeness centrality scores*	Distribution of closeness centrality scores**
Original subway network		
Kudanshita **Iidabashi** **Ōtemachi**	0.092 0.091 0.091	
Damaged subway network		
Shimo **Hasune** **Nishidai**	0.500 0.410 0.411	
Largest subgraph of the damaged subway network		
Ichigaya **Iidabashi** **Kudashita**	0.110 0.107 0.105	

* The measure of how close a vertex is to all other vertices in a graph. Scores lie between 0 and 1; high scores are given to stations that are, on average, closest to all other stations (see section 3.7.1).

** Colours as described in Table 3.3.

Out of the 158 operational stations in the damaged network, 59.5% were ranked higher with regards to betweenness centrality values. With a number of network 'hubs' being deleted in the east, shortest paths changed to use other 'hubs' in the mid-west of the network, increasing their betweenness ranking (Table 3.5). Of the stations that fell in rank (29.1%), most were those that connected the deleted peripheral subway lines to the east. The removal of these stations heavily decreased the number of shortest paths that they would now be involved with. No change was evident for 18 stations.

Table 3.5: Station betweenness centrality before and after deletion of inundated components.

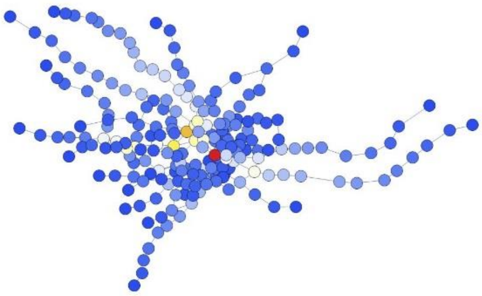
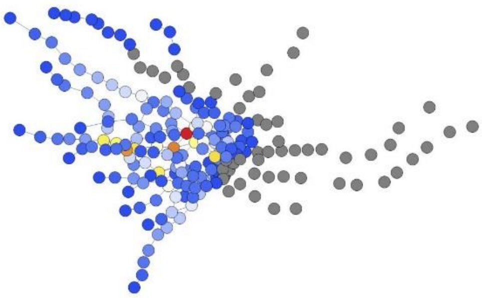
Highest ranked stations	Betweenness centrality scores*	Distribution of betweenness centrality scores**
Original subway network		
Ōtemachi	6847	
Iidabashi	5474	
Ichigaya	4823	
Damaged subway network		
Iidabashi	2902	
Ichigaya	2587	
Shinjuku	2510	

* Scores quantify the number of times a station is a connector along the shortest path between two other stations (see section 3.7.1).

** Colours as described in Table 3.3.

An eigenvector score measures how important a vertex's neighbours are and therefore its influence. Of the remaining operational stations in the damaged network 33.5% rose in rank with regards to eigenvector scores. This demonstrated that these stations' connections are now more important than they were before. Overall, the stations in the southwest increased the most in rank as the 'centre' of the network, and therefore the stations with the higher centrality measures, were now located in this area (Table 3.6). There was also a decrease in difference in the range of eigenvector values, meaning more stations shared higher eigenvector scores and not just one outlier. As their connections became less important, 65.2% of stations dropped in rank. Only two stations retained the same overall rank.

Table 3.6: Station eigenvector centrality before and after deletion of inundated components.

Top ranked stations	Eigenvector centrality scores*	Distribution of eigenvector centrality scores**
Original subway network		
Ōtemachi	0.059	
Hibiya	0.038	
Nihombashi	0.033	
Damaged subway network		
Nagatachō	0.052	
Akasaka-Mitsuke	0.046	
Aoyama-Itchōme	0.038	

* The measure of a station's influence in a graph or how many important neighbours it has. Scores are the sum of the centrality values of all stations connected to a station and are normalised to sum to one (see section 3.7.1).

** Colours as described in Table 3.3.

Ōtemachi Station had the highest centrality scores overall in the original network, with the most connections, being the closest to all other stations and being a vital connection between other stations. In the damaged network, Ōtemachi Station's centrality dropped slightly in comparison with other stations in all centrality measures apart from the degree centrality. This showed that Ōtemachi Station became less central but still retained all its direct connections (neighbours).

3.6 Discussion

We used a hypothetical hazard footprint with simplified assumptions to explore the usefulness of graph theory to map network failures and disruption from natural hazard shocks. Overall, the modelled damage to the Tokyo Subway system from the inundation scenario resulted in 26% of the network being deemed non-operational, potentially impacting over 5.48 million passengers daily. The network was fragmented into three separate networks, creating two small isolated groups of stations in the northwest of the network, north of Itabashi and Kita Wards. The third and largest section contained the central body of the original network.

When calculating network connectedness measures, the largest remaining operational section of the network became more connected and more robust to failure than the original network. This is because the majority of vertices impacted in this particular scenario were peripheral vertices with low vertex degrees – in other words a low number of connections. In contrast, damage to a small number of stations in the centre of this subway system would cause only minor disruptions, requiring detours and a change of passenger loads at stations; overall the network would remain fully connected.

The most vulnerable sections of the subway system are the outer branches of single track lines. When station or track failures occur between these outer lines and the central highly-connected hub of the network, the failures cannot be bypassed resulting in the isolation of entire lines. This is a common issue identified in subway networks (Angeloudis and Fisk 2006). Ieda et al. (2001) suggested that more transfer stations in the outer parts of the Tokyo Subway network should be added to avoid network fragmentation. Alternatively, Majima et al. (2007) proposed providing alternative transport services such as a water bus system. This was aimed at alleviating congestion; however, having alternative transport options could also help during network failure in a disaster, that is, if these options weren't impacted by the same shock. Compared with random failures or attacks, natural hazard shocks are more likely to fragment a network as they generally affect a larger area, and therefore potentially a higher number of network components. In these cases graph theory techniques for determining alternative paths, changes in component importance and highlighting areas of isolation may become redundant if there is no network left to analyse. When large portions of lifeline infrastructure components are exposed to disruption from a natural phenomenon, network modelling would not provide much insight during the event itself; however, these techniques can still be use in recovery.

Station centrality – or importance – increased in the southwest of the network and decreased in the north and east as shortest path routes changed with the non-operability of stations in the north and east. The change in the importance of stations can lead to, or be a result of, a change in the flow, i.e. passenger traffic, which could impact station capacities. As detours are created, a quiet station may become a hub that many transport routes flow through, causing congestion. However, as noted by Soh et al. (2010), important stations with regards to graph theory centrality measures do not always relate to real-world importance. For example Ōtemachi station (estimated 374,000 average daily passengers) is deemed one of the most important with regards to degree, closeness, betweenness and eigenvector centralities but Shibuya station, which does not feature in the top three of any of these measures, actually has the most passenger usage of 943,000 average daily passengers. Therefore it is important to be able to put these measures into context by understanding how a network is used.

The example provided here demonstrates that graph theory measures, such as shortest paths – when associated with weights or attributes such as time, distance or number of users – can be of great benefit for network navigation and assessing impedance of flow during component failure. When analysing critical infrastructure disruption, it is not just the robustness of a network to failure that is important, it is the dependence on that network that determines the magnitude of disruption. Network fragmentation and the loss of operation of sections of any critical infrastructure would obviously be costly and add to the disruption already caused by the hazard event. However, even when a network remains connected after a shock, any detours or extended travel time needed between remaining operational components can come at a cost. The termination of a single transport route/connection, although not heavily impacting the network's traversability, could have detrimental outcomes for a particular business, supply chain or community.

The importance of network analysis in the case of natural hazards or other disasters is in identifying at risk critical infrastructure and determining the expected disruptions caused by service failure. Identifying the capacity of essential services and the areas that may be disconnected is vital for emergency response and recovery in a disaster. Identification of the most likely functioning transportation routes, for example, is important for evacuation and emergency responder access, and for detecting areas at risk of isolation. Considering utility networks, another example would be identifying areas that might lose access to water and would therefore require drinking water supplies and alternative sanitary solutions, and could potentially lose the ability to combat secondary hazards such as fires.

Here I have considered just one scenario impacting a single network. In this preliminary investigation, I was not able to include load capacities to determine whether alternative lines and stations could cope with additional loads. This study could also be enhanced by investigating network recovery optimisation and alternative transport options. However, I have demonstrated that the techniques used in this study have the potential to be applied to any natural hazard scenario (e.g. earthquake, fire, flood or volcanic eruption) or infrastructure system (e.g. power, water or telecommunications). I have shown that graph theory techniques are useful for disaster-recovery management, for example, damaged or potentially-damaged networks could be analysed to determine which components would be the most beneficial to reopen. These techniques also have applications in modelling business-interruption losses and supply-chain disruption, ultimately helping to understand the true impact of natural hazards.

3.7 Supplementary material

3.7.1 Common network terms and measures

Vertex degree –for a vertex *v*, this is the number of edges incident to *v*. In other words, the number of connections the vertex has to other vertices. The non-increasing list of all vertex degrees in a graph is called the *degree sequence*. In Figure 3.12, vertex **a** has the largest degree of four, being connected to vertices **b**, **c**, **f** and **e**. The *average vertex degree* is the sum of vertex degrees in a graph over the number of vertices, in this case 14/6 or 2.33.

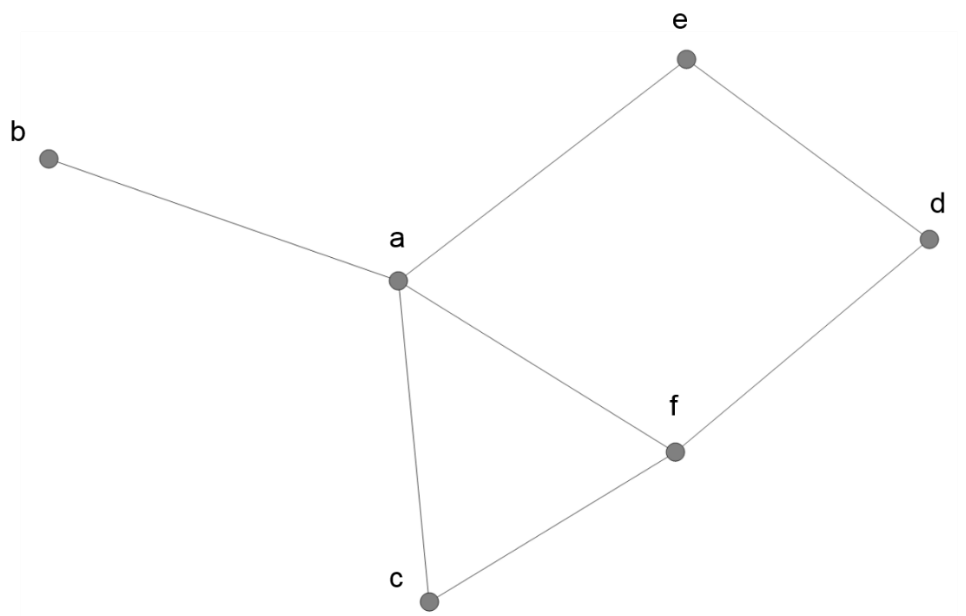


Figure 3.12: Sample undirected and unweighted graph with six vertices and seven edges.

Degree distribution – the probability distribution of vertex degrees over the whole graph. Most real world networks have degree distributions that are right-skewed, where the majority of vertices have low degrees and a small number have very high degrees; these vertices are known as "hubs". These networks are termed *scale-free* and have degree distributions that typically follow a power law (Albert and Barabási 2002, Barabási 2002).

Path – considered to be an alternating sequence of vertices and edges connecting two individual graph vertices v_i and v_j. Two vertices are said to be *connected* if there exists a path between them; a graph is connected if all pairs of vertices are connected.

Shortest Path – is the path between two vertices v_i and v_j containing the minimal number of edges, or, in a weighted network, the minimal weight among all possible paths. A shortest path is also known as a *geodesic*. In the unweighted example graph (Figure 3.12), the shortest path between vertices **a** and **d** involves two edges; either going through vertex **e** or **f**. The *average shortest path* is the average length of all shortest paths between all pairs of vertices in a graph. In Figure 3.12 there are 15 possible shortest paths (only one shortest path is counted between vertex pairs) when considering all vertices. The sum of all the shortest path lengths is 24 edges; therefore the average shortest path is 24/15 or 1.6.

Diameter – is the longest shortest path or *geodesic* amongst all possible pairs of vertices in a graph. The graph in Figure 3.12 has a diameter of 3, with the longest shortest path being between vertices **b** and **d**.

Clustering coefficient –This measure requires a vertex v to be adjacent to at least two other distinct vertices. The clustering coefficient is equal to 1 if every adjacent vertex connected to v is also connected to every other vertex within the neighbourhood, and 0 if no vertex that is connected to v connects to any other vertex that is connected to v.

- *Global clustering coefficient* – The global clustering coefficient of a graph is the fraction of closed triplets over the total number of triplets (both open and closed). A triplet consists of three vertices that are connected by either two (open triplet) or three (closed triplet) undirected edges (Figure 3.13).

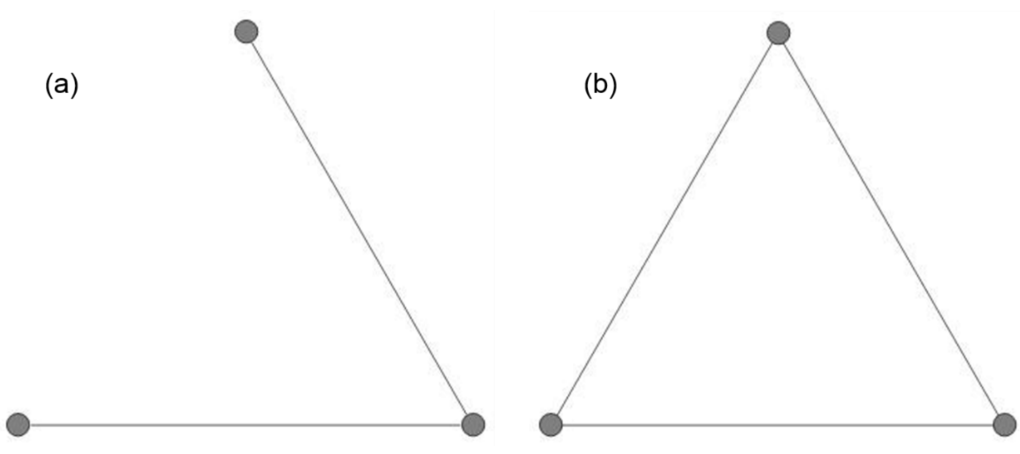


Figure 3.13: Graph (a) represents an open triplet and graph (b) a closed triplet.

This measure gives an indication of the clustering in the whole network (global) and is often called transitivity. With three closed triplets over 12 triplets total, the graph in Figure 3.12 has a global clustering coefficient of ¼ or 0.25.

- *Local clustering coefficient* – The local clustering coefficient is the fraction of pairs of neighbours of a vertex that are connected over all pairs of neighbours. In Figure 3.12, vertex **c** has the highest local clustering coefficient of 1, with all of its neighbours being connected to each other.

- *Average clustering coefficient* – the overall clustering of a graph can also be measured by the average of the local clustering coefficients of all vertices in a graph. With (1/6 + 0 + 1 + 1/3 + 0 + 0)/6, the average clustering coefficient of the graph in Figure 3.12 is 1/4 or 0.25.

Centrality Measures – indicators of centrality identify the most important vertices in a graph.

- *Degree centrality* – measures how connected a vertex is and gives high centralities to vertices that have high vertex degrees. This is the same as the degree sequence for a graph. The degree centralities for the graph in Figure 3.12 are {**a** = 4, **f** = 3, **c** = 2, **d** = 2, **e** = 2, **b** = 1}. Vertex **a** has the highest degree of 4, and therefore the highest degree centrality.

- *Closeness centrality* – is the measure of ease of reaching all other vertices from a vertex v_i. High centralities will be given to vertices that are at the shortest average distance from every other reachable vertex. Closeness centralities scores lie between 0 and 1 inclusively. The closeness centralities for a graph are given by ($1/l_1$, $1/l_2$, …), where l_i is the average distance from a vertex v_i to all other vertices v_j in the graph that are connected. l_i is given by the sum of the distances to all connected vertices ($\sum_j d_{i\,j}$) over the number of connected vertices (k). The closeness centrality for isolated vertices is 0 (Wolfram 2016b). The closeness centralities for the example graph in Figure 3.12 are (**a** = 0.83, **b** = 0.5, **c** = 0.63, **d** = 0.56, **e** = 0.63, **f** = 0.71). Vertex **a** has the highest centrality score of 0.83, with the sum of distances to all other vertices being six and the number of vertices connected to vertex **a** being five; therefore, l_i = 1.2 and 1/1.2 = 0.83.

- *Betweenness centrality* – the measure of a vertex's role as an intermediate connector. Betweenness centrality quantifies the number of times a vertex acts as a connector along the shortest path between two other vertices. High centralities will be given to vertices that are on many shortest paths of other vertex pairs. Betweenness Centrality scores lie between 0 and (*n*-1)(*n*-2)/2, where *n* is the number of vertices in a graph. In a connected graph the betweenness centrality is given by:

$$\frac{1}{2}\sum v_s \neq v_i \sum v_t \neq v_i \frac{\sigma\, v_s\, v_t\, (v_i)}{\sigma\, v_s\, v_t}$$

Where ½ $\sum_{vs\neq vi} \sum_{vt\neq vi}$ is equal to (n-1)(n-2)/2, and $\sigma\ v_s\ v_t$ is the number of shortest paths from v_s to v_t, and $\sigma\ v_s\ v_t\ (v_i)$ is the number of shortest paths from v_s to v_t passing through v_i (Wolfram 2016a). The Betweenness centralities for the graph in Figure 3.12 are {**a** = 5.5, **b** = 0, **c** = 0, **d** = 0.5, **e** = 1, **f** = 2}. Again vertex **a** has the highest centrality score, 5.5, with 10 X (5.5/10). Note when there are two possible shortest paths, i.e. between vertex **e** and **f**, either going through vertex **a** or vertex **d**, both vertices **a** and **b** are assigned half a point each.

- *Eigenvector centrality* – is the measure of a vertex's influence in a graph. The eigenvector centrality scores all vertices in a graph based on the assumption that each vertex's centrality is the sum of the centrality values of the vertices that it is connected to. Eigenvector centrality scores are always normalised so that they sum to 1. In a undirected connected graph the eigenvector centrality is given by the eigenvector equation:

$$c = 1/\lambda_1 a^{\tau}.c$$

With c being the centrality and λ_1 being the largest eigenvalue of the adjacency matrix a for a graph (Wolfram 2016c).

The maximum eigenvalue for the graph in Figure 3.12 is 2.599, the Eigenvector centralities are {**a** = 0.24, **b** = 0.09, **c** = 0.17, **d** = 0.14, **e** = 0.15, **f** = 0.21}. Again vertex **a** has the highest centrality score of 0.24.

Chapter 4 Exposure of roads to volcanic ash from a future eruption from Mount Fuji, Japan: Implications for evacuation and clean-up

4.1 Chapter overview

Building from chapter 3, this chapter further examines the use of graph theory as a tool for disaster response and recovery. This chapter uses a real-world scenario of a future explosive volcanic eruption at Mount Fuji, Japan. Graph theory techniques are combined with existing ash dispersal simulations to explore the impact that ash induced road closures could have on emergency response during, and recovery following, an eruption. In particular, these techniques are used to assess the impacts of ash fall on the evacuation plans for Yamanashi Prefecture with regards to a future 1707 Hoei type eruption at Mount Fuji.

4.2 Key findings

In the case of a future Hoei type eruption from Mount Fuji, with similar westerly wind conditions, ash induced road closures would impact current evacuation plans for Yamanashi Prefecture. Due to the importance of roads for evacuation in this area, it is advisable to begin evacuation well before the onset of an eruption to avoid volcanic ash fall disrupting road transportation. After a future eruption of this magnitude and wind conditions, evacuees would likely have to remain in host cities until roads are cleaned and roofs are cleared of thick ash deposits, especially residents from Yamanakako City, which would likely receive large ash loads. In this scenario ash would also impact host cities to the east, especially Doshi, Otsuki and Uenohara. Due to the potential disruptions caused by ash fall in this area it would be advised that, if an eruption was to occur during similar wind conditions, those that need to evacuate should relocate to host cities in the north or west instead. The use of graph theory techniques alongside hazard modelling, with an understanding of the use of impacted roads, helped to envisage the potential problems that could result from road closures and results can aid in disaster planning.

4.3 Introduction

With 110 active volcanoes throughout the country, much of Japan is exposed to volcanic hazards (Machida 1999, Japan Meteorological Agency 2013). Volcanic eruptions can produce a variety of hazards, impact areas far from source, and have the potential to persist over weeks or months (Wilson et al. 2014). Hazards such as lava flows, lahars, pyroclastic flows and ash fall can occur simultaneously or consecutively, and can cause damage and disruption to society and the built environment (Jenkins et al. 2014). Volcanic ash in particular can be heavy, highly abrasive, corrosive and conductive, and can spread far and wide. Only millimetres of ash fall accumulation is needed to disrupt essential services and critical infrastructure, such as electricity, water supply, waste systems, communications and transportation (Blong 1984, Jenkins et al. 2014, Wilson et al. 2014, Blake et al. 2016, Wilson et al. 2017). These lifelines are essential for maintaining modern society's socioeconomic activities and, importantly for the interests of this study, controlling emergency response and assisting post-event recovery.

4.3.1 Future eruption hazard at Mount Fuji

A future eruption from Mount Fuji was chosen as a scenario due to its violent potential and close proximity to urban environments and lifeline infrastructure. Mount Fuji is the largest volcanic edifice in Japan (3,776 m in elevation) and a national symbol (Miyaji et al. 2011, Yamamoto and Nakada 2015). Throughout its history Fuji volcano has erupted repeatedly in a variety of styles, volumes and frequencies, producing namely basaltic pyroclasts and lavas (Miyaji 2002, Yamamoto and Nakada 2015). Its last eruption occurred in 1707, over 300 years ago. The 1707 Hoei eruption, named after the era in which it occurred, is one of the most violent eruptions the volcano has produced (Shimozuru 1983, Miyaji 2002, Miyaji et al. 2011). The Hoei eruption was the most recent eruption from the Younger Fuji volcano, one of two volcanoes that make up Mount Fuji. The Younger Fuji edifice has been built up from many lava flows and pyroclastic deposits over the past 11,000 years, with activity shifting from the summit to flank craters about 2,200 years ago (Miyaji 2002). The Hoei eruption produced wide-spread ash fall covering most of the south Kanto plain to the east of the volcano, impacting large proportions of Kanagawa and Chiba Prefectures, highly populated areas of Tokyo prefecture and parts of Shizuoka, Saitama and Yamanashi Prefectures (Figure 4.1) (Miyaji 2002, Magill et al. 2015). Ash from this eruption has also been found 280 km from source in deep sea cores in the Pacific Ocean (Miyaji 2002). During this eruption proximal downwind areas were severely damaged; buildings were burnt or collapsed and agricultural areas were smothered in thick ash (Miyaji 2002, Miyaji et al.

2011). Subashiri village, 10 km east of the vent, received ~ 2.5-3 m of ash which buried and crushed 72 houses and three Buddhist temples (Miyaji 2002, Inoue 2011). Impacts to more distal reaches were limited to respiratory problems, most likely due to inhalation of fine ash (Miyaji et al. 2011). Although there were no known direct deaths from the eruption itself, thousands later died from starvation due to food shortages (Miyaji 2002, Inoue 2011). Areas downstream from thicker ash fall deposits, from the Sakawa River catchment (20-30 km from source) across to Yokohama (~60-70 km from source), were also subsequently subjected to destructive mud flows and large floods, resulting from clogged river beds and the remobilisation of ash by heavy rain (Sumiya et al. 2002, Inoue 2011). The impacts of these secondary flows were felt for almost 100 years after the eruption.

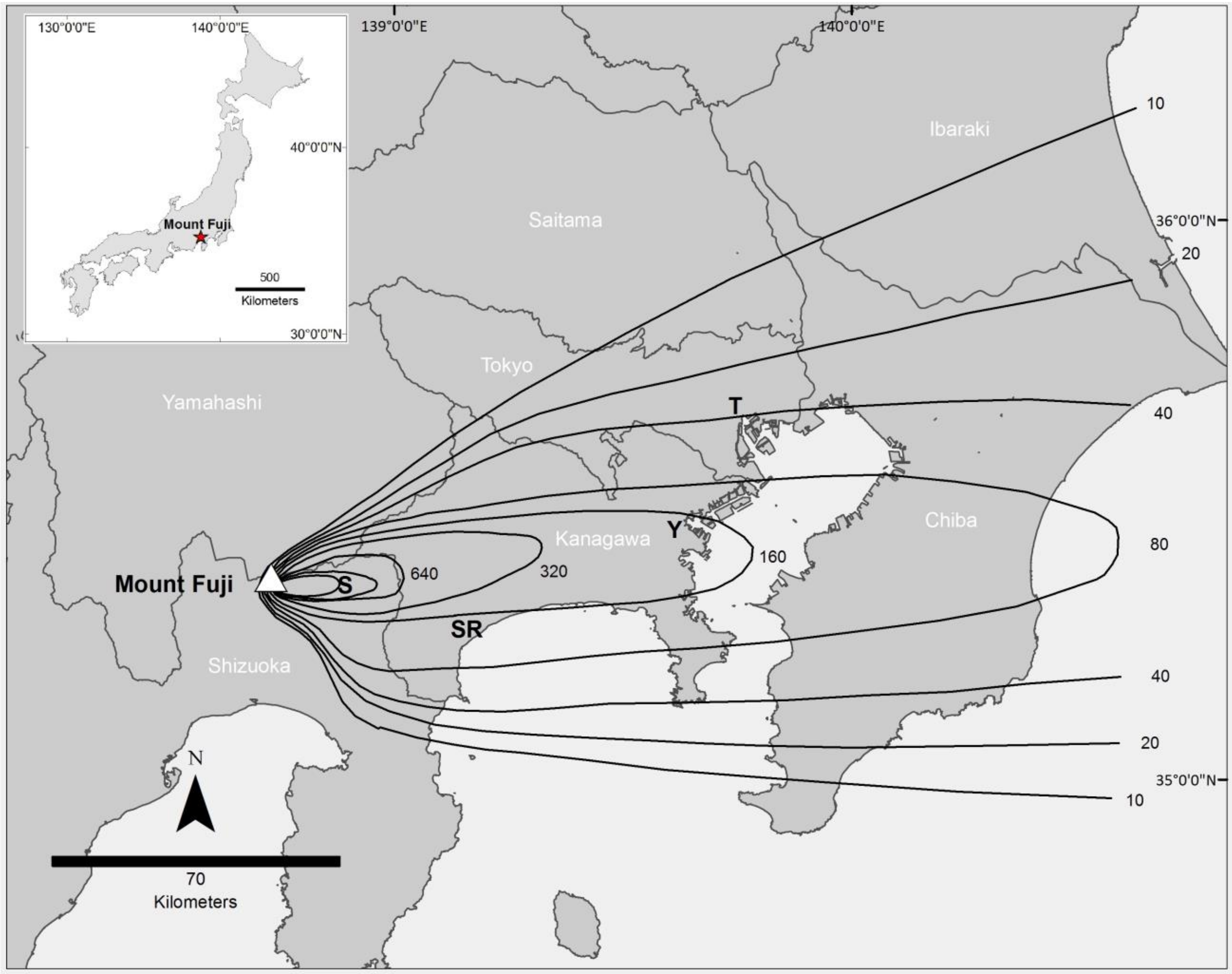


Figure 4.1: Ash fall thickness (mm) isopach map of the 1707 Hoei eruption (modified from Miyaji et al. (2011)). T = present day Tokyo, Y = Yokohama, S = Subashiri and SR = Sakawa River. Note that inner isopachs represent 1280 and 2560 mm.

Mount Fuji's variable history makes it hard to predict the nature of future activity. Mount Fuji has had both small and large eruptions and has produced lavas flows as well as explosive plinian eruptions (Miyaji et al. 2011). However, it is presumed that Fuji volcano has shifted into a new stage of activity since AD 1,100, where plinian type eruptions are now more common, and it is said that future eruptions from Mount Fuji are likely be of a similar explosive style to that of the Hoei eruption (Shimozuru 1983, Yamamoto and Nakada 2015). Although the Hoei eruption is seen as the worst-case scenario from Mount Fuji in terms of ash fall hazard (Miyaji 2002), it would be ill-advised not to plan for the worst.

4.3.2 Current disaster mitigation plans for Mount Fuji

The realness of a future threat from Mount Fuji was realised in 2000-2001 when there was an increase in deep low frequency earthquakes beneath the volcano – a sign of magma movement (Miyaji 2002). This activity sparked the Cabinet Office of Japan to create a committee to draft a hazard map for Mount Fuji. This was the first comprehensive research compiled to estimate potential damage from a future Hoei type eruption (Miyaji 2002, Cabinet Office Government of Japan 2004, Miyaji et al. 2011, Yamamoto and Nakada 2015). The areas impacted by the eruption in 1707 have become highly developed and densely populated, increasing the exposure of these areas to a similar event. Consequently, impacts to buildings, transport networks, industries and tourism would result in huge costs to society and the economy, with a similar eruption estimated to cause an economic loss of up to JPY2.5 trillion (~AUD30 billion) (Cabinet Office Government of Japan 2004, Yamamoto and Nakada 2015).

The Fuji Volcano Disaster Prevention Council used the hazard maps created by the Cabinet Office of Japan to construct an evacuation plan for the three prefecture government areas that surround Mount Fuji: Yamanashi, Shizuoka and Kanagawa (Fuji Volcano Disaster Prevention Council 2016). The plan is entitled *Mt. Fuji Volcano Wide Evacuation Plan* and was finalised in 2016. The plan requests the evacuation of 750,000 residents from 14 cities and villages under Yamanashi and Shizuoka prefectural government areas, in the case of a future eruption, and is particularly concerned with lava and pyroclastic flow hazards. In addition, 470,000 residents are to be evacuated in the case of volcanic ash fall, primarily in Kanagawa Prefecture (The Japan Times 2014). The magnitude and type of volcanic hazards considered in the *Mt. Fuji Volcano Wide Evacuation Plan* are based on the 2004 Mt. Fuji hazard map review committee report (Cabinet Office Government of Japan 2004), as well as updated hazard information from subsequent research. The volcanic hazards of interest in the 2016 plan are: crater formation, pyroclastic flow/surge, pumice fall, lava flow, volcanic mud flow, ash fall, remobilisation of volcanic debris, and small ejecta/volcanic bombs. For each volcanic hazard at Mount Fuji there is an assumed impact range and area requiring evacuation. Crater formation, pyroclastic flow, large ejecta and lava flows are dealt with collectively, with the remaining hazards (volcanic mud flow (from melted ice), ash fall, debris flow (after ash fall), and small ejecta) accounted for separately (Fuji Volcano Disaster Prevention Council 2016).

The evacuation policy outlined in the *Mt. Fuji Volcano Wide Evacuation Plan* (Fuji Volcano Disaster Prevention Council 2016) is based on the Report on the Fuji Volcano wide area disaster prevention measures review meeting (Cabinet Office Government of Japan 2005) and the Fuji volcano wide area disaster prevention countermeasure basic policy (Central Disaster Management Council 2006). The plan also coordinates with the eruption warning level system for Mount Fuji, which was introduced by the Japan Meteorological Agency (JMA) in December 2007. For wide area evacuation this plan makes reference to the *Guidelines for Determination of Specific and Practical Evacuation Plan at the Time of Eruption* (Committee on Promotion of Volcanic Disaster Prevention Measures 2012), but it is the responsibility of prefecture governments to refine their own plans and carry out the actual evacuation process if needed. Evacuees include general residents, residents needing assistance and tourists/climbers.

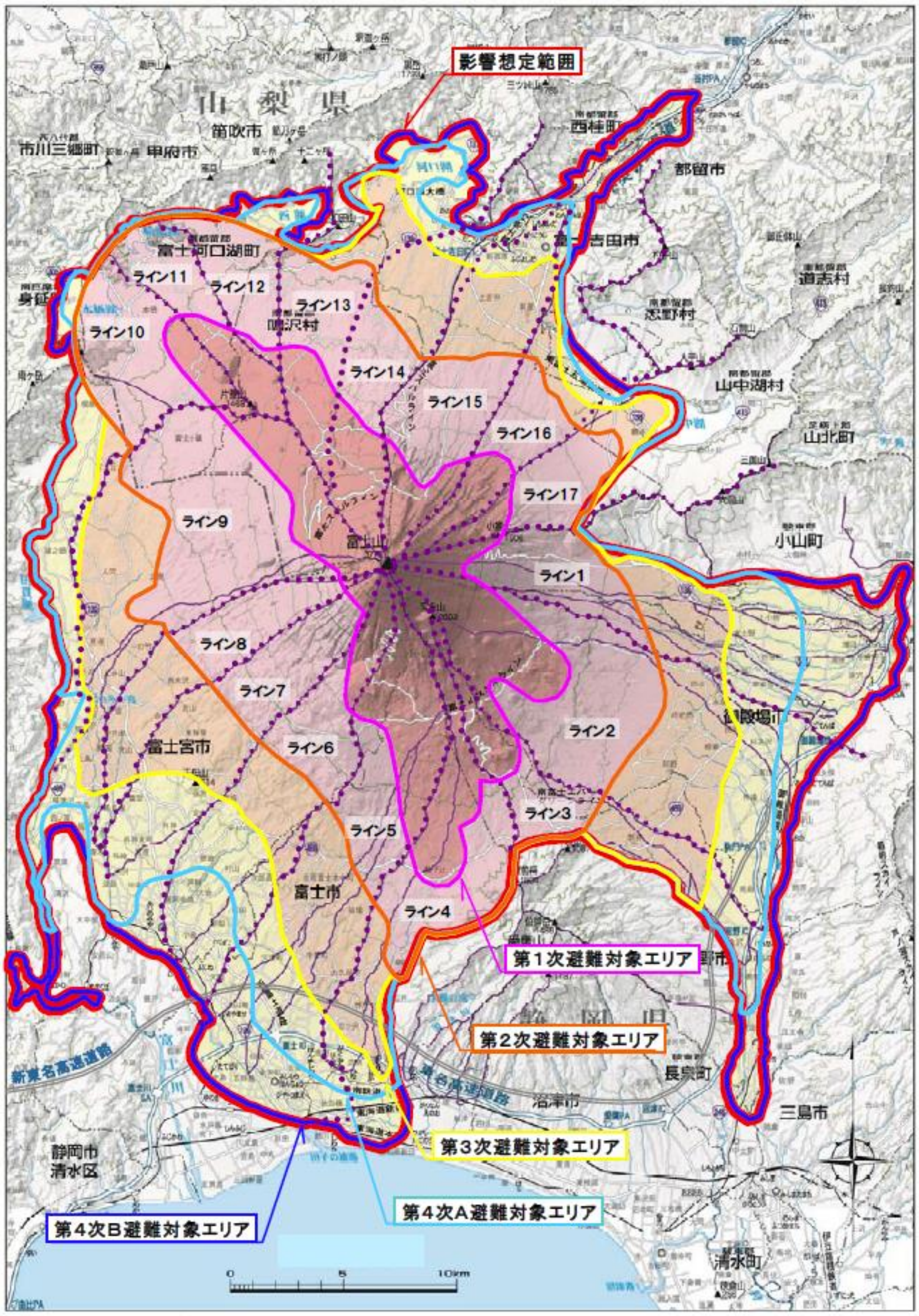
Evacuation timing and host destinations were determined by the nature and speed of eruption phenomena (Fuji Volcano Disaster Prevention Council, 2016). Most volcanic hazards can occur quickly and are a great danger to life; therefore residents at risk from these hazards need to be evacuated to a safe distance as quickly as possible, preferably before the eruption begins. For less hazardous phenomena such as ash fall, lava flow and small debris flows, the 2016 plan states that residents exposed to these hazards are to first move to safe places/structures within their city, at the onset of an eruption. When the hazard or number of evacuees exceeds the acceptable limit, residents will then be moved farther afield, outside the evacuation area, to other cities or villages in the same prefecture. There is also the potential that any volcanic hazard from a future eruption at Mount Fuji may require the evacuation of residents to a neighbouring prefecture. In this case the prefectures will cooperate with each other to ensure the safety of residents.

According to the plan, pre-eruption evacuation will be determined by eruption warning level announcements by the JMA (Fuji Volcano Disaster Prevention Council 2016). Eruption warning levels range from 1 to 5 (Japan Meteorological Agency 2018) (Table 4.1). Mount Fuji is currently at level 1 (potential for increased activity). Level 2 is designated when the location of an eruption is known and announced. However, for Mount Fuji the vent location of the next eruption is unknown, therefore when the volcanic system becomes increasingly active the eruption warning will go straight to level 3 (Fuji Volcano Disaster Prevention Council 2016). Level 5 occurs when an eruption is imminent and when residential areas are to evacuate. The plan noted that eruption warnings may not occur in order and whole levels can be skipped. It is also possible that an eruption may occur before warning levels are raised.

Table 4.1: Japanese volcanic alert levels and necessary responses for volcanoes where volcanic alert levels are applied. Modified from the Japan Meteorological Agency (*http://www.data.jma.go.jp/svd/vois/data/tokyo/STOCK/kaisetsu/English/level.html*).

Level	Action	Affected areas	Classification	Expected volcanic activity	Action taken by residents
5	Evacuate	Residential and non-residential areas nearer the crater	Emergency warning	Eruption or imminent eruption that may cause serious damage in residential areas and non-residential areas nearer the crater	Evacuate from the danger zone (target areas and evacuation measures are determined in line with current volcanic activity)
4	Prepare to evacuate			Possibility or increasing possibility of eruption that may cause serious damage in residential areas and non-residential areas nearer the crater	Prepare to evacuate from alert areas. Have disabled people evacuate (target areas and evacuation measures are determined in line with current volcanic activity)
3	Do not approach the volcano	Non-residential areas near the crater	Warning	Eruption or possibility of eruption that may severely affect places near residential areas (possible threat to life in such areas)	Stand by and pay attention to changes in volcanic activity. Have disabled people prepare to evacuation in line with current volcanic activity
2	Do not approach the crater	Around the crater		Eruption or possibility of eruption that may affect areas near the crater (possible threat to life in such areas)	No action required
1	Potential for increased activity	Inside the crater	Forecast	Calm: Possibility of volcanic ash emissions or other related phenomena in the crater (possible threat to life in the crater)	No action required

Areas to evacuate in the case of a Fuji eruption have been predetermined. These areas are located closest to the volcano and are therefore most at risk from hazards such as crater formation, pyroclastic flows, large ejecta and lava flows (Fuji Volcano Disaster Prevention Council 2016). The *Mt. Fuji Volcano Wide Evacuation Plan* integrated these hazards into one evacuation map due to the overlapping nature of the areas at risk from each hazard (Figure 4.2).



※この地図の作成に当たっては、国土地理院長の承認を得て、同院発行の20万分1 地勢図及び数値地図50mメッシュ（標高）を使用した。（承認番号　平25情使、第717号）

図 10　溶岩流等の影響想定範囲と避難対象エリア

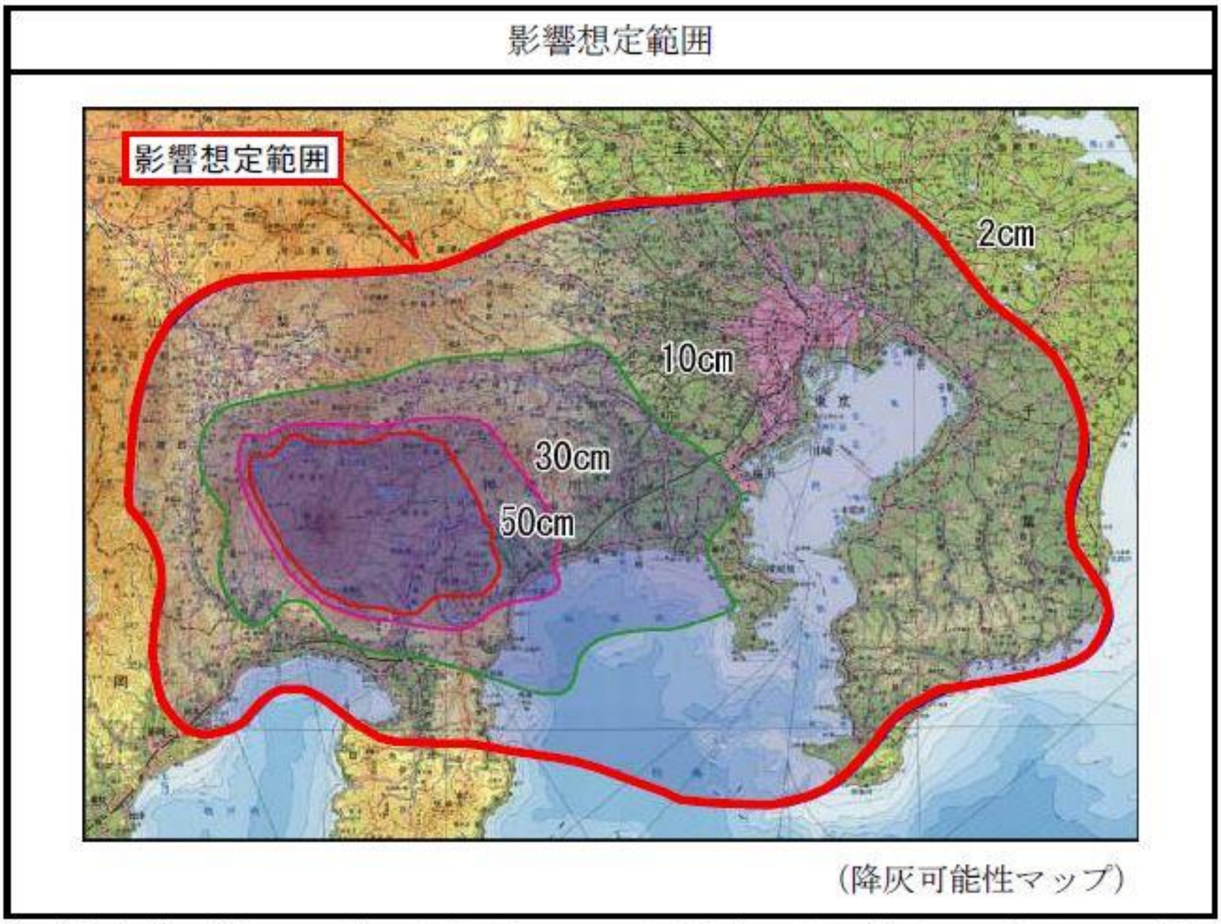
Figure 4.2: The Mt. Fuji Volcano Wide Evacuation Plan map of evacuation zones. The caption reads 'Assumed Range and Area to Evacuate'. The pink area represents evacuation zone 1, orange – zone 2, yellow – zone 3, light blue – zone 4A and dark blue zone 4B. The red represents the total evacuation area (Fuji Volcano Disaster Prevention Council 2016, page 25).

The 1st zone to evacuate is the area where the next crater is estimated to be formed (Table 4.2). Evacuation in this zone will commence before the onset of an eruption. The 2nd zone is the area where pyroclastic flows and large ejecta may impact, and where lava flows can reach within 3 hours. This zone is expected to be evacuated at the onset of the eruption. The 3rd, 4th A and 4th B zones are based on lava flow arrival times and will be evacuated after the onset of the eruption. Areas in these zones, outside the areas of immediate risk, are expected to wait for further advice from their municipalities, who will receive information from the JMA and other relevant agencies. Using this information, the individual municipalities and cities will decide when to evacuate, where to evacuate to, and the evacuation routes to use.

Table 4.2: Evacuation zones and corresponding eruption hazard. Derived from the Mt. Fuji Volcano Wide Evacuation Plan (Fuji Volcano Disaster Prevention Council 2016, page 24).

Target area for evacuation	Description of hazard
Evacuation zone 1	Assumed area for crater formation
Evacuation zone 2	Pyroclastic flows, large ejecta and potential lava flow extent within 3 hours of eruption onset
Evacuation zone 3	Lava flow extent – 3-24 hours
Evacuation zone 4A	Lava flow extent – 24 hours-7 days
Evacuation zone 4B	Lava flow extent – 7-40 days

The *Mt. Fuji Volcano Wide Evacuation Plan* states that ash fall depths of 30 cm or more can result in roof collapse and areas exposed to these conditions will need to evacuate. To identify areas with the potential to receive 30 cm or more of ash, the JMA constructed an ash fall possibility map using simulations of a Hoei scale eruption during each month of the year (Figure 4.3). At the onset of an eruption this map will be used as a guide for evacuation preparation while authorities await further information. The areas impacted by volcanic ash strongly depend on weather conditions, such as wind direction and speed at the time of eruption, and the duration and characteristics of the eruption itself. Therefore, the hazard from ash fall will be observed and monitored after the onset of the eruption by the JMA who will provide further advice. Areas that have the potential to receive over 30 cm of ash fall are to prepare to evacuate outside this hazard area, and areas to receive 2-30 cm are to move to suitable indoor locations (predetermined robust buildings) within their own municipalities.



※宝永規模の噴火の月別降灰分布図を 12 ヶ月分重ね合せた図（富士山ハザードマップ検討委員会報告書（平成 16 年）から引用）

Figure 4.3: Ash fall possibility map. Potential ash fall distribution and thicknesses for given eruptions simulated for wind conditions representing 12 months of the year (Fuji Volcano Disaster Prevention Council 2016, page 31).

A problem with this plan is the potential for communities, who may have to evacuate after the onset of an eruption, to become isolated if transportation routes are blocked by thick ash deposits. It is important to note here that roof collapse can occur at ash fall depths less than 30 cm, especially if wet, and I would recommend that this threshold is re-evaluated to be based on weight than depth of ash (Spence et al. 1996, Blong 2003, Magill et al. 2006, Blong et al. 2017). In assessing building damage after the 1994 Rabaul eruption in Papua New Guinea, Blong (2003) found that some structures experienced severe damage with ash fall loads as low as 100 to 200 mm. In addition the construction type of these structures should also be considered. The Fuji plan states that this threshold needs further examination and may be revised in the future. However, the threshold of 30 cm will continue to be used in this case for the purposes of this scenario as current plans specify this threshold.

On top of the potential severe consequences of ash fall, such as roof collapse and associated injury, this hazard also has the ability to impact areas far from source. Although ash fall deposits of less than 30 cm are not seen as an immediate threat to lives, there is still potential for thinner ash fall to impact the livelihoods of residents, for example, by affecting health (Hansell et al. 2006, Stewart et al. 2006, Damby et al. 2013, Baxter and Horwell 2015), destroying crops and impacting farming operations (Wilson et al. 2011, Magill et al. 2013, Craig et al. 2016). Moreover, small amounts of ash fall can impact the operation of critical lifeline services such as electricity infrastructure and roads, which could potentially hinder disaster response plans (Wilson et al. 2012, Wilson et al. 2014, Blake et al. 2017a, Wilson et al. 2017). In the case of a future eruption from Mount Fuji, the production of large amounts of ash fall is possible and the potential extent exceeds that of other volcanic phenomena, as outlined in the *Mt Fuji Volcano Wide Evacuation Plan* (Fuji Volcano Disaster Prevention Council 2016). This means that residents outside of the defined hazard zones could still be impacted by ash fall, and that evacuated residents could experience ash fall even after evacuation from immediately dangerous areas. We therefore need to ask to what extent volcanic ash could impact lifeline infrastructure and whether the effects of lifeline service failure would flow on to disaster response and recovery?

To help address these questions, Dr Tetsuya Okada and I undertook field visits to Yamanashi, Shizuoka and Kanagawa Prefectures, in July 2016. We conducted interviews with representatives from prefecture governments, research institutes and lifeline sectors to determine the current inclusion of lifeline disruption in mitigations plans for Mount Fuji. Representatives from Yamanashi Prefectural Office; Shizouka Prefectural Office; the Central Nippon Expressway Company (NEXCO); Railway Technical Research Institute; Hot Springs Research Institute of Kanagawa Prefecture; and the Mount Fuji Research Institute made themselves available to be interviewed and provided important information and context for this case study. Note that I do not have ethical clearance to name or identify individual interviewees here.

The interviews were set up via email and phone by Dr Tetsuya Okada before we travelled to Japan. The emails included the outline of my research project and some preliminary interview topics (a list of the topics and broad questions can be found in supplementary material 4.7.1) and were translated into Japanese. The interviews were semi-structured to open in nature, as, although I had specific questions, I wanted it to be open so that the interviewees could discuss topics they felt were important. This was a discovery assignment to determine the direction of my research. During the interviews in Japan Dr Okada translated between the interviewees and myself. Dr Okada's and my notes were collated on return to Macquarie University and put into NVivo, a qualitative data analysis computer software package (© QSR International Pty Ltd. https://www.qsrinternational.com/nvivo/home). This program was used to 'code' (select and organise) the interviews and pull out important themes.

From the interviews it was determined that road and rail infrastructure are expected to be impacted by a future 1707 type eruption of Mount Fuji. Both prefecture governments and lifeline sectors stated the importance of roads, especially expressways, and were concerned about the potential loss of road transportation. Throughout interviews it was noted that roads are vital for freight, evacuation and access to other lifeline infrastructure such as train lines. Road infrastructure would therefore require priority for ash fall removal due to the need for its continual operation.

In comparison, rail infrastructure would not only have to wait for the cessation of an eruption but also the recovery of other lifeline services such as electricity, water and road transportation before ash fall clean-up and maintenance could begin (Pers. Comm. Railway Technical Research Institute). There was a readiness from the expressway sector to learn more about ash fall impacts. Overall there was a collective interest in the impacts of ash fall on road-based evacuation, and ash fall removal and clean up. Due to these observations, it was decided that this thesis chapter would concentrate on road infrastructure and the impacts of volcanic ash on road usage in the case of a future eruption from Mount Fuji.

4.3.3 Vulnerability of road transportation to volcanic ash

The impact of volcanic ash on road transportation has been documented during past eruptions such as Mount St Helens (1980), Pinatubo (1991), Sakurajima (1955 onwards), Pacaya (2010) and Shinmoedake (2011) (Schuster 1983, Blong 1984, Nairn 2002, Wilson et al. 2012, Magill et al. 2013, Wilson et al. 2014, Hayes et al. 2015). Falling or remobilised ash has been found to significantly reduce driver visibility, and ash fall thicknesses of less than 1 mm can obscure road markings (Figure 4.4) (Wilson et al. 2014, Blake et al. 2016, Blake et al. 2017a, Wilson et al. 2017). Fine ash can make road surfaces slippery, especially when wet, can abrade vehicle components and clog air and oil filters (Wilson et al. 2012, Wilson et al. 2014). General ash fall accumulation thresholds for road and other infrastructure vital for evacuation and community recovery are displayed in Table 4.3.

Figure 4.4: Ash on roads during the 2011 Shinmoedake eruption. Photos by Dr Christina Magill and Dr Tetsuya Okada.

Road infrastructure is a fundamental component of modern society, supporting the mobility of people and the distribution of goods and services. The disruption of road networks during a disaster can result in the isolation of populations and can hinder evacuation and rescue operations. After a disaster, road closures can dramatically increase travel times, disrupt supply chains and hamper recovery efforts such as stopping access needed to repair and maintain other critical infrastructure. The 2016 Kaikōura earthquake in New Zealand, and subsequent landslides, caused road closures to the north and south of Kaikōura Township, completely isolating the community (GNS Science 2016, Kaiser et al. 2017). This region strongly relies on road transportation for tourism and the movement of people and freight. In rural locations the loss of road access made travelling to school, doctors and vets challenging (Meduna 2017). In preparation for understanding the true impacts of future natural hazard events on economies and societies we need to better understand the vulnerabilities of transportation systems and to identify vulnerable populations that rely on their operation. In the case of a future eruption from Mount Fuji, the most important need for roads is in the evacuation of residents at close proximity to the volcano.

Table 4.3: Proposed ash fall accumulation thresholds with expected disruption and damage to road and other infrastructure, which have the potential to impact evacuation and recovery. Aggregated from various literature (GNS Science 2012, Wilson et al. 2014, Hasegawa et al. 2015, Blake et al. 2016, Fuji Volcano Disaster Prevention Council 2016, U.S. Geological Survey 2017, Wilson et al. 2017).

Threshold depth (mm)	Direct damage to roads	Indirect disruption to roads
<1	- Minor damage to vehicles - Remobilised ash has minor impact on visibility - Loss of vehicle traction, especially when ash is wet - Obstruction of road markings	
1-10	- Remobilised ash has major impact on visibility - Extensive closure of roads due to ash build up and clean-up operations - Ash removal vehicles typically cannot operate at thicknesses of ≥ 5 mm if raining	- Power outages from electrical flashover, potential to impact water pumps for clean-up operations - Roads need to be cleared of ash to prevent storm-water systems being clogged, potential for flooding if rains
10-100	- Major ash removal needed in urban areas - Roads impassable when ash is wet - Potential damage to bridge structures - Ash removal vehicles cannot operate at thicknesses of ≥ 50 mm	
100-300	- Complete road burial - Roads impassable if ash is unconsolidated	- Damage to trees, fallen trees could block roads or down power lines
>300	- Roads completely unusable	- Collapse of most roads - Damage to powerlines and telephone poles - Extensive infrastructure damage

As previously discussed, the *Mt. Fuji Volcano Wide Evacuation Plan* currently addresses volcanic ash fall hazard separately from other volcanic hazards such as lava flow, pyroclastic flow, and crater formation. Evacuation is set to occur where ash fall may accumulate to 30 cm or greater; but also of concern is thinner ash fall deposits that could hinder the evacuation of those in danger from other volcanic hazards, such as lava flows. The *Mt. Fuji Volcano Wide Evacuation Plan* is currently a broad evacuation plan and work is to be continued by individual cities and towns to finalise evacuation methods, routes and conduct evacuation drills. At the time of our interviews, Yamanashi and Shizuoka Prefectures had not yet addressed the potential impacts of ash fall on roads nor ash fall clean up; however, both aspects were of interest to the prefecture governments and they were noted as concerns for future research. This chapter hopes to close this gap by assessing the impact of ash induced road closures on current evacuation plans and event recovery, and providing methods to further explore lifeline failure in a disaster. This chapter will look at the impact of ash fall on roads in Yamanashi Prefecture only. However, information from all interviewed parties will be taken on board and used throughout to help place the results of the case study in context.

The next section of this chapter outlines the methodologies used to: create and model a future 1707 eruption scenario; quantify the impact of volcanic ash on Yamanashi Prefecture roads; determine the potential impact of road closures on the current *Mt. Fuji Volcanic Wide Evacuation Plan* for Yamanashi Prefecture; and assess the extent of ash fall clean-up. The results section is split into two parts: Part One looks at ash fall accumulation in the first few hours of the eruption to assess the impact of ash induced road closures on evacuation, and Part Two looks at the entire ash fall accumulation of a Hoei type eruption to assess the impact of road closures on recovery after the eruption and looks at road prioritisation for ash fall clean-up. This chapter then concludes with a discussion on the methods and findings used.

4.4 Methodology

4.4.1 Mount Fuji eruption scenario

4.4.1.1 1707 Hoei eruption timeline

Mount Fuji is the largest volcano edifice in Japan and was chosen for this scenario due to its violent potential and close proximity to urban environments and lifeline infrastructure. The 1707 Hoei eruption was one of the most violent the volcano has produced, sending ash fall as far as central Tokyo, ~100 km east of the volcano (Shimozuru 1983, Miyaji 2002, Miyaji et al. 2011). The eruption lasted 16 days, beginning the morning of 16 December 1707 and ceasing on 1 January 1708, (Miyaji 2002, Miyaji et al. 2011). The eruption produced a total mass of ~1.8×10^{12} kg of eruptive material, which, due to pauses and fluctuations of the eruption column, was deposited in a series of layers (Miyaji et al. 2011). Based on varying characteristics of the eruption, Miyaji et al. (2011) divided the eruption into three stages, seven eruptive pulses and 17 deposition units (Table 4.4).

The stages were characterised by (Miyaji et al. 2011) as:

- Stage 1: Quick eruption of two energetic pulses (pulse 1 (units A and B) and 2 (units C-I)), each starting with an intense outburst then decreasing in intensity, producing a plinian eruption column that reached an estimated 20 km.

- Stage 2: A number of discrete sub-plinian eruptive pulses (Pulses 3-6 (units J-L)).
- Stage 3: Sustained eruption activity producing a column of up to 16 km (Pulse 7 (units M-Q)).

The eruption sequence shows an initial rupture of dacite and andesite magma chambers followed by the withdrawal of basaltic magma supply from a greater depth (Miyaji et al. 2011).

Table 4.4: Eruptive units of the Hoei eruption described by Miyaji et al. (2011).

Unit	**Description**	**Date (Dec 1707)**	**Time (HH:MM)**	**Pulse**	**Group**	**Stage**
A	Very coarse pumice single layer	16	10:00	1	Ho-I	1
B	Very coarse pumice single later	16	11:30			
Repose		16	15:30			
C	Very Coarse single layer	16	17:00	2	Ho-II	
D	Fine thin alteration	17	01:00			
EF	Coarse thick single layer, lithic-rich	17	06:00			
G	Fine thin alteration	17	21:30		Ho-III	
H	Fine to medium thick alteration	18	13:00			
I	Medium thick alteration	19	06:30			
Repose		19	22:30			
J	Fine to medium thick alteration	20	15:30	3-4		2
Repose		21	07:00			
J	Fine to medium thick alteration	21	21:30			
Repose		21	22:30			
K	Medium thick alteration	22	20:00	5		
Repose		23	04:30			
L	Medium to fine thick alteration	23	19:30	6		
Repose		24	04:30			
M	Fine thin single layer	25	12:30	7		3
N	Medium thick alteration	25	20:30		Ho-IV	
O	Fine thick alteration	26	01:00			
P	Medium thick alteration	27	10:30			
Q	Fine thick alteration	27	22:00			
End		30	07:00			

Note, tephra is the collective term used for the fragmented material produced in an eruption, which includes clasts from greater than 64 mm (blocks/bombs) to less than 2 mm (ash). However, in this chapter, I refer to all material as volcanic ash as this is the size fraction which typically falls at the distances of interest to this study.

4.4.1.2 Ash fall scenario of a future Hoei type eruption

This scenario explores the impact that another Hoei type eruption would have today. In particular, the impact of ash fall on road infrastructure and how that would affect current evacuation plans and post event recovery. To understand how ash fall induced road closures could impact both emergency response and recovery, the eruption scenario is divided into two parts.

Part One of the eruption scenario will replicate the deposition of ash fall from unit A of the first pulse of stage 1 of the 1707 eruption, as described by Miyaji et al. (2011). Unit A lasted 1.5 hours, producing approximately 5.7 x 10^{10} kg of material with an eruption column height reaching over 20 km (Miyaji et al. 2011). The first part of this scenario is used as a representative illustration of the potential conditions that residents could face if they evacuate soon after the onset of the eruption. Yamanashi residents in evacuation zones 1 will evacuate before the onset of an eruption, if possible, therefore this part of the scenario does not apply to them (see Table 4.2 and Figure 4.2) (Fuji Volcano Disaster Prevention Council 2016). Evacuation zones 3-4B are based on estimates of lava flow times, ranging from 3 hours to 40 days to reach particular locations. Evacuation in these areas will be based on further advice from their municipalities, who will receive information from the JMA and other relevant agencies. Therefore residents in zones 3-4B will have time and resources to determine when to evacuate, where to evacuate to, and the evacuation routes to use. Residents in evacuation zone 2, on the other hand, are set to evacuate at the onset of an eruption, likely with minimal information on the eruption behaviour. Of concern is that these residents may encounter ash fall during evacuation, which may hinder transportation to evacuation centres. Large amounts of ash fall can deposit quickly, as unit A shows, and could potentially create dangerous driving conditions and block transportation routes. Further eruptive phases (units B-Q) will not be looked at separately in this study, therefore, the evacuation conditions beyond 1.5 hours after the onset of the eruption is not being assessed here.

Part Two of the ash fall scenario looks the total ash fall accumulation for the 1707 eruption sequence (units A-Q). The combined ash fall accumulation of all Hoei eruptive units is used to anticipate the conditions Yamanashi Prefecture could face after the cessation of a Hoei type eruption. This phase explores the potential impact of ash fall on evacuated locations and host centres, and considers road access for the return of evacuated residents. This part assumes that no clean-up of ash occurred during the 16 days of the eruption, nor that there was any erosion from rainfall.

The vent location of a future eruption at Mount Fuji is unknown. This scenario uses the same vent location (Hoei craters) and wind conditions (westerly) of the 1707 eruption. Westerly is the predominant wind direction for this area (Kalnay et al. 1996); however, conditions can change seasonally (shifting to the northwest – and even easterly at higher latitudes – in spring and summer), and are also possible during the duration of an eruption. Although different wind conditions are not addressed in this study, it is important to keep this in mind for further hazard and risk assessments. This is where probabilistic modelling, which would include all potential wind conditions, would complement this scenario.

For Part One and Two of this scenario ash fall thickness thresholds of 0.2, 1, 10, 100 and 300 mm, needed to disrupt road and other critical infrastructure (Table 4.3), are used to determine the impact to road usability.

4.4.1.3 Ash fall dispersal modelling

This study uses simulations of the 1707 eruption modelled by Magill et al. (2015). Ash fall of the 1707 eruption was modelled using *Tephra2*, an analytical tephra advection-diffusion model (Bonadonna et al. 2005, Connor and Connor 2006). *Tephra2* calculates particle diffusion, transport and sedimentation to estimate ash fall accumulation at specific locations around a volcano (Bonadonna et al. 2005). Magill et al. (2015) used inversion techniques and high-resolution data describing the 17 units of the eruption by Miyaji et al. (2011) to replicate the physical parameters of the eruption. The ash fall threshold isopachs used in this chapter are derived from Magill et al. (2015) model outputs for unit A and for the total 1707 eruption ash fall.

Simulated results were used rather than published isopachs by Miyaji et al. (2011) as these maps only captured ash fall of 1 cm or greater and did not provide the thresholds relevant for this study, including ash fall thicknesses < 1 mm. Modelling by Magill et al. (2015) also provided information for areas where geological data were lacking. Magill et al. (2015) used a 1 km resolution grid over the whole ash dispersal area to calculate ash loads (kg/m^2) for each eruptive phase. These loads were converted to threshold thickness (mm) isopachs using GMT code for the purposes of this study by assuming a deposit density of 1,000 kg/m^3.

4.4.2 Road network analysis

4.4.2.1 Road data, formatting and visualisation

Road data (in the form of polylines) for Yamanashi Prefecture were downloaded from

OpenStreetMap and formatted and visualised in ArcGIS Desktop 10.5 (© 1999-2016 Esri Inc.) (Figure 4.5).

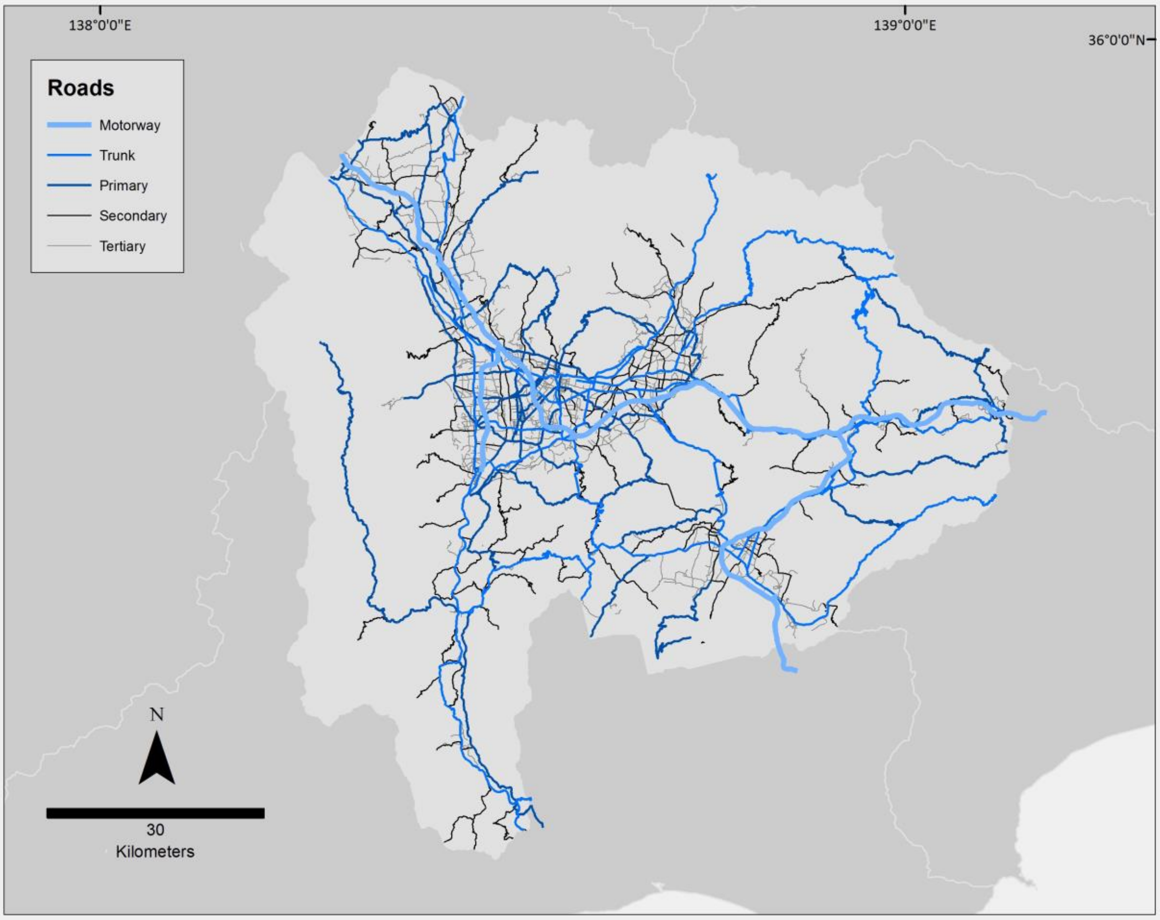


Figure 4.5: Yamanashi Prefecture roads.

All roads were assumed to be unidirectional; therefore, duplicate road lanes were deleted to form single edges and to avoid loops. The raw polylines were segmented at random nodes, with one road being cut into many parts. To turn these lines into graphable vertex and edge data all polyline segments for individual roads were combined and then divided only at junctions with other roads (intersections). Where road segments over passed other roads, such as motorway overpasses, junctions were not formed. Tunnels were not identified and it was assumed that all roads are exposed. Road segments and junctions were then transformed into edge and vertex lists and imported into Mathematica 10.1 (© 2015 Wolfram Research, Inc., https://www.wolfram.com/mathematica/), where the extent of network disruption was analysed using graph theory-based algorithms (Figure 4.6) (see chapter 3 for more information on this process).

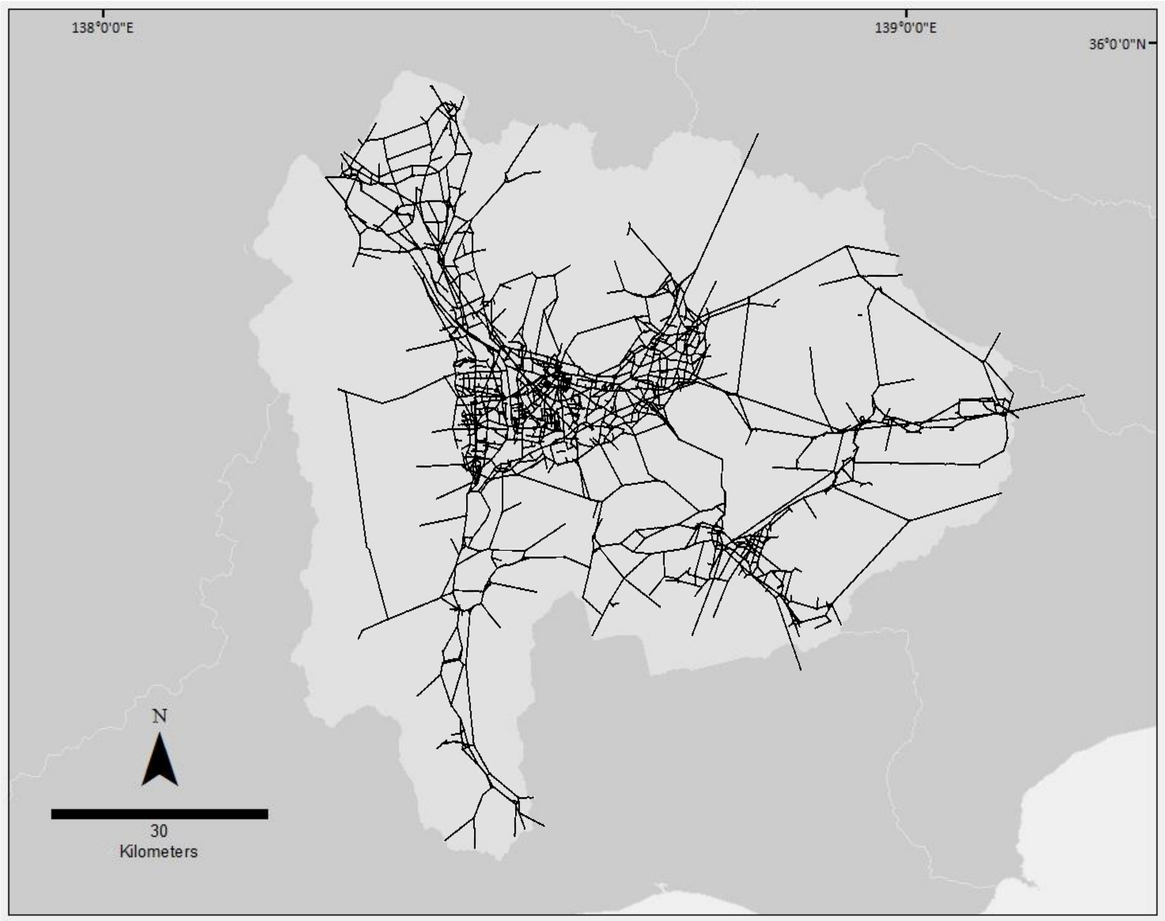


Figure 4.6: Graph representation of the Yamanashi road network.

4.4.2.2 Evacuation centres and routes

Evacuation plans for Yamanashi Prefecture are primarily based on lava and pyroclastic flow hazards and currently there is one evacuation plan for all Mount Fuji eruption scenarios, whether effusive or explosive (Fuji Volcano Disaster Prevention Council 2016). Six cities in Yamanashi Prefecture: Fujiyoshida-shi, Nishikatsura-cho, Oshino-mura, Yamanakako-mura, Narusawa-mura and Fujikawaguchiko-machi, have been determined to be most at threat to lava and pyroclastic flow hazards and residents have been allocated evacuation destinations in host cities to the northern boundary of the Prefecture if full evacuation is needed (Pers. Comm. Yamanashi Prefecture Government) (Figure 4.7). Evacuation zone 2 (Figure 4.2), of interest to this study, incorporates all of these six cities.

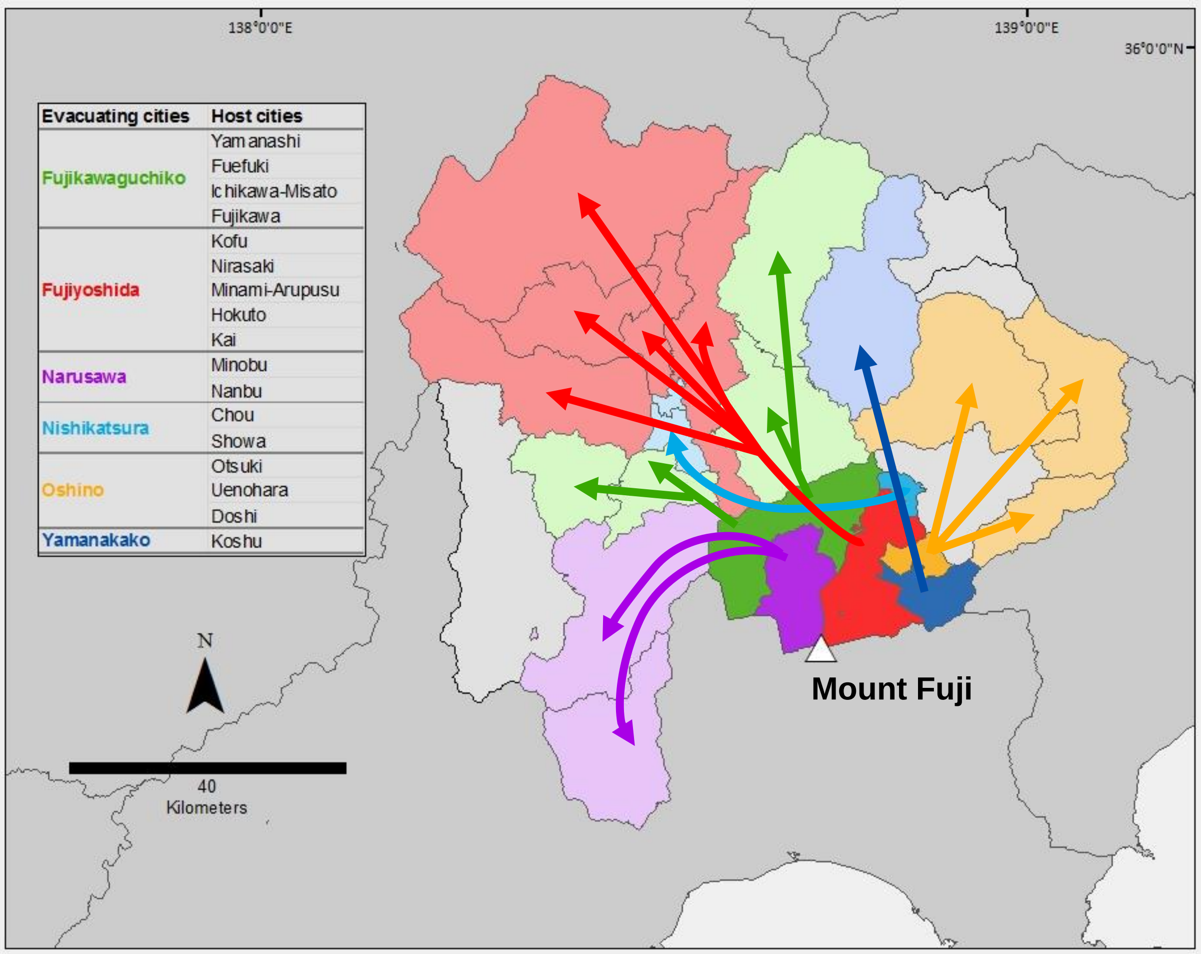


Figure 4.7: Mt. Fuji wide evacuation plan for Yamanashi Prefecture (Pers. Comm. Yamanashi Prefecture Government.) with the cities to be evacuated and their respective host cities highlighted. White triangle marks the location of Mount Fuji. Legend lists the six evacuating cities and associated host cities.

During interviews with the Yamanashi Prefecture Government it was stated that residents are likely to use their own motor vehicles to evacuate, except for the sick and elderly. This study considers the evacuation of general residents only, not those needing special assistance nor tourists. Residents are to evacuate to predetermined evacuation centres, first within their own municipality (outside area of risk) where they will receive further information and direction, then, if necessary, to centres in assigned host cities further afield (Fuji Volcano Disaster Prevention Council 2016). This chapter will focus on road usage between the initial evacuation locations inside the six evacuating municipalities/cities and evacuation centres in the predetermined host cities outside of the evacuation zone. This study also only considers evacuation within Yamanashi Prefecture and not between Yamanashi and other prefectural areas.

For each city involved in Yamanashi Prefecture's evacuation plan (Figure 4.7), evacuation points, in both evacuating and host cities – such as schools and town halls, were obtained from city websites (Table 4.5). The coordinates of these locations were acquired from Google Maps and imported into ArcGIS (Figure 4.8). A full list of evacuation centres can be found in the supplementary material section (section 4.7).

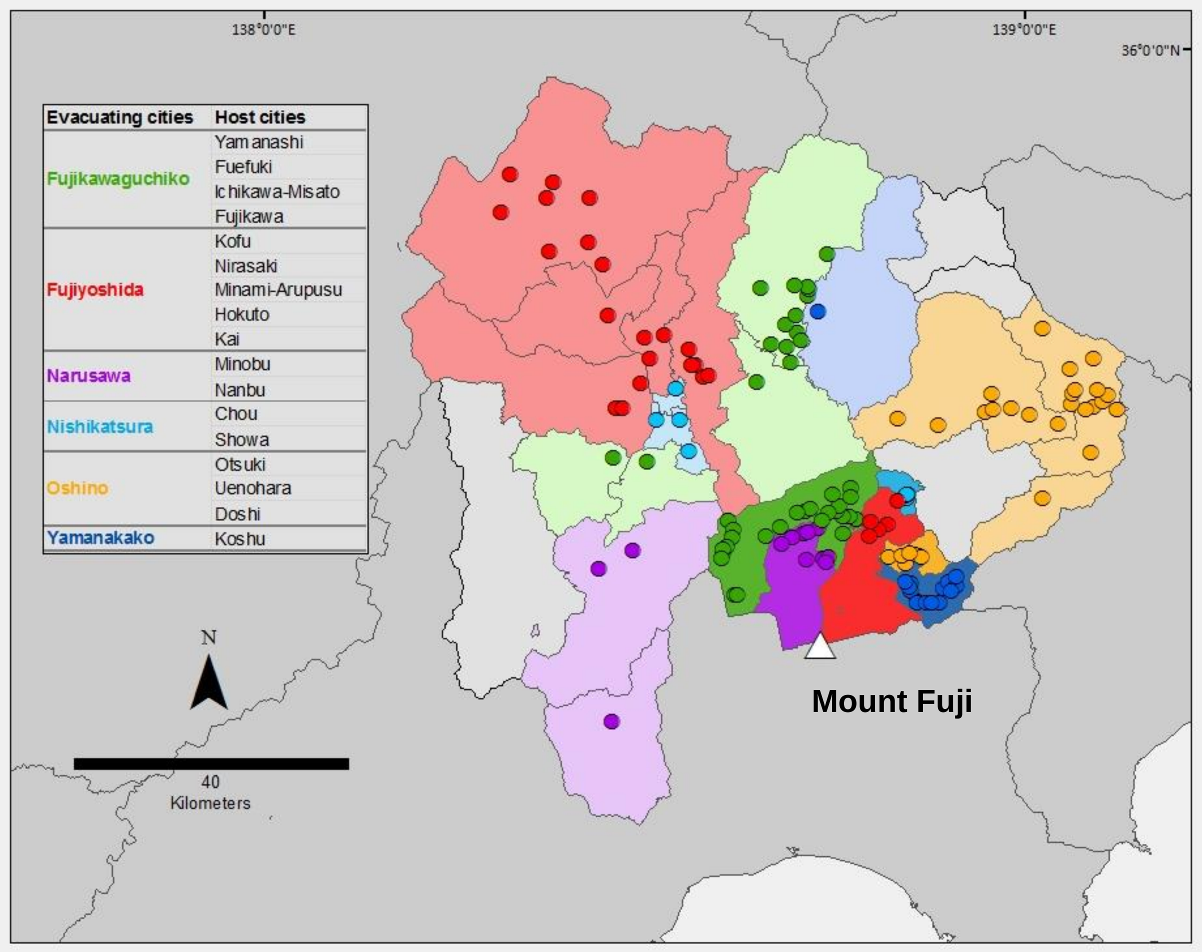


Figure 4.8: Location of evacuation centres in evacuating and host cities involved in Yamanashi Prefecture's evacuation plan for Mount Fuji. Legend lists the six evacuating cities and associated host cities.

These evacuation centres were used as 'to' and 'from' locations to determine the shortest paths for evacuation and resident return after the eruption. The shortest path is the path between two vertices involving the least number of edges (see chapter 2 for further explanation). This is similar to the methods used in recent studies using network analysis to determine evacuation routes (Ashar et al. 2018, Trindale et al. 2018). These studies used GIS-based network analysis and Tsunami hazards maps to determine optimal evacuation paths and potential evacuation centre locations. Where this chapter builds on this work is by considering the impact of roadblocks in evacuation efficiency, rather than simply calculating shortest paths. This chapter also explores how network analysis can be used to better inform recovery and clean-up decisions.

Some cities that may require evacuation already have predetermined partnerships to specific host evacuation centres, however, this information was not available for this study. Therefore, paths between all centres within an evacuee and host partnership were analysed. To calculate the shortest paths, each evacuation centre was allocated a nearest vertex (intersection) in the road network graph (Figure 4.6). Where evacuation centres shared the same vertex the centres were merged into one. Shortest paths between evacuating and host evacuation centres were calculated and then re-calculated, after various road closure scenarios, to determine impacts both on evacuation and resident return.

Table 4.5: Source websites used to obtain evacuation centre locations in Yamanashi Prefecture.

	City	**Source**
Evacuating cities	Fujiyoshida	http://www.city.fujiyoshida.yamanashi.jp
	Nishikatsura	https://www.town.nishikatsura.yamanashi.jp
	Oshino	http://www.vill.oshino.lg.jp
	Yamanakako	http://www.vill.yamanakako.lg.jp
	Narusawa	http://www.vill.narusawa.yamanashi.jp/
	Fujikawaguchiko	https://www.town.fujikawaguchiko.lg.jp
Host cities	Kofu	http://www.city.kofu.yamanashi.jp
	Nirasaki	https://www.city.nirasaki.lg.jp
	Minami-Arupusu	http://www.city.minami-alps.yamanashi.jp
	Hokuto	https://www.city.hokuto.yamanashi.jp
	Kai	http://www.city.kai.yamanashi.jp
	Chuo	http://www.city.chuo.yamanashi.jp
	Showa	http://www.town.showa.yamanashi.jp
	Otsuki	http://www.city.otsuki.yamanashi.jp
	Uenohara	https://www.city.uenohara.yamanashi.jp
	Doshi	http://www.vill.doshi.lg.jp
	Koshu	http://www.city.koshu.yamanashi.jp
	Minobu	https://www.town.minobu.lg.jp
	Nanbu	http://www.town.nanbu.yamanashi.jp
	Yamanashi	https://www.city.yamanashi.yamanashi.jp
	Fuefuki	http://www.city.fuefuki.yamanashi.jp
	Ichikawa-Misato	http://www.town.ichikawamisato.yamanashi.jp
	Fujikawa	http://www.town.fujikawa.yamanashi.jp

Different ash fall thicknesses can cause a range of disruption or damage to road infrastructure, vehicles and drivers, from obscured road markings at less than 1 mm to complete burial over at 100 mm (see Table 4.3). It is not the aim of this study to state a definitive ash fall threshold where road transport is no longer viable, especially in an emergency situation where normal cautions might be ignored. It is up to the prefecture governments and emergency services to determine what conditions are deemed safe for vehicle evacuation. The aim of this study is to explore the impact of road closures at a various thicknesses to understand the potential disruption for a number of road closure cases.

Road closures were calculated for each ash fall threshold thickness: 0.2, 1, 10, 100 and 300 mm, for both Part One (unit A) considering evacuation, and Part Two (all combined units) for consideration of resident return. These threshold extents were derived from the modelled ash fall loads simulated by Magill et al. (2015). Isopachs of each ash fall threshold were overlaid onto the road data to determine the exposure of roads. All road segments and intersections that coincided with the ash fall threshold footprint of interest were deemed unusable and therefore deleted from the road network. Shortest paths between evacuating and host evacuation centres were then re-calculated to determine impacts both on evacuation and resident return, including complete loss of access and long detours.

4.4.3 Ash fall clean-up

The next aim of this study was to determine the total amount of ash fall accumulation on Yamanashi roads, how long this might take to clean up and test methods for clean-up prioritisation.

4.4.3.1 Clean-up initiation threshold

Road infrastructure can be impacted by less than 1 mm of ash fall (GNS Science 2012, Wilson et al. 2014, Hasegawa et al. 2015, Blake et al. 2016, U.S. Geological Survey 2017, Wilson et al. 2017) (see Table 4.1). In fact road markings can be obscured by as little as 0.2-0.8 mm (Blake et al. 2016). In this study the loss of road markings is used as the driver for the initiation of clean-up operations due to the impact that the obstruction of markings can have on road safety. To determine the minimum ash fall threshold needed to obscure road markings I used the recent research by Blake et al. (2016), who assessed threshold ash fall thicknesses needed to cover road markings, using various ash compositions and road characteristics. Using their outputs along with the 1707 eruption ash fall characteristics described by Miyaji et al. (2011) a minimum ash fall threshold of 0.2 mm was determined to obscure markings. This threshold was used to calculate the road length and area that would need to be cleaned today following an eruption with the characteristics of that in 1707. It is unknown whether roads would be completely closed at this threshold thickness but road access at this time might be limited while ash fall clean-up occurs.

4.4.3.2 Clean-up volume

Different parts of the road network are owned and operated by various sectors such as private expressway companies, prefecture government and city councils. Representatives from NEXCO stated that they would endeavour to keep motorways clear of ash throughout any future eruption in order to keep the route clear for the movement of goods and people (Pers. Comm. NEXCO). However, despite this intention, it is necessary to determine whether the rate of ash fall accumulation throughout the eruption could be meet by NEXCO’s clean-up capacity in order to continuously keep roads clear. Yamanashi and Shizuoka Prefectures stated that ash fall clean-up on prefecture and local roads would not commence until ash fall abated, to avoid potential hazards and the risk of injury. Because the majority of roads of interest in this study are managed by prefecture and local governments, I have assumed that any ash fall clean-up on roads does not begin until the eruption has ended. The total amount of ash fall accumulation on roads was calculated using gridded load information calculated by Magill (2015) and converted to thickness by assuming 1 kg/m^2 of ash fall accumulation equals 1 mm ash fall thickness (Figure 4.9). The outlines of each 1 km^2 grid cell were used to split the roads into associated segments. Isopachs were extended outside the modelled area and thicknesses interpolated to include all road sections of interest in this study. Each road segment corresponding to a modelled cell was then assigned the ash fall thickness for that particular cell (Figure 4.10). This thickness was multiplied by the road segment area to get the total ash fall volume. The road area was calculated by multiplying the road length with road width. Road lengths were calculated in ArcGIS and road widths were calculated by multiplying the number of lanes by lane width (Table 4.6). Road widths were calculated with the assumption that motorways and trunk roads have 4 lanes and all other road types have 2 lanes (through google map satellite search). Each lane is roughly 3 m in width (using data from Japan Road Bureau 2015). Any centre road medians have been ignored and were not counted in clean up calculations.

Table 4.6: Approximate road widths.

Road type	No. of lanes	Road width m (*1 lane = 3 m)	Ownership
Motorway	4	12	Nexco Central
Trunk	4	12	Yamanashi Prefecture
Primary	2	6	Yamanashi Prefecture
Secondary	2	6	Yamanashi Prefecture
Tertiary	2	6	Yamanashi Prefecture

* Road width = No. of lanes × 3. The average lane width is 3 m (Japan Road Bureau 2015).

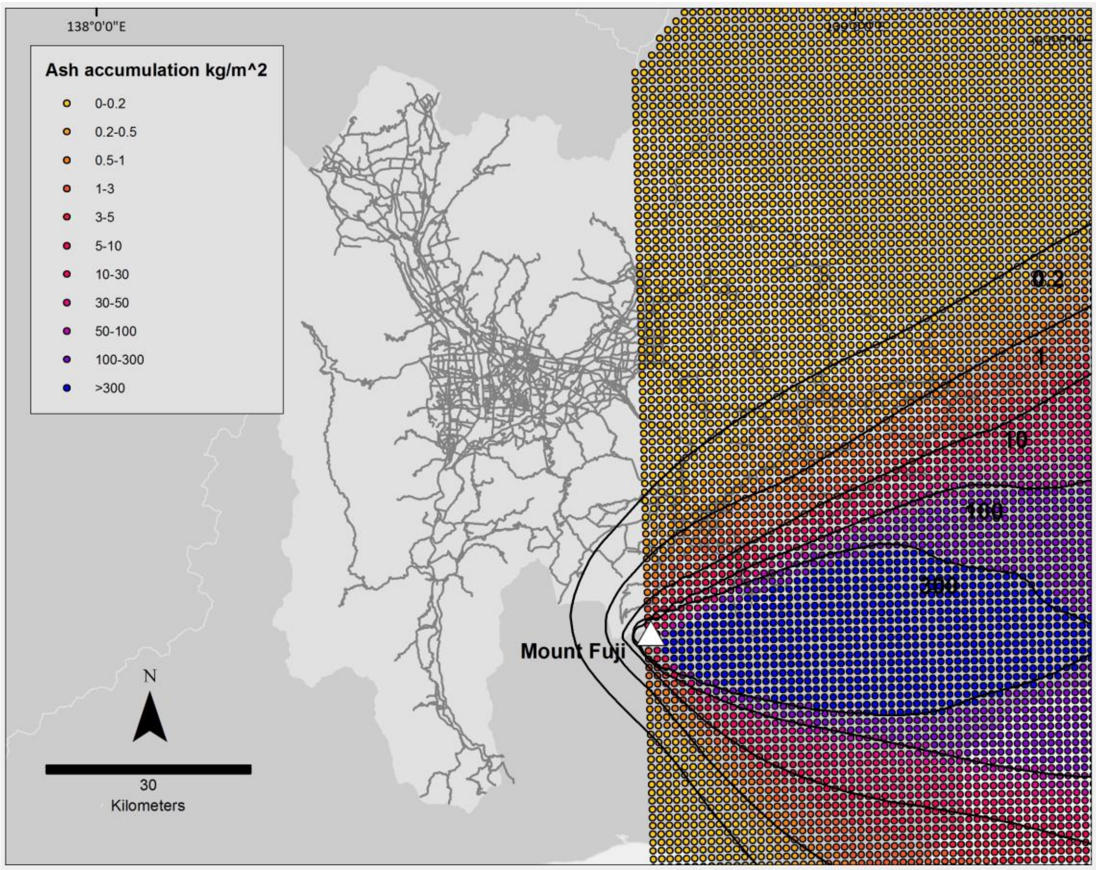


Figure 4.9: Simulated gridded ash fall accumulation load (kg/m^2) and isopachs of the Hoei eruption modelled by Magill et al. (2015) overlayed onto Yamanashi Prefecture roads.

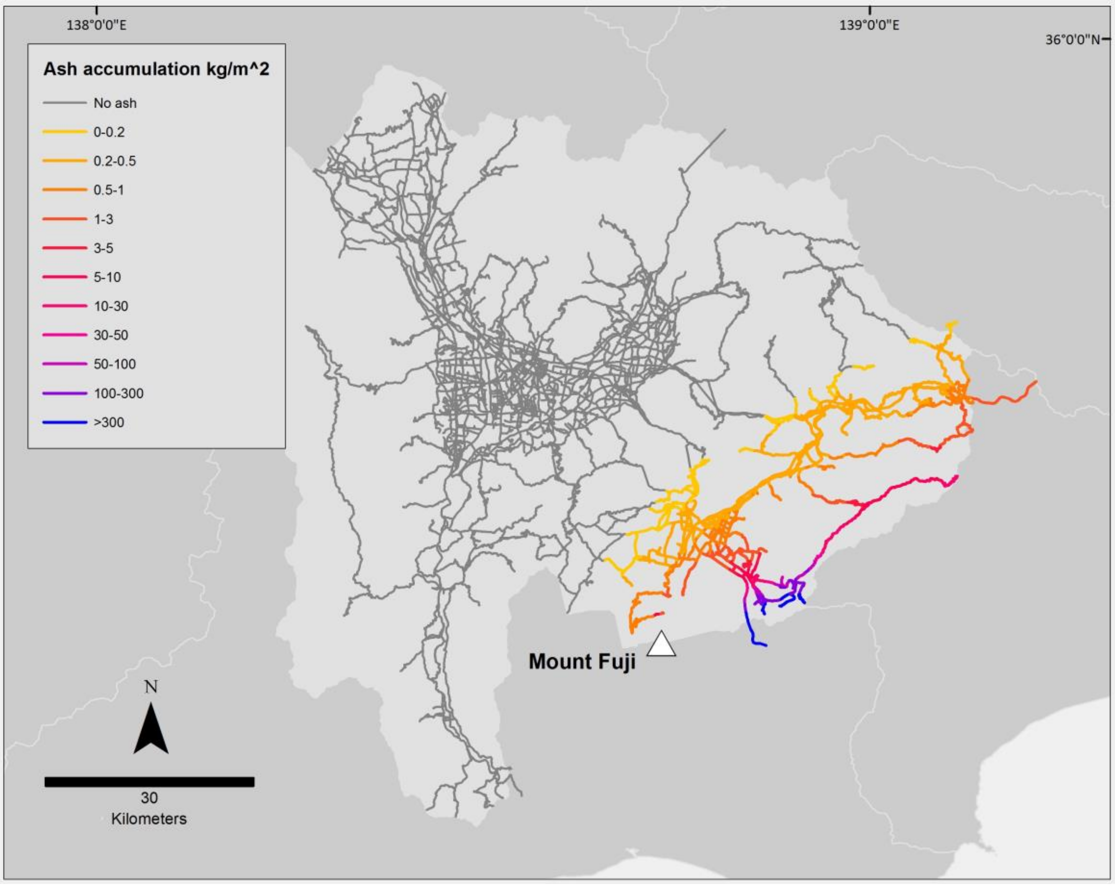


Figure 4.10: Exposure of roads to modelled ash fall accumulation loads (kg/m^2) of the Hoei eruption using data from Magill et al. (2015). Cooler colours indicating higher ash loads.

4.4.3.3 Clean-up prioritisation

Road prioritisation for clean-up has not yet been addressed by Yamanashi Prefecture Government. Graph theory measures such as betweenness centrality can be used to determine important components of a network and are explored here to provide a method for assigning clean-up optimisation. Betweenness centrality scores equate to the number of times an edge (road) is used in a shortest path between two vertices (intersections). Edge (road) betweenness centralities were calculated using the shortest paths from all vertices to all vertices (intersections) (vertex betweenness explained in chapter 3). Figure 4.11 shows the resulting betweenness scores for the whole Yamanashi Prefecture road network. This measure was used to determine clean-up priorities for impacted roads in this scenario.

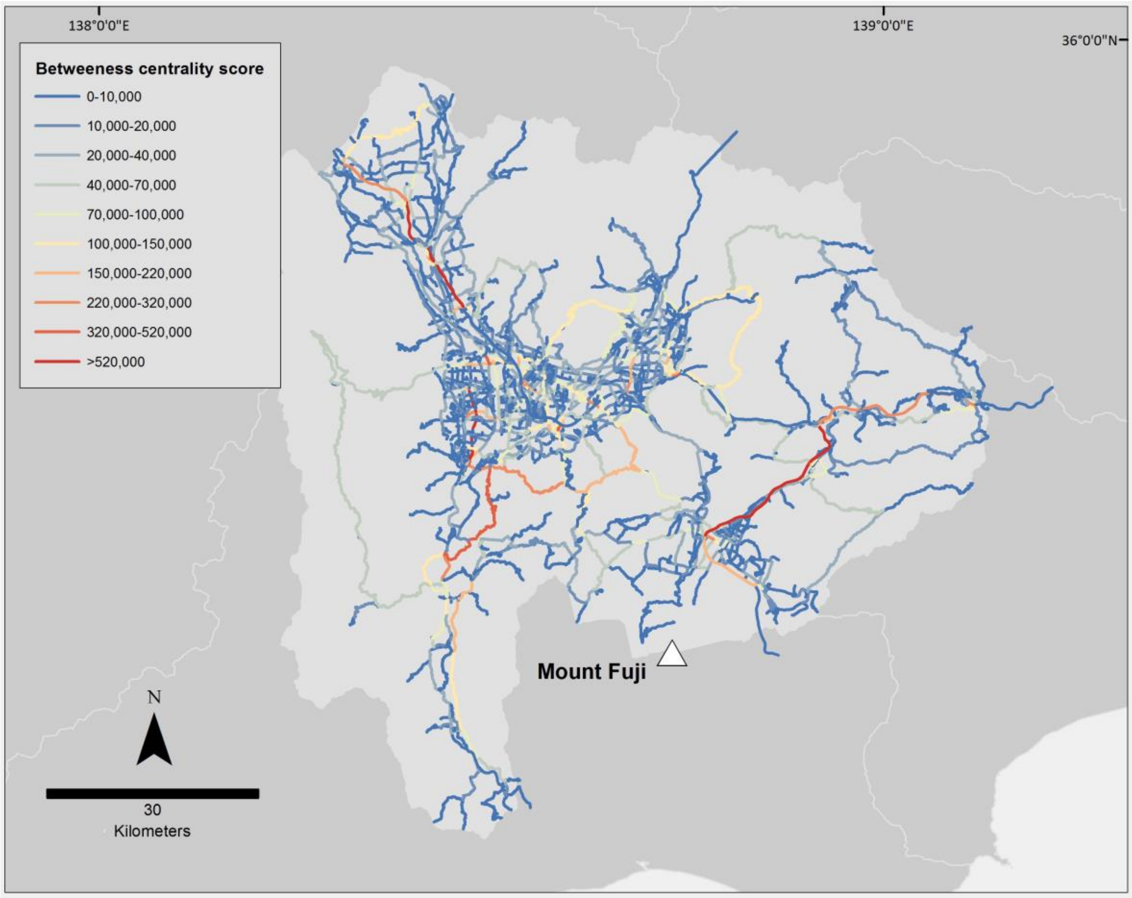


Figure 4.11: Betweenness centrality scores for the entire Yamanashi road network. High betweenness scores indicate component importance for network connectivity. Warmer colours indicate high scores, cooler colours indicate low scores.

4.5 Results

4.5.1 Part One: The impact of the initial phase of the eruption on Yamanashi Prefecture evacuation plans

Part One of this scenario looks at the ash fall accumulations of unit A of the Hoei eruption, based on the data of Miyaji et al. (2011) and simulation by Magill et al. (2015). This unit was used to study the impact of ash fall from a Hoei type eruption on Yamanashi Prefecture's evacuation plan for Mount Fuji. In particular this unit was used to simulate potential conditions residents may face during evacuation, if initiated at or soon after the onset of the eruption (i.e. evacuation zone 2). Figure 4.12 displays the distribution of various threshold ash fall thicknesses (mm) from unit A. As outlined in the previous section, the ash fall thicknesses looked at in this scenario are based on thresholds needed to disrupt road and other critical infrastructure (see Table 4.3).

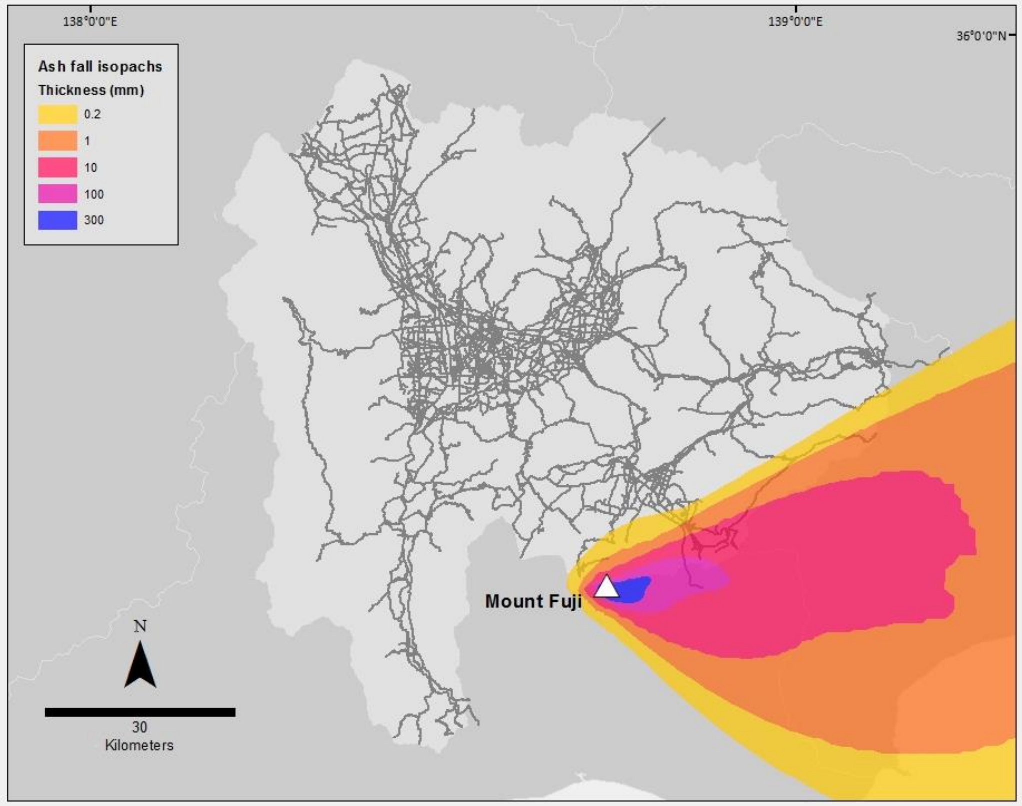


Figure 4.12: Ash fall thickness isopachs (mm) for unit A of the Hoei eruption (modified from Magill et al. (2015)).

Different ash fall thicknesses can cause a range of disruption or damage to road infrastructure, vehicles and drivers. At just 0.2 mm road markings can be obscured enough to inhibit safe driving. At this thickness road clean-up would likely begin and roads could be closed for maintenance. However, in an emergency situation, the need for evacuation may outweigh the risk of driving on roads coated in small ash fall thicknesses, especially when traffic will be dominantly going in one direction. The cessation of road access for each ash fall thickness is explored to understand the impact of road closures on current evacuation plans if any condition were deemed too unsafe for driving. Figure 4.13 highlights the roads segments exposed to ash fall that made up the depositional unit A. Table 7 gives a summary of the length and type of roads impacted by various thicknesses of ash fall during this phase.

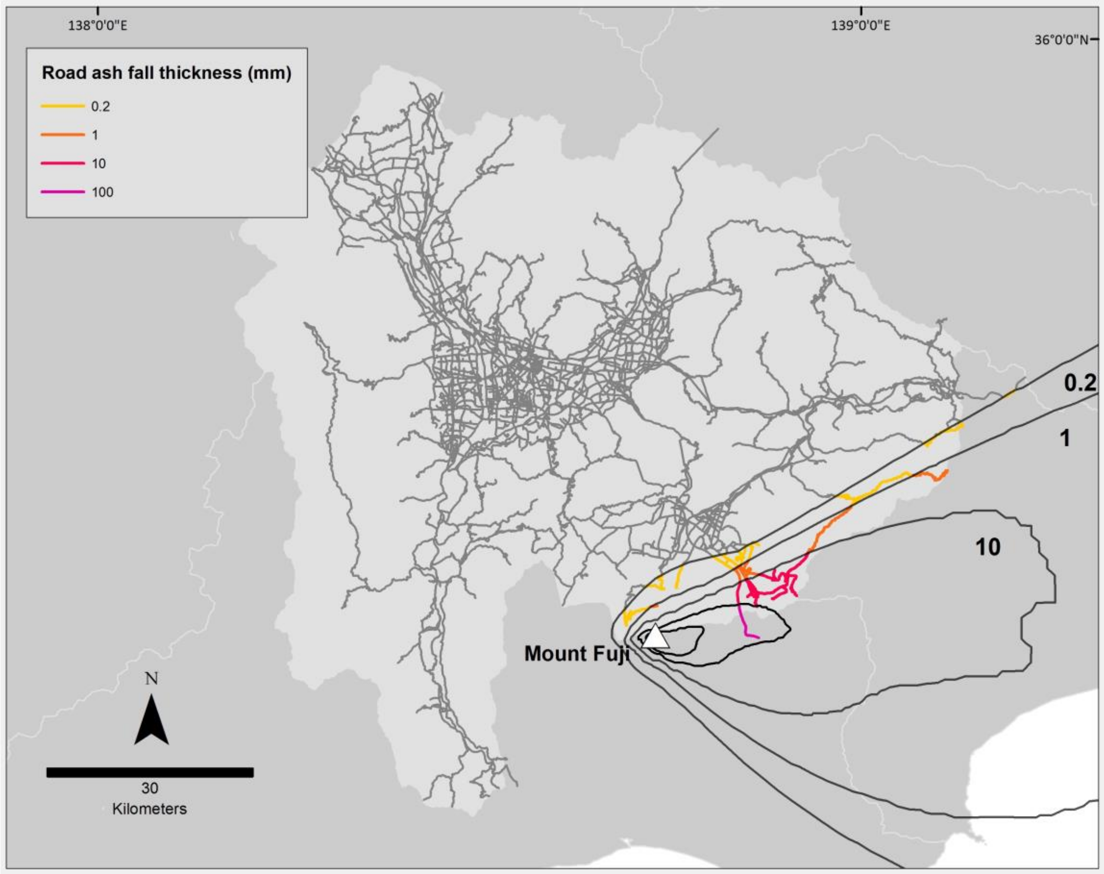


Figure 4.13: Exposure of prefecture roads to ash fall from unit A. Isopachs outlined in black and roads coloured with ash fall depths (mm). Note the inner isopachs represent 100 and 300 mm.

Table 4.7: Approximate road lengths (km) impacted by various ranges of ash fall accumulation during the deposition of unit A (see Figure 4.13). Road maps and classifications from OpenStreetMap; isopach contours derived from Magill et al. (2015).

Ash accumulation (mm)	**Motorway**	**Trunk**	**Primary**	**Secondary**	**Tertiary**	**All roads**
0.2-1	5.537	14.27	30.223	6.735	10.516	67.281
1-10	3.085	21.172	1.067	2.044	7.417	34.785
10-100	3.325	13.348	0	7.064	20.608	44.345
100-300	6.575	0	0	0	0.139	6.714
>300	0	0	0	0	0	0
Total	18.522	48.79	31.29	15.843	38.68	**153.125**

The location of evacuation centres in the cities that will be evacuating and in the host cities where residents will be travelling to were used as start and stop points, representing evacuation routes taken by evacuees (Figure 4.8). Road segments that intersected with 0.2, 1, 10, 100 and

300 mm isopachs, respectively, were each deleted from the road network, and the routes between evacuee and host locations were recalculated to determine the impact of road closures of evacuation routes. Table 4.8 indicates that the modelled ash fall dispersal for unit A would impact evacuation plans for Oshino and Yamanakako cities if road closures occurred at 0.2, 1 or 10 mm ash fall in this scenario. Evacuation plans for Fujikawaguchiko, Fujiyoshida, Narusawa and Nishikatsura would not be impacted by any road closures in this particular scenario. The following sections take a more in depth look into the impacts to Oshino and Yamanakako Cities' evacuation plans.

Table 4.8: The impact of various ash fall depths from unit A on city evacuation plans.

Ash depth (mm)	Fujikawaguchiko	Fujiyoshida	Oshino	Narusawa	Nishikatsura	Yamanakako
0.2	Not impacted	Not impacted	**Some paths blocked**	Not impacted	Not impacted	**All paths blocked**
1	Not impacted	Not impacted	**Some detours needed**	Not impacted	Not impacted	**All paths blocked**
10	Not impacted	Not impacted	**Some detours needed**	Not impacted	Not impacted	**Some paths blocked**
100	Not impacted	Not impacted	Not impacted	Not impacted	Not impacted	Not impacted
300	Not impacted	Not impacted	Not impacted	Not impacted	Not impacted	Not impacted

4.5.1.1 Impact to Oshino evacuation plan

Figure 16 shows the location of known evacuation centres in Oshino and the three host cities to the northeast (Otsuki, Uenohara and Doshi). It also shows the road network in graph form and highlights the calculated shortest routes to and from these locations. Ash fall thicknesses of 0.2, 1 and 10 mm from unit A were determined to impact these evacuation routes and are looked at here in further detail.

Figure 4.15 shows the roads that would be impacted if road closures occurred at 0.2 mm of ash fall. The closure of these roads, in this case, would result in two out of the five centres in Oshino being completely cutting off residents at these centres, stopping them from evacuating further to their allocated host cities. Two host centres, one in Doshi and one in Uenohara, would also be inaccessible. In this eruption scenario, with similar characteristics and wind conditions, the residents of Oshino may need to evacuate to alternative host centres in the north instead of the east and, if adequate warning can be given, leave well before the onset of an eruption to avoid interaction with ash fall. If evacuation is needed after ash fall has commenced it would be likely that residents in the southeast of Oshino would need assistance to travel on roads impacted by 0.2 mm of ash, if this threshold is deemed unsafe. Road visibility during ash fall would also impair drivers due to ash in the air and, potentially, car windscreens becoming damaged by the abrasive ash particles. Vehicles may also cease to operate when ash is ingested into air filters, damaging the motor and stranding occupants.

Figures 4.16 and 4.17 show the roads that would be impacted if closures occurred above depths of 1 mm and 10 mm respectively. In both cases road closures would not inhibit access to centres in host cities from centres in Oshino. However, both scenarios would result in an average increase of 11.5 km travel distance from centres in Oshino to the evacuation centre in Doshi. Being able to predict this ahead of time would allow detours to be set up and stop residents from potentially getting stuck on route or having to turn back. In this scenario, if confident that the wind will not change direction, it would be recommended that residents of Oshino evacuate to the north before heading east to the host locations to avoid using easterly roads likely to be impacted by ash fall.

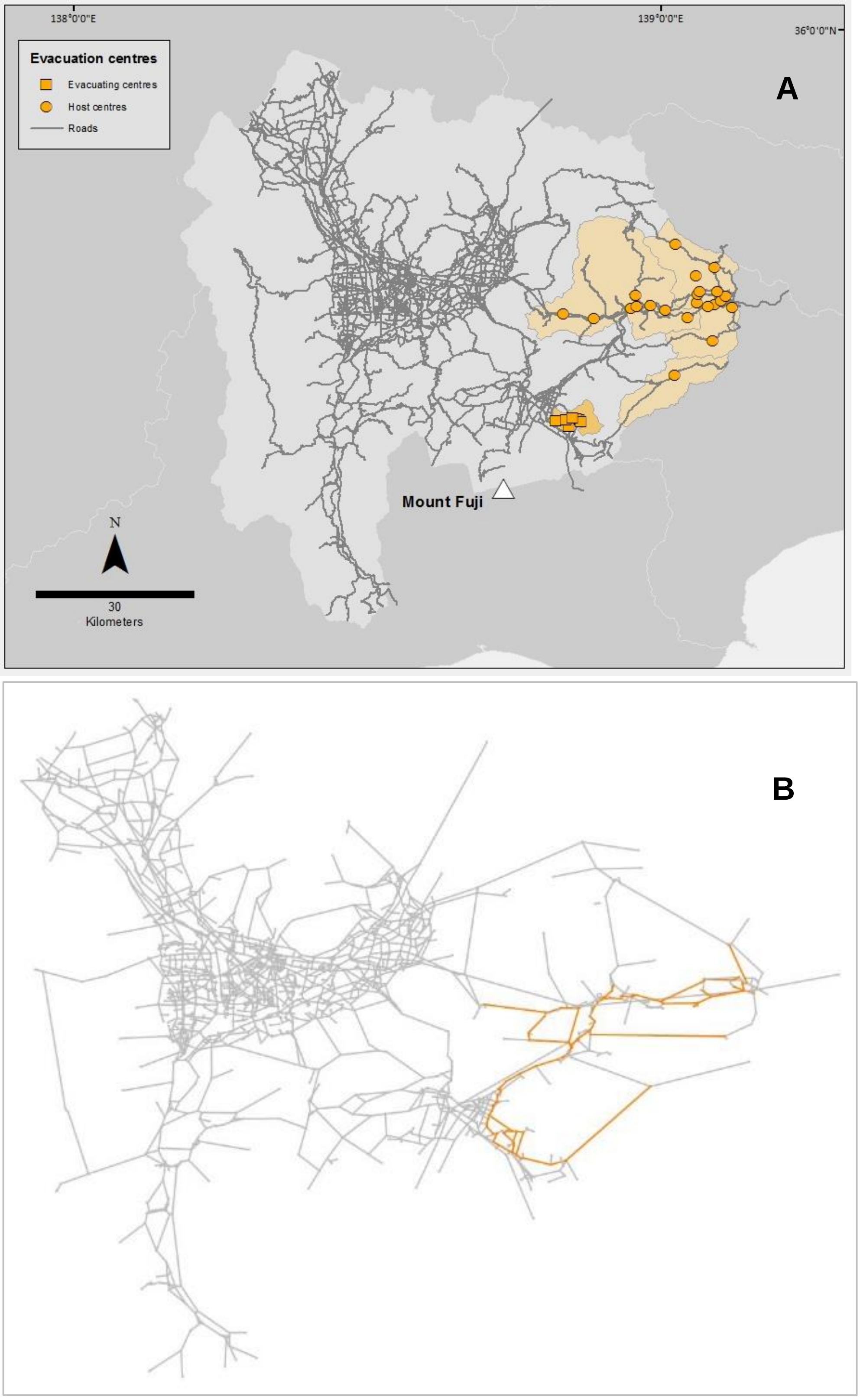


Figure 4.14: A) Evacuation centres in Oshino, Otsuki, Uenohara and Doshi cities and B) the shortest transport routes between them.

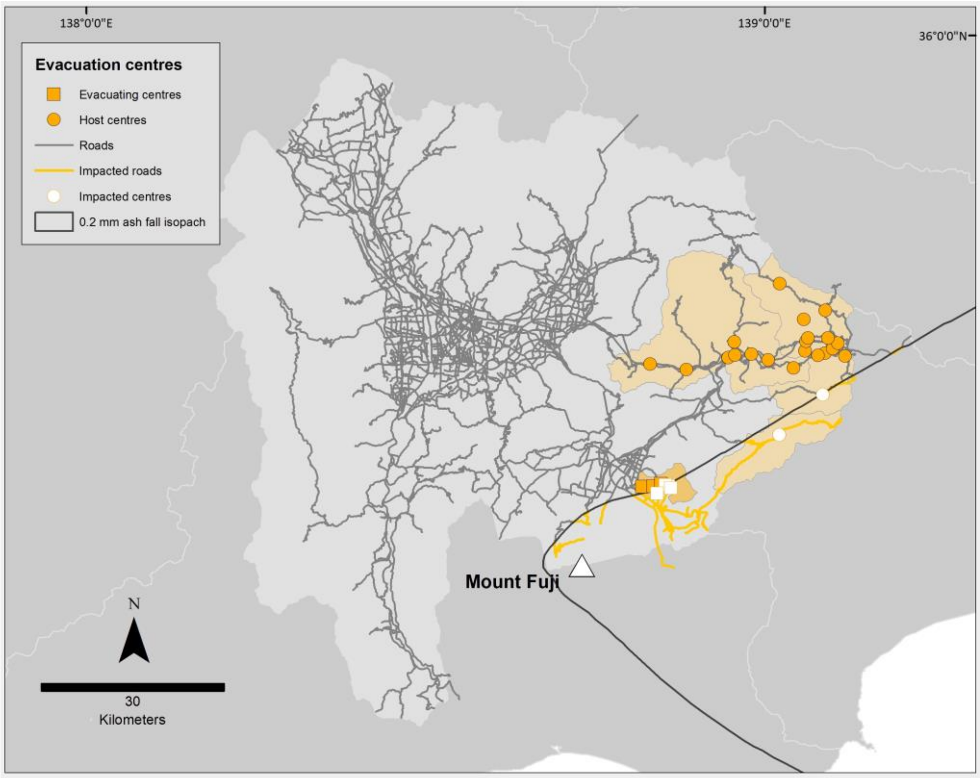


Figure 4.15: The exposure of roads and evacuation centres to 0.2 mm or more of ash fall from unit A. Impacted roads are in yellow and isolated centres in white.

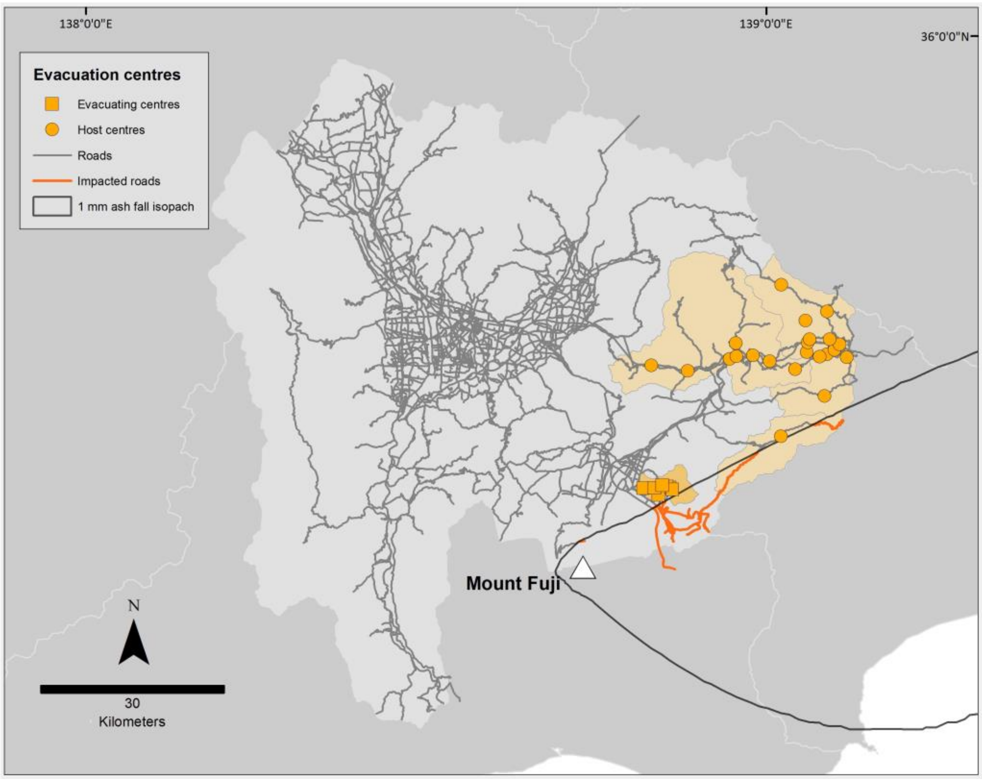


Figure 4.16: The exposure of roads and evacuation centres to 1 mm or more of ash fall from unit A. Impacted roads are in orange.

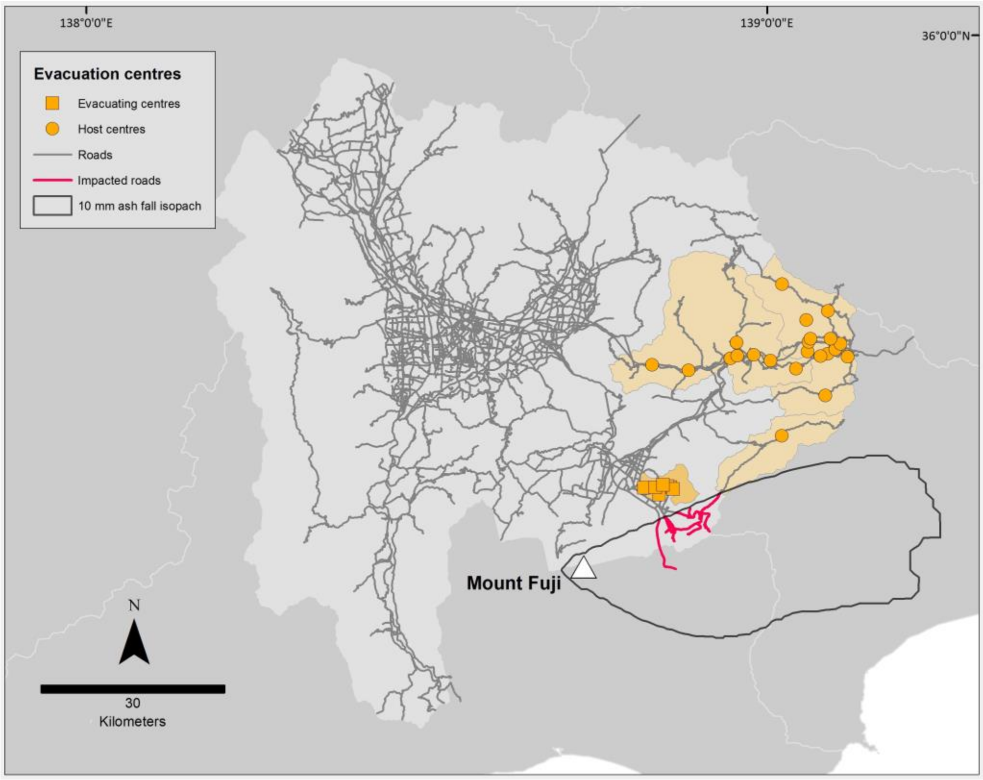


Figure 4.17: The exposure of roads and evacuation centres to 10 mm or more of ash fall from unit A. Impacted roads are in red.

4.5.1.2 Impact to Yamanakako evacuation plan

Figure 4.18 shows the location of evacuation centres in Yamanakako and the host city of Koshu to the north and displays the graph representation of the road network and the shortest routes between centres highlighted in blue. Again, how road closures at 0.2, 1 and 10 mm would impact these paths was investigated by omitting roads in each case and recalculating transport routes.

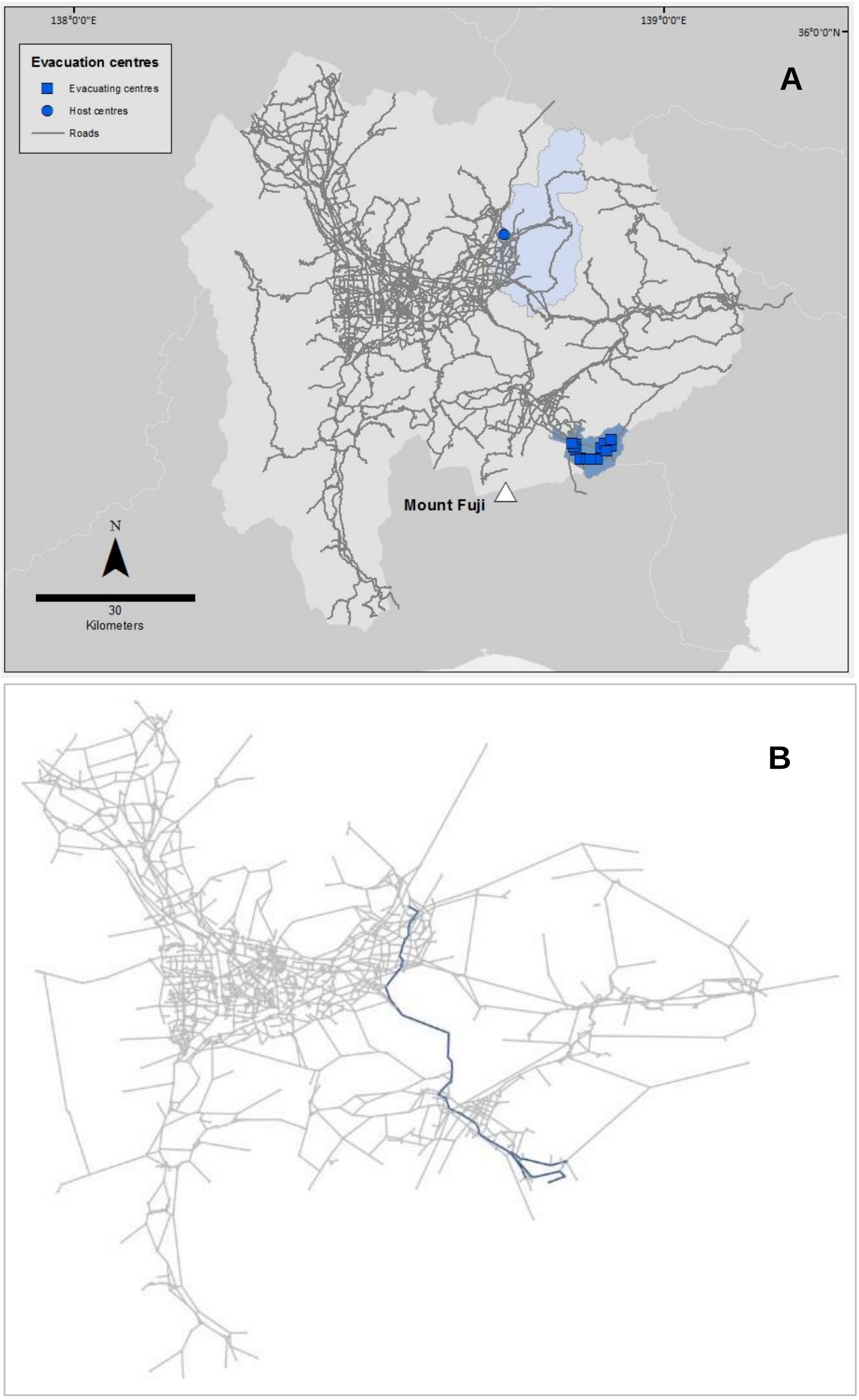


Figure 4.18: A) Evacuation centres in Yamanakako and Koshu cities and B) the shortest transport routes between them.

Figures 4.19 and 4.20 show the roads impacted if road closures occurred at an ash fall thickness of 0.2 and 1 mm respectively. In both scenarios road closures would inhibit evacuation from Yamanakako entirely, which the city being entirely covered by ash fall thicknesses of up to 1 mm. Where wind conditions are predominantly westerly or south-westerly, and if adequate warning is available, it would be advised to evacuate residents from Yamanakako before the onset of a future eruption. If evacuation is needed after ash fall has commenced it would be likely that residents in Yamanakako would need assistance if ash fall thresholds of 0.2 or 1 mm were deemed unsafe for road transportation. Along with poor visibility, ash fall depths of 1 mm can result in a loss of traction between vehicle wheels and the road surface, especially if wet, creating difficult and potentially dangerous driving conditions. Ash fall thicknesses of 1 mm or greater can also cause flashovers to occur on power lines (Wilson et al. 2012), which could impact electricity supply, and traffic signals and streetlights that rely on it.

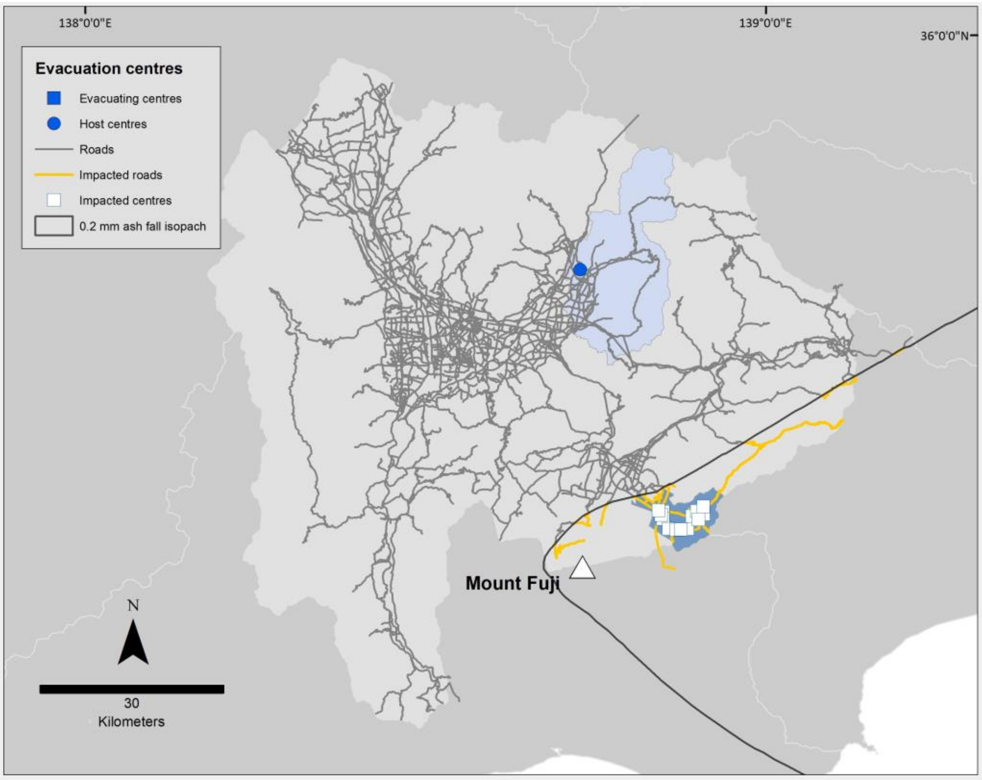


Figure 4.19: The exposure of roads and evacuation centres to 0.2 mm or more of ash fall from unit A. impacted roads in yellow and isolated centres in white.

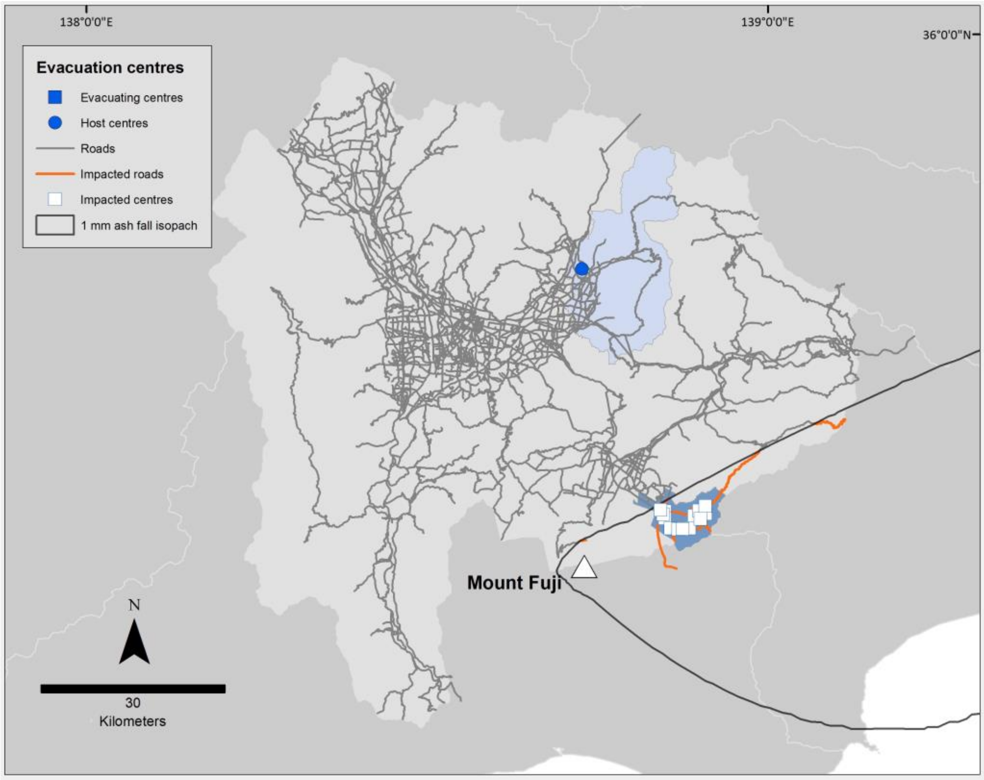


Figure 4.20: The exposure of roads and evacuation centres to 1 mm or more of ash fall from unit A. impacted roads in orange and isolated centres in white.

Figure 4.21 shows the roads that would be impacted if road closures occurred at 10 mm of ash fall. The closure of these roads, in this case, would result in eight out of the eleven centres in Yamanakako not being able to evacuate. Only three centres to the northwest of the city would be free to evacuate if roads were not closed until 10 mm of ash fall was reached. As in all cases looked at here, the evacuation centre in Koshu is not impact at all by ash fall. However, from most locations in Yamanakako, residents would have to evacuate well before ash fall commenced if they are to evacuate to Koshu safely. If evacuation did not occur until after the onset of the eruption, in a similar scenario residents of Yamanakako might have to drive through ash fall depths of up to 10 mm to evacuate the city. A reduction in speed would be needed due to poor driving conditions including a loss of road/tire traction and poor visibility from continual ash fall or remobilisation from automobiles. In wet conditions ash can make the road even more slippery and can also be washed from the road surface into drainage systems potentially leading to flooding of roads. Residents would need great assistance in these conditions and roads may have to be cleared to allow safe passage. As the Hoei eruption continued for a further 15 days, more volcanic ash was expelled and deposited to the east of the Mount Fuji.

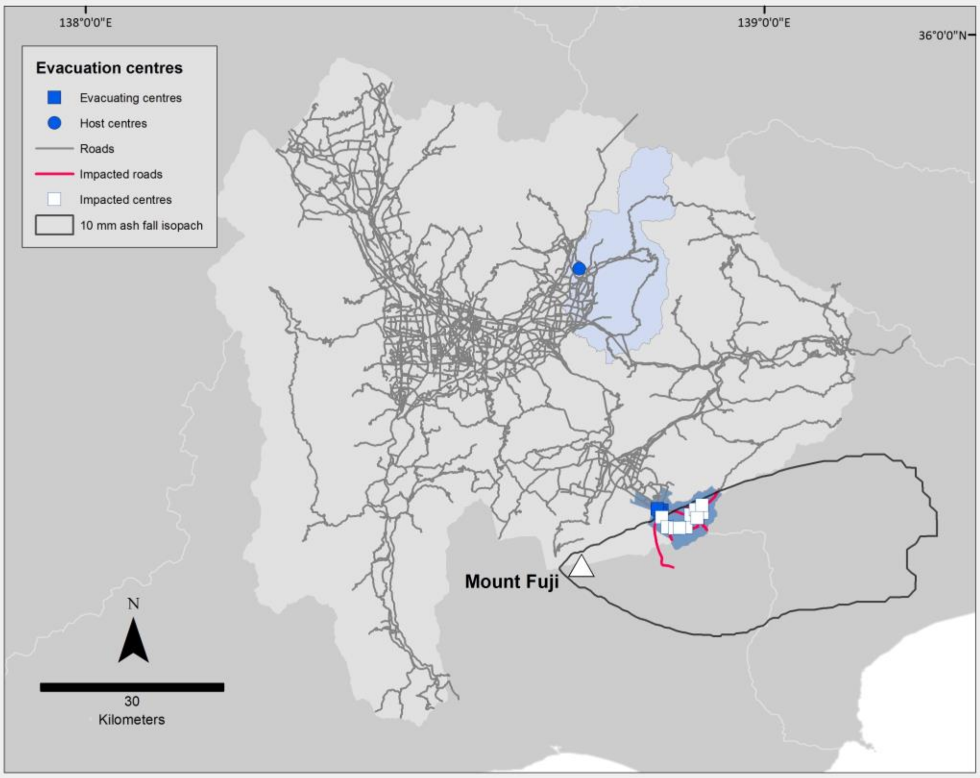


Figure 4.21: The exposure of roads and evacuation centres to 10 mm or more of ash fall from unit A. impacted roads in red and isolated centres in white.

It is of interest to this study to now look at the combined accumulation of ash fall from the entire eruption sequence. This represents the conditions that Yamanashi Prefecture would face after the event. What impact would ash fall have on host cities? What further disruption would ash have on road transport and how would this impact resident return? What would be the extent of clean-up needed to clear roads in order to enable community recovery?

4.5.2 Part Two: Potential impact of the entire ash fall accumulation on evacuation centres and prefectural roads after the eruption

Phase 2 of this scenario used the combined ash fall accumulation of all 17 phases of the Hoei eruption to simulate the conditions that Yamanashi Prefecture could face after a future eruption at Mount Fuji (Figure 4.22). This study assumes that no clean-up of ash occurred during the 16 days of the eruption, nor that any erosion from rainfall occurred. Using the total ash fall accumulation this study explores the potential impact of ash fall on host centres, evacuated locations and road access for evacuated residents to return home. Figure 4.23 shows the exposure of prefecture roads to various ash fall thicknesses and Table 4.9 gives the summary of the length and type of roads impacted.

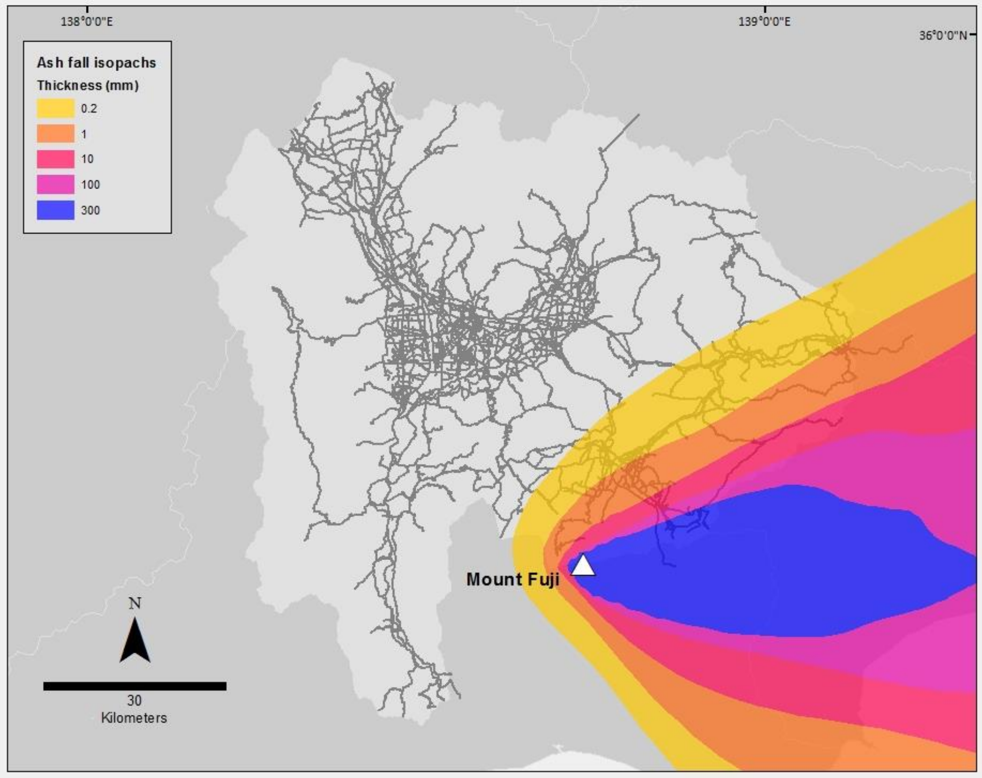


Figure 4.22: Ash fall thickness isopachs (mm) for the entire Hoei eruption (derived from Magill et al. (2015)).

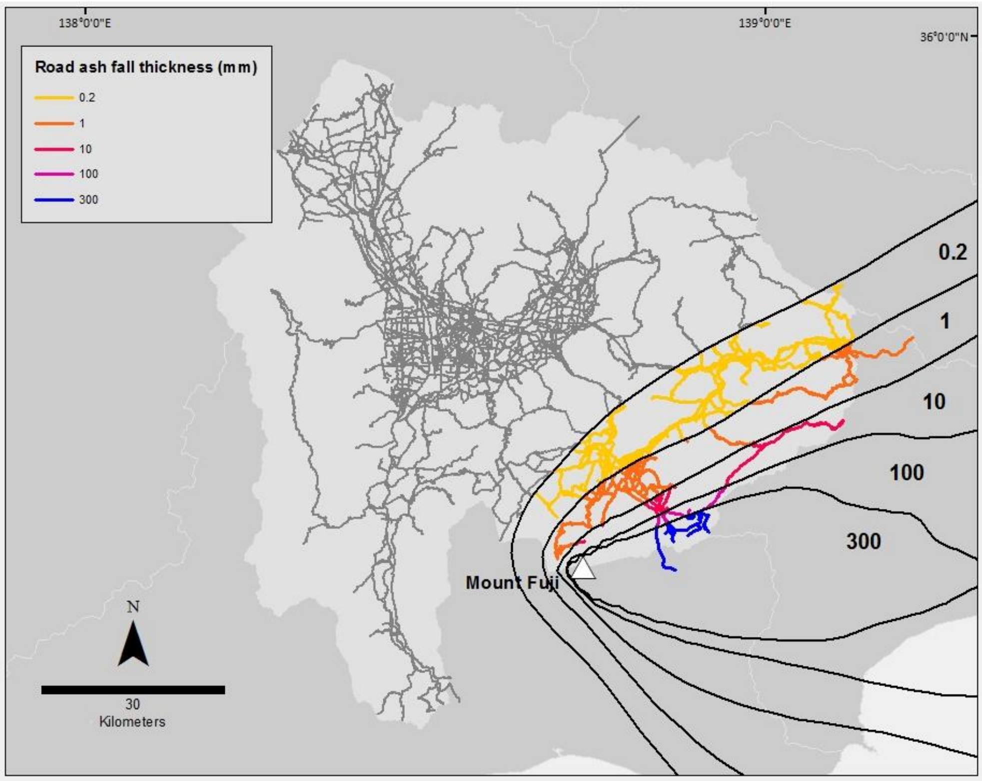


Figure 4.23: Exposure of prefecture roads to combined ash fall accumulation of all 17 units of the Hoei eruption. Isopachs outlined in black and roads coloured by ash fall thicknesses.

In total ~769 km of roads would be impacted by ash fall greater than 0.2 mm. Using the same evacuation locations as in Figure 4.8 we looked at their exposure to ash fall and the ability of residents to return home.

Table 4.9: Approximate road lengths (km) impacted by various ranges of ash fall accumulation (see Figure 4.23). Road maps and classifications from OpenStreetMap; isopach contours derived from Magill et al. (2015).

Ash accumulation (mm)	Motorway	Trunk	Primary	Secondary	Tertiary	All roads
0.2-1	58.518	102.888	66.323	117.704	104.71	450.143
1-10	22.12	20.159	70.35	38.017	52.213	202.859
10-100	4.06	30.957	6.769	4.591	11.031	57.408
100-300	2.099	8.163	0	0	8.196	18.458
>300	8.661	8.302	0	7.064	16.170	40.197
Total	95.458	170.469	143.442	167.376	192.32	769.065

Using the same paths that were calculated in the previous section Table 4.8 depicts how various ash fall thicknesses impact access routes between host and evacuee centres.

Table 4.10: The impact of various ash fall depths from all phases on city evacuation plans.

Ash depth (mm)	Fujikawaguchiko	Fujiyoshida	Oshino	Narusawa	Nishikatsura	Yamanakako
0.2	**Some paths blocked and some detours needed**	**All paths blocked**	**All paths blocked**	**Some paths blocked**	**All paths blocked**	**All paths blocked**
1	Not impacted	**Some paths blocked**	**All paths blocked**	Not impacted	Not impacted	**All paths blocked**
10	Not impacted	Not impacted	**Some paths blocked**	Not impacted	Not impacted	**All paths blocked**
100	Not impacted	Not impacted	**Some detours needed**	Not impacted	Not impacted	**Some paths blocked**
300	Not impacted	Not impacted	**Some detours needed**	Not impacted	Not impacted	**Some paths blocked**

A portion of evacuees from all cities would not be able to return home if road closures were enforced at ash fall depths of 0.2 mm. In fact access for Oshino and Yamanakako residents would be impacted if road closures occurred at any ash fall threshold. Here we explore the impact to each evacuated cities' residents in turn.

4.5.2.1 Impact to Fujikawaguchiko resident return

Figure 4.24 shows the impact to residents from Fujikawaguchiko if roads were closed at ash fall depths of 0.2 mm. In this case 11 out of 21 locations in Fujikawaguchiko would not be able to be accessed from the host locations in the north and west.

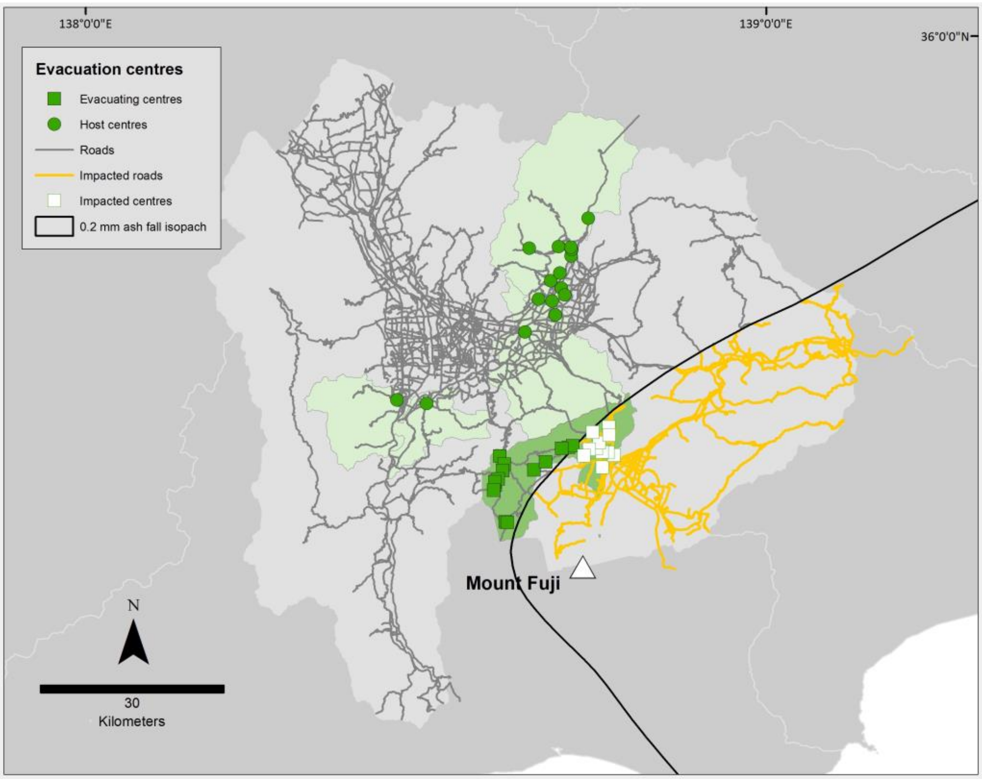


Figure 4.24: The exposure of roads and evacuation centres in Fujikawauchiko, Yamanashi, Fuefuki, Ichikawa-Misato and Fujikawa to 0.2 mm or more of ash fall from combined units. Impacted roads are in yellow and isolated centres in white.

Residents located in these areas would need to wait until roads were cleared before returning home to clean up their properties and attend to livestock. For three locations in central Fujikawaguchiko, residents would have to take a detour, driving up to 17 km more to get home when coming from the north. Residents returning to western and southern regions of Fujikawaguchiko would not be inhibited in returning home in this scenario. Road closures at any other ash fall threshold would not impact the return of residents to Fujikawaguchiko.

4.5.2.2 Impact to Fujiyoshida resident return

Figures 4.25 and 4.26 show the impact of road closures at 0.2 mm and 1 mm ash fall thickness respectively to the residents of Fujiyoshida City. In the first case the whole city would be cut off from the host cities in the northwest. No resident would be able to return home until roads were cleared. In the second case, three out of the five locations would still be inaccessible. In fact only the very north of Fujiyoshida would be reachable.

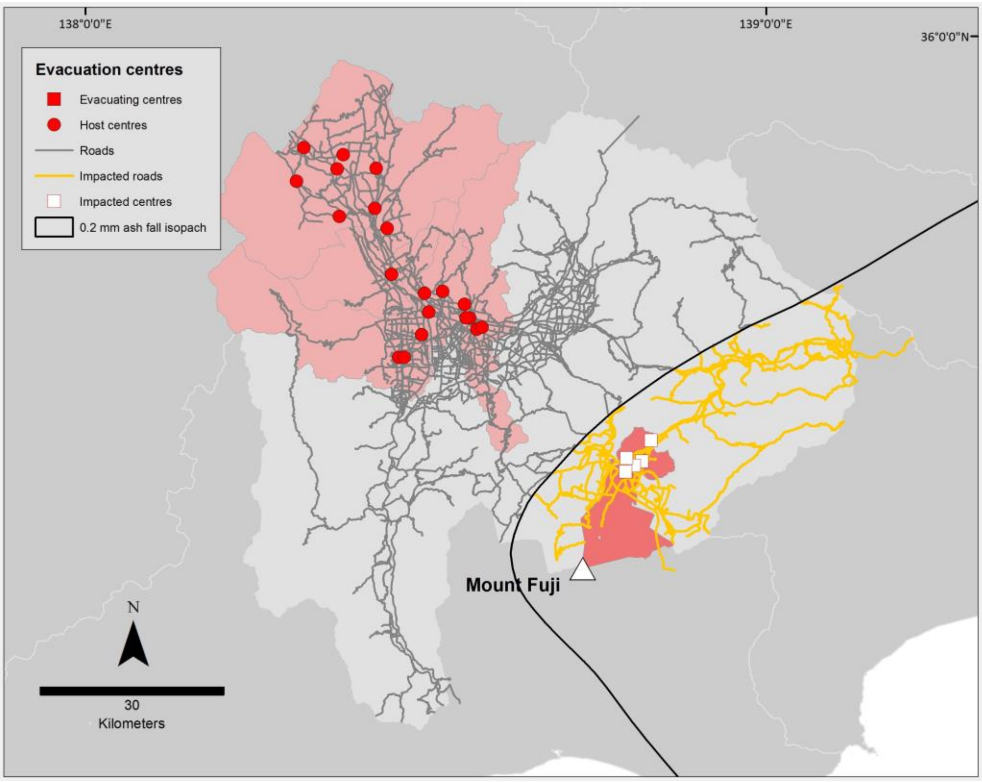


Figure 4.25: The exposure of roads and evacuation centres in Fujiyoshida, Kofu, Nirasaki, Minami-Arupusu, Hokuto and Kai to 0.2 mm or more of ash fall from combined units. Impacted roads are in yellow and isolated centres in white.

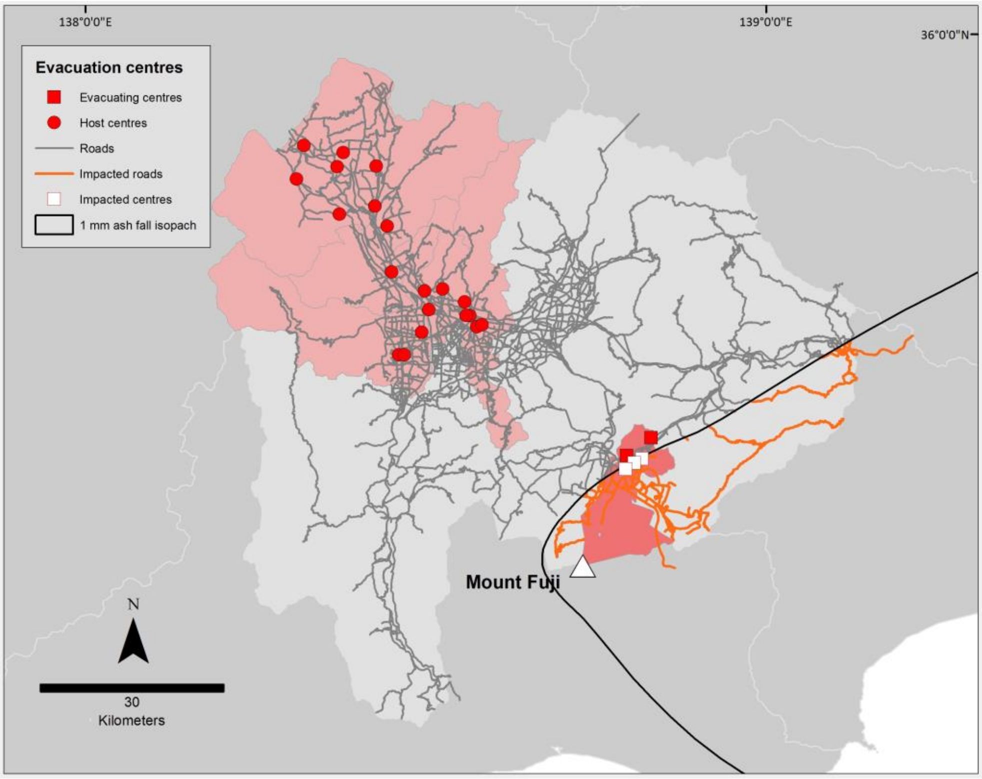


Figure 4.26: The exposure of roads and evacuation centres in Fujiyoshida, Kofu, Nirasaki, Minami-Arupusu, Hokuto and Kai to 1 mm or more of ash fall from combined units. Impacted roads are in orange and isolated centres in white.

4.5.2.3 Impact to Oshino resident return

Figures 4.27 to 4.31 illustrate the impact that road closures would have on residents' return home to Oshino from host cities in the northeast. In the first case, looking at road closures at 0.2 mm of ash fall, nearly all centre locations, including the hosts, would be isolated. Both evacuated residents and host residents in the impacted area would not be able to drive on roads until they were cleared. In the second case, with roads closures occurring at 1mm, only a few host centres to the east would be impacted. However, all centre locations in Oshino would still be cut off, delaying residents' return home until roads reopened. If roads were closed at 10 mm, one location in Oshino and one in Doshi would remain isolated from road access. Road closures at 100 and 300 mm would not impact the accessibility of any location but any resident that evacuated to the centre in Doshi would need to take a detour between 8 and 15 km to get home.

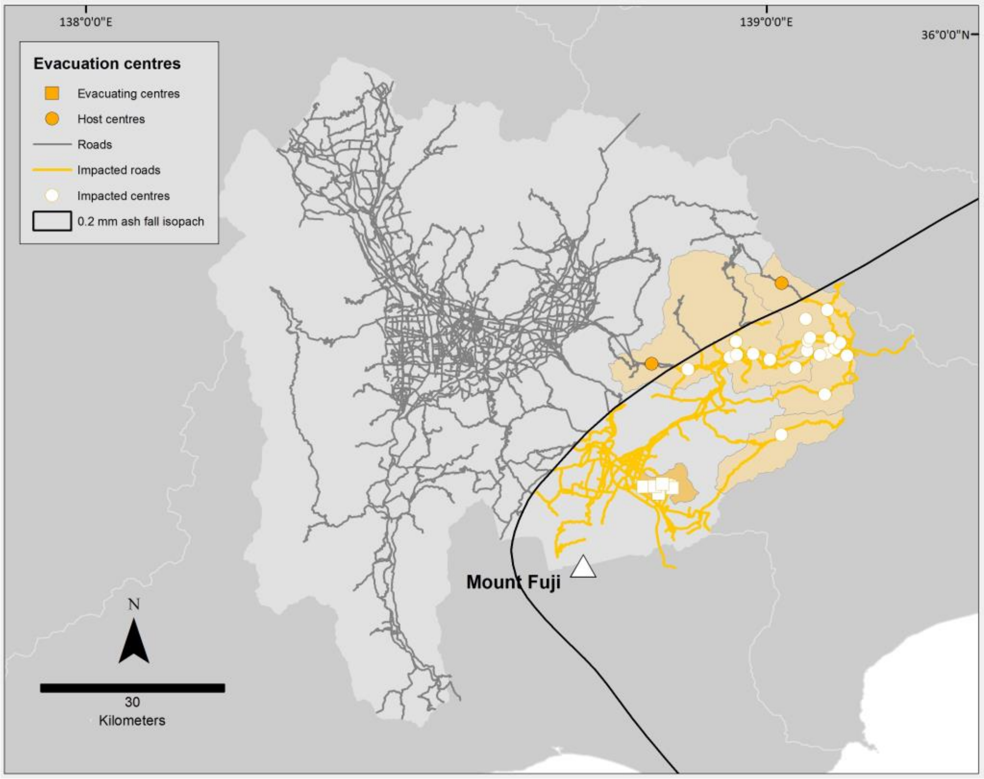


Figure 4.27: The exposure of roads and evacuation centres in Oshino, Otsuki, Uenohara and Doshi to 0.2 mm or more of ash fall from combined units. Impacted roads in yellow and isolated centres in white.

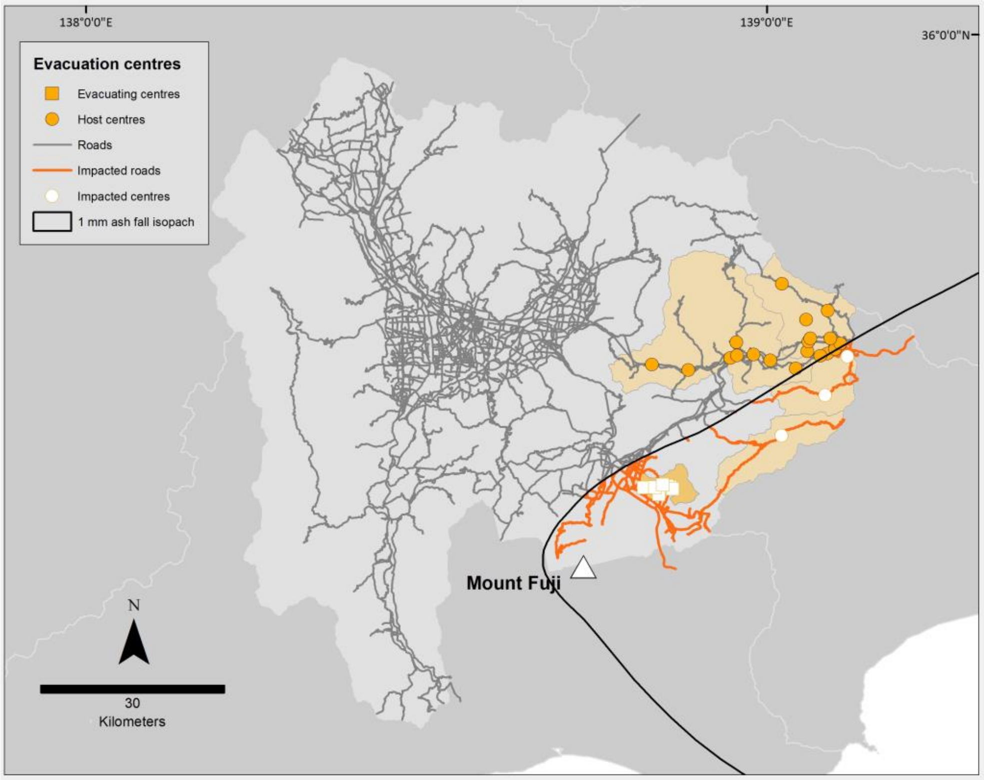


Figure 4.28: The exposure of roads and evacuation centres in Oshino, Otsuki, Uenohara and Doshi to 1 mm or more of ash fall from combined units. Impacted roads are in orange and isolated centres in white.

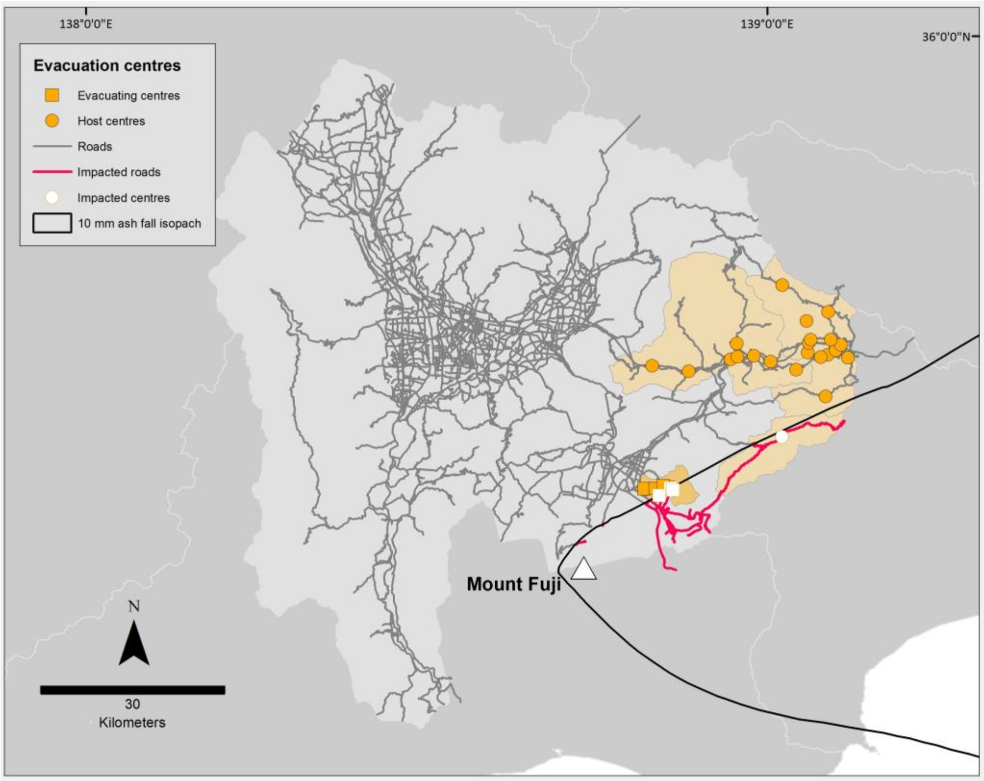


Figure 4.29: The exposure of roads and evacuation centres in Oshino, Otsuki, Uenohara and Doshi to 10 mm or more of ash fall from combined units. Impacted roads are in red and isolated centres in white.

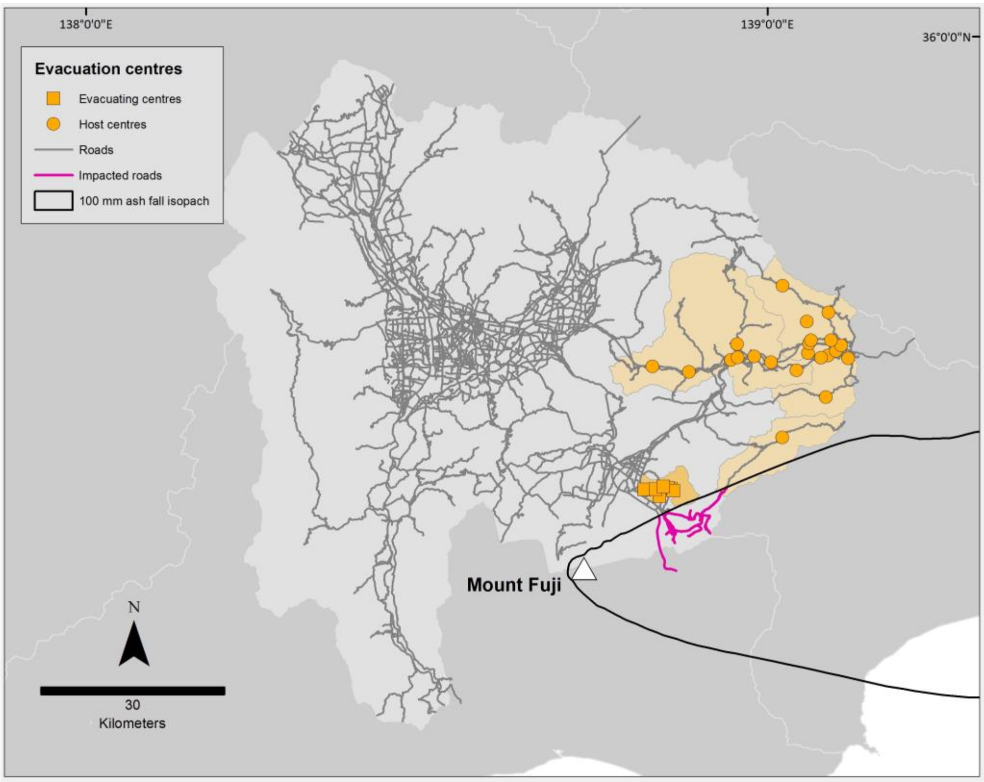


Figure 4.30: The exposure of roads and evacuation centres in Oshino, Otsuki, Uenohara and Doshi to 100 mm or more of ash fall from combined units. Impacted roads are in pink.

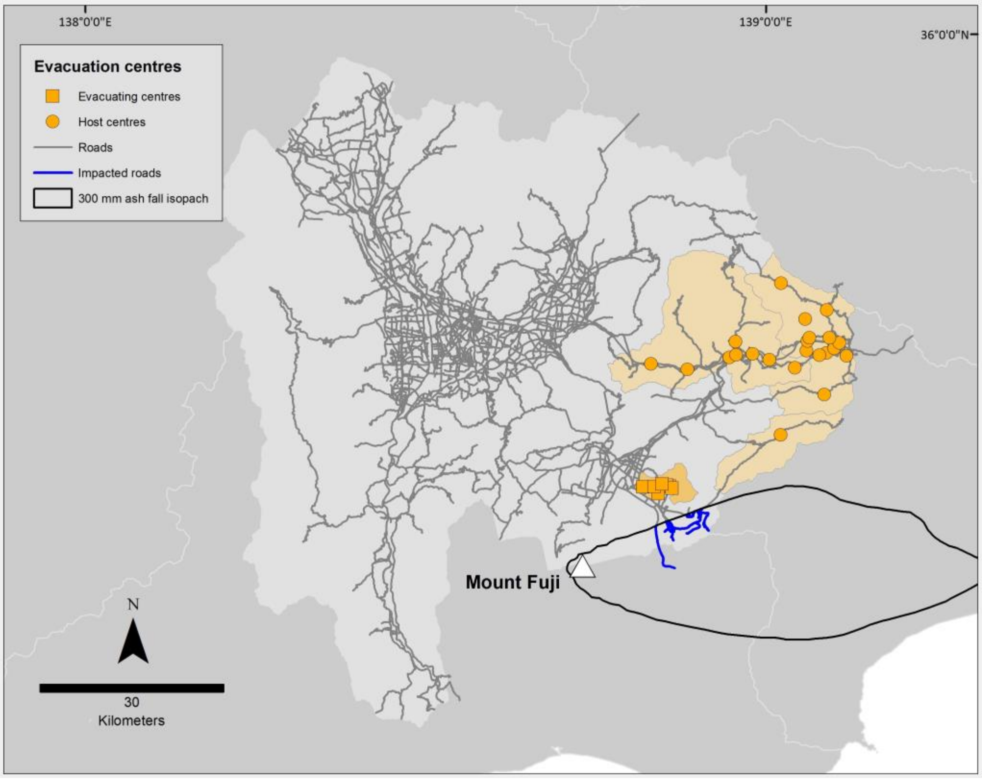


Figure 4.31: The exposure of roads and evacuation centres in Oshino, Otsuki, Uenohara and Doshi to 300 mm or more of ash fall from combined units. Impacted roads are in blue.

4.5.2.4 Impact to Narusawa resident return

Figure 4.32 shows that all centres in Narusawa would be cut off if road closures were enforced at ash fall thicknesses of 0.2 mm. Residents should be advised to stay at host locations until roads are cleared. If roads remain open until ash fall thicknesses of 1 mm are reached, the majority of locations in Narusawa would be reachable and most residents could return home (Figure 4.33). Only those in the southeast of the city would remain cut off.

4.5.2.5 Impact to Nishikatsura resident return

Residents returning home to Nishikatsura would be impacted by road closures at 0.2 mm and should be aware, that in this scenario, their ability to go home might be delayed until roads are cleared (Figure 4.34). If roads are closed at any other ash fall thickness greater than 0.2 mm Nishikatsura will be fully accessible from host cities Chou and Showa.

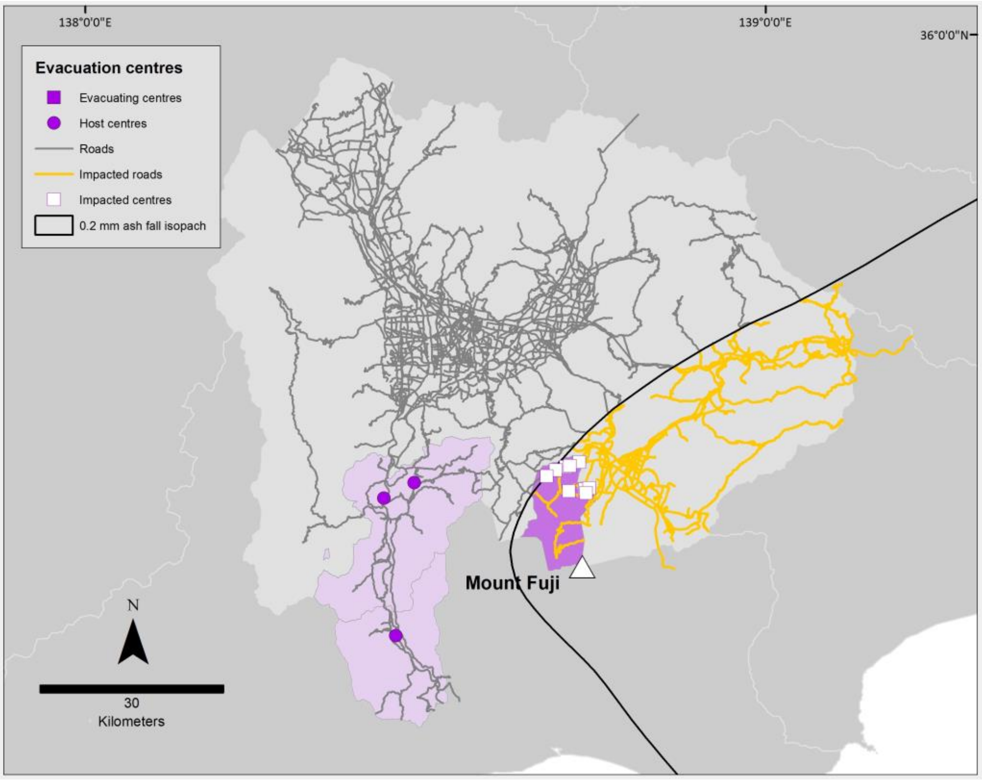


Figure 4.32: The exposure of roads and evacuation centres in Narusawa, Minobu and Nanbu to 0.2 mm or more of ash fall from combined units. Impacted roads are in yellow and isolated centres in white.

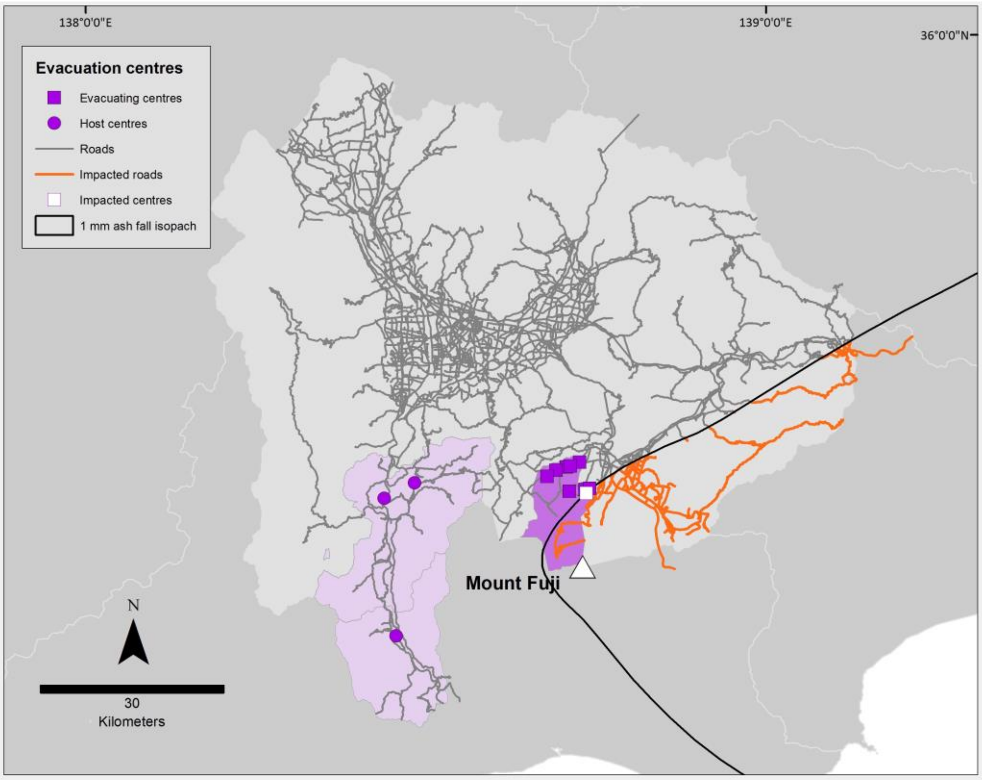


Figure 4.33: The exposure of roads and evacuation centres in Narusawa, Minobu and Nanbu to 1 mm or more of ash fall from combined units. Impacted roads are in orange and isolated centres in white.

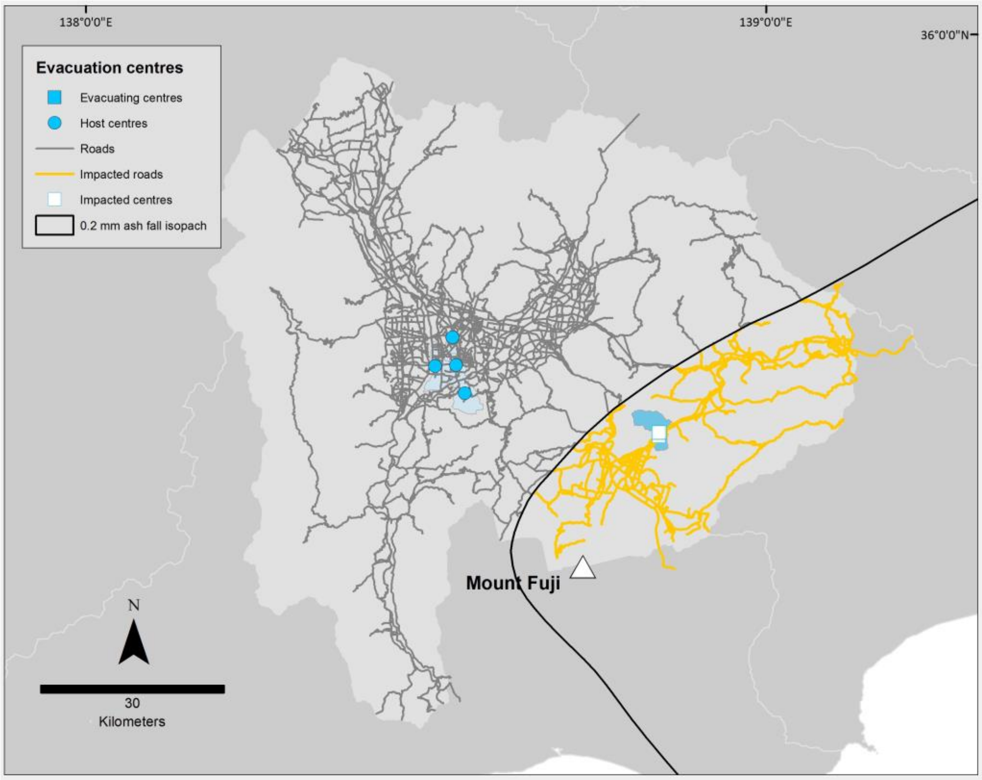


Figure 4.34: The exposure of roads and evacuation centres in Nishikatsura, Chou and Showa to 0.2 mm or more of ash fall from combined units. Impacted roads are in yellow and isolated centres in white.

4.5.2.6 Impact to Yamanakako resident return

Yamanakako would be completely cut off if road closures occurred at ash fall thicknesses between 0.2 and 10 mm (Figures 4.35 - 4.37). Even with a threshold of 100 or 300 mm, most of the southeast of the city would remain inaccessible, with only very northern Yamanakako gaining access (Figures 4.38 and 4.39). Ash fall thicknesses of 100 to 300 mm would completely bury roads and rendering them completely impassable. Moreover, ash thicknesses in this range would likely cause the downing of powerlines and trees, which could further block roads and create further hazards. Yamanashi Prefecture Government stated that if 300 mm of ash fall was reached, residents would not be able to return home until the ash was cleared due to the danger of roof collapse (Pers. Comm.). Therefore even if roads were cleared it would be too dangerous for residents to return home to Yamanakako until roofs were cleared and essential infrastructure restored. Residents from Yamanakako should be prepared for a longer evacuation period than that of the eruption duration, if ash fall is deposited predominately to the east of Mount Fuji.

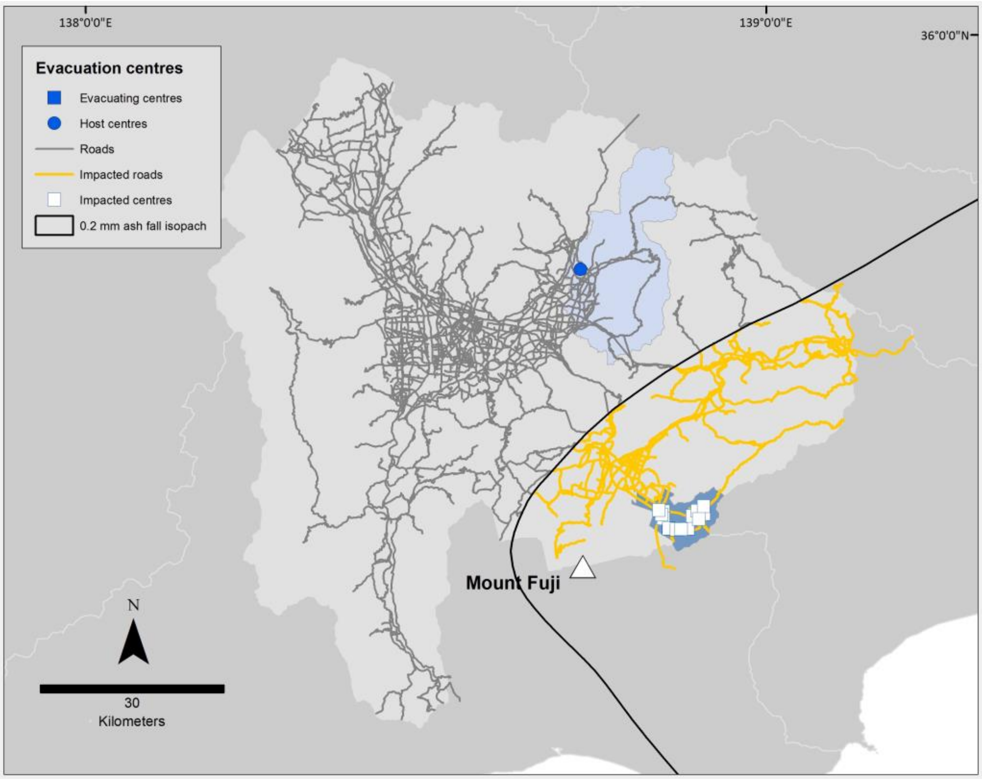


Figure 4.35: The exposure of roads and evacuation centres in Yamanakako and Koshu to 0.2 mm or more of ash fall from combined units. Impacted roads are in yellow and isolated centres in white.

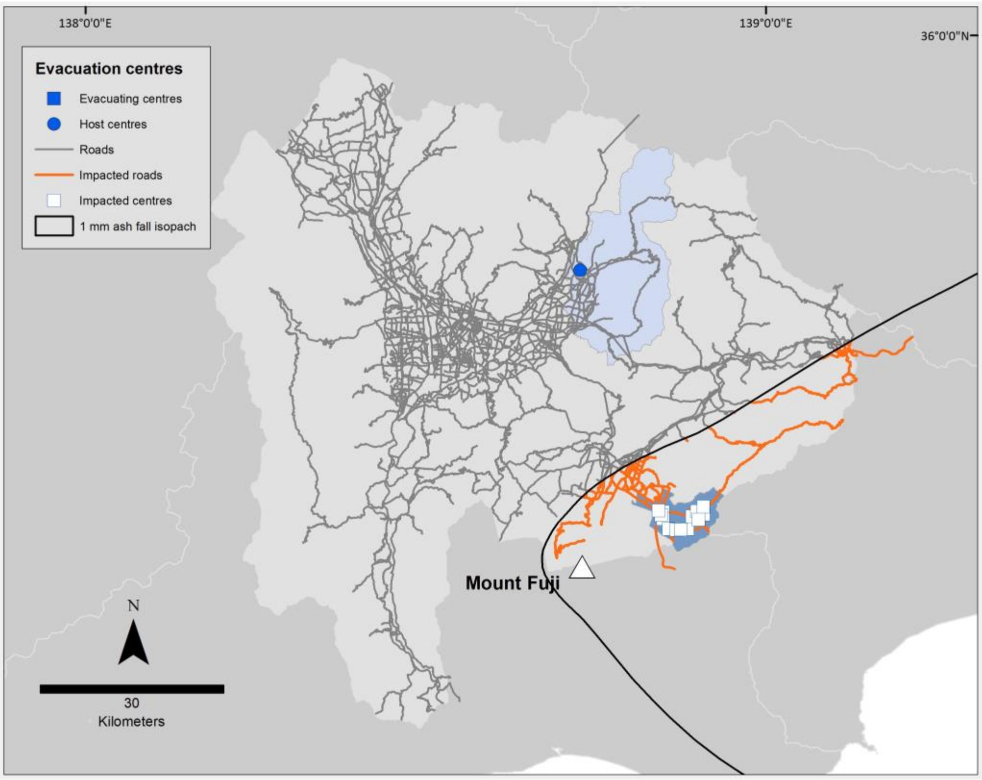


Figure 4.36: The exposure of roads and evacuation centres in Yamanakako and Koshu to 1 mm or more of ash fall from combined units. Impacted roads are in orange and isolated centres in white.

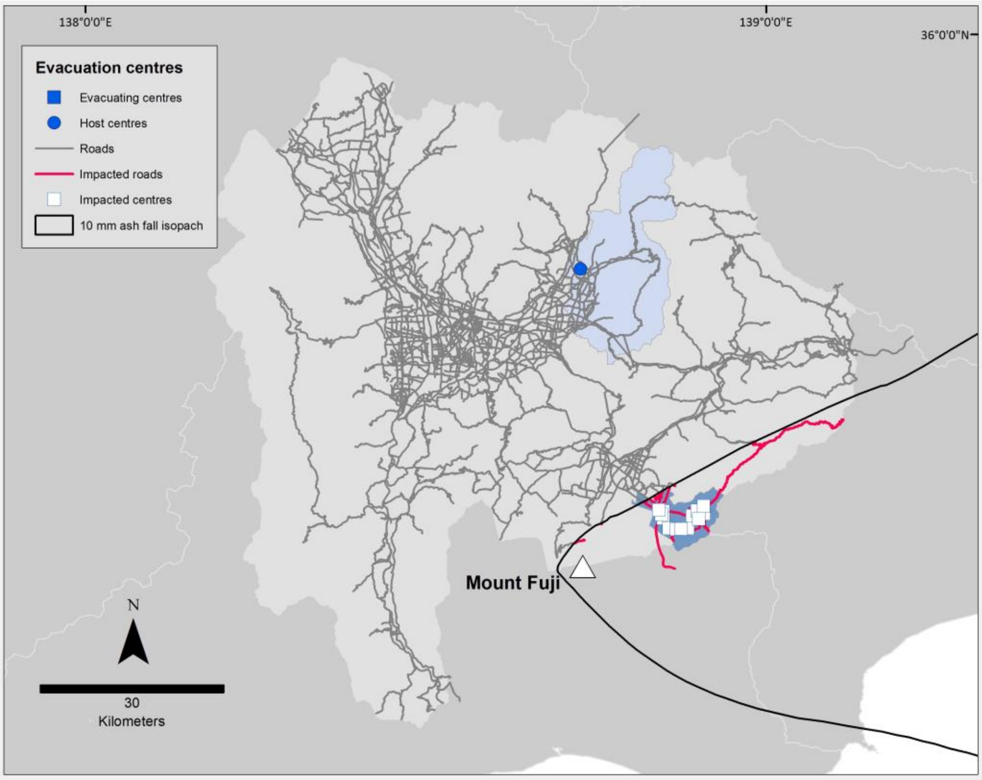


Figure 4.37: The exposure of roads and evacuation centres in Yamanakako and Koshu to 10 mm or more of ash fall from combined units. Impacted roads are in red and isolated centres in white.

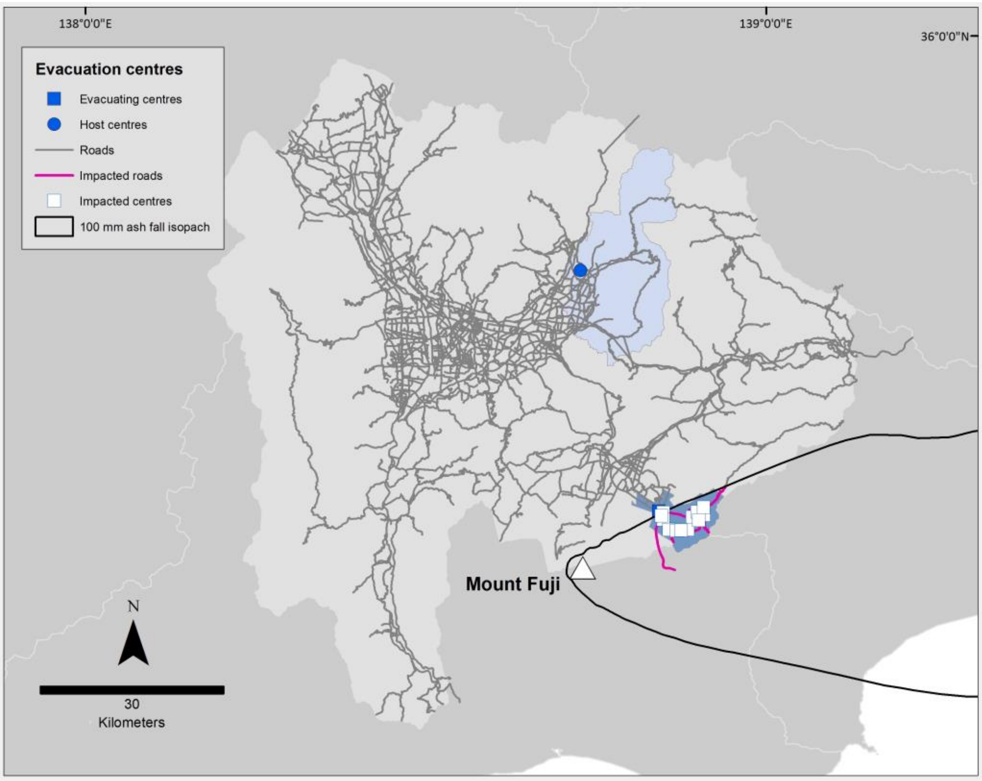


Figure 4.38: The exposure of roads and evacuation centres in Yamanakako and Koshu to 100 mm or more of ash fall from combined units. Impacted roads are in purple and isolated centres in white.

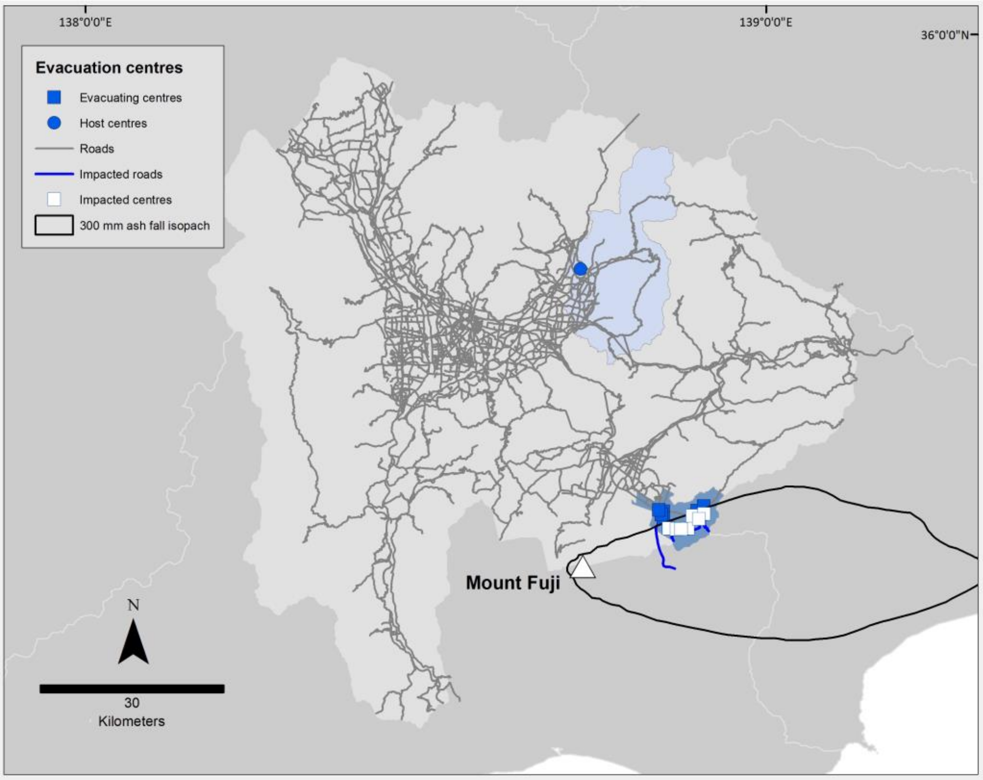


Figure 4.39: The exposure of roads and evacuation centres in Yamanakako and Koshu to 300 mm or more of ash fall from combined units. Impacted roads are in blue and isolated centres in white.

This section has looked at the impacts of various ash fall depths on roads and the impact of road closures on the return of evacuated residents. At the conclusion of the eruption it is assumed that the need for emergency evacuation is over. Because of this is it likely that road clean-up would begin at ash fall depths of 0.2 mm due to the loss of road markings. Road closures at this thickness would impact the return of almost all evacuated residents. To enable their return and normal use of the roads the ash will have to be cleared. The next section looks at ash fall clean-up and how graph theory measures can help with prioritisation.

4.5.3 Estimating road clean-up

In this scenario it is assumed that all roads with over 0.2 mm of ash fall will need cleaning. Table 4.11 shows estimates of ash fall amounts to be cleared. These amounts were calculated using Magill et al. (2015) ash fall accumulation data (kg/m^2) and the road area exposed to ash fall greater than 0.2 mm. It is estimated that 229 x 10^6 kg (or 2.29 x 10^5 m^3) of volcanic ash would need to be cleared off roads in Yamanashi Prefecture from a future 1707 type eruption. However, since motorways are owned and managed by NEXCO, clean-up of these roads would not be the responsibility of the Prefecture government. Therefore Yamanashi Prefecture would be responsible for approximately 674 km of road to be cleared of 744 kg of ash.

Table 4.11: Approximate road surface area requiring clean-up and ash fall volumes to be removed.

Road type	No. of lanes	Road width m (*1 lane = 3 m)	Road length km	Road area km^2	Ash volume m^3	Ash Mass kg	Ownership
Motorway	4	12	95.458	1.145	1.54×10^5	154.39×10^6	Nexco central
Trunk	4	12	170.469	2.046	3.27×10^4	326.83×10^6	Yamanashi Prefecture
Primary	2	6	143.442	0.861	8.91×10^2	0.89×10^6	Yamanashi Prefecture
Secondary	2	6	167.376	1.004	1.41×10^4	14.14×10^6	Yamanashi Prefecture
Tertiary	2	6	192.32	1.154	2.67×10^4	26.72×10^6	Yamanashi Prefecture
Total	-	-	769.06	6.210	2.29×10^5	228.82×10^6	

* Road width = No. of lanes x 3. The average lane width is assumed to be 3 m.

An estimate of clean-up time was calculated using observations from the 2011 Shinmoedake eruption. After the Shinmoedake eruption, Takahura City was responsible for cleaning approximately 95 x 10^6 kg of volcanic ash off 307.4 km of roads (Magill et al. 2013). Small sweeper trucks could clean 1.6 km/day of roads and large sweeper trucks could clean 3.9 km/day. Using this rate of clean-up the total number of days needed to clear 673.61 km of roads in this scenario was estimated with respect to the number of road sweeper trucks available for both large and small vehicles (Figure 4.40). Around 20 large sweeper trucks or 50 small sweeper trucks per day (assuming this equipment is available) would be needed to clear all roads of ash fall greater than 2 mm within 10 days. This is a very crude estimate as the ash fall amounts from the Shinmoedake eruption were a lot less than estimated for this scale of eruption from Mount Fuji. The *Mt. Fuji Volcano Wide Evacuation Plan* also stated that street sweepers cannot operate under ash fall conditions of greater than 50 mm/day or 5 mm/day when raining. This adds another limitation to this estimate. More information and work is needed in this area to determine equipment availability, capacities, limits and logistics.

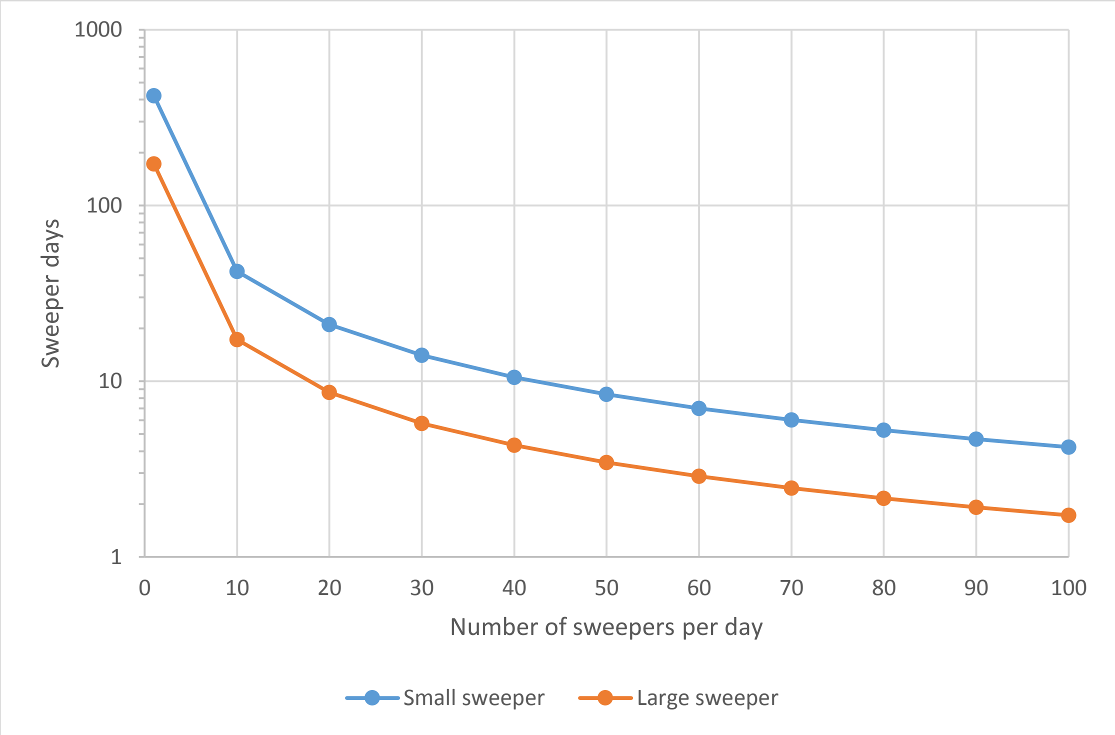


Figure 4.40: Road sweeper numbers and corresponding number of days to clean Yamanashi Prefecture roads. Estimate using Magill et al. (2013) observations from the 2011 Shinmoedake eruption.

4.5.4 Clean-up prioritisation

The clearing of 674 km of roads would be a large task and clean-up can be optimised by prioritising important and most used roads. Using the shortest paths from all vertices to all vertices (intersections), the edge (road) betweenness centrality (vertex betweenness explained in chapter 3) was calculated for impacted roads (>0.2 mm ash fall thickness). Figure 4.41 shows the betweenness scores for those roads. Here the motorways are highlighted as important connectors between locations. The motorways will be prioritised and cleared by NEXCO. To visualise which remaining roads should be cleaned first the motorways were removed but the betweenness values were not changed. Figure 4.42 displays the ranking of the remaining roads based on betweenness values. The most important roads were found to be those that connect the cities and villages within Yamanashi Prefecture. Roads of all types (trunk, primary, secondary and tertiary) are included in this list, which shows that road type might not give the best representation of importance in terms of use.

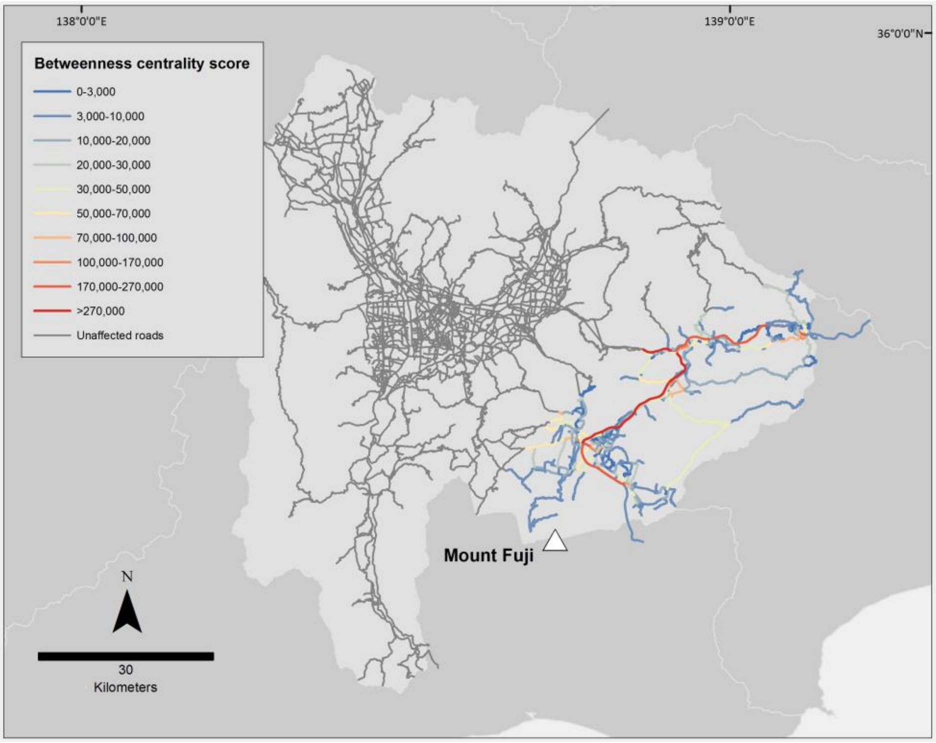


Figure 4.41: Road optimisation using betweenness centrality. Edge betweenness centrality scores equate to the number of times an edge (road) is used in a shortest path between two vertices (intersections). Warmer colours indicate high scores, cooler colours indicate low scores. Grey roads are not impacted by ash in this scenario so the betweenness is not displayed.

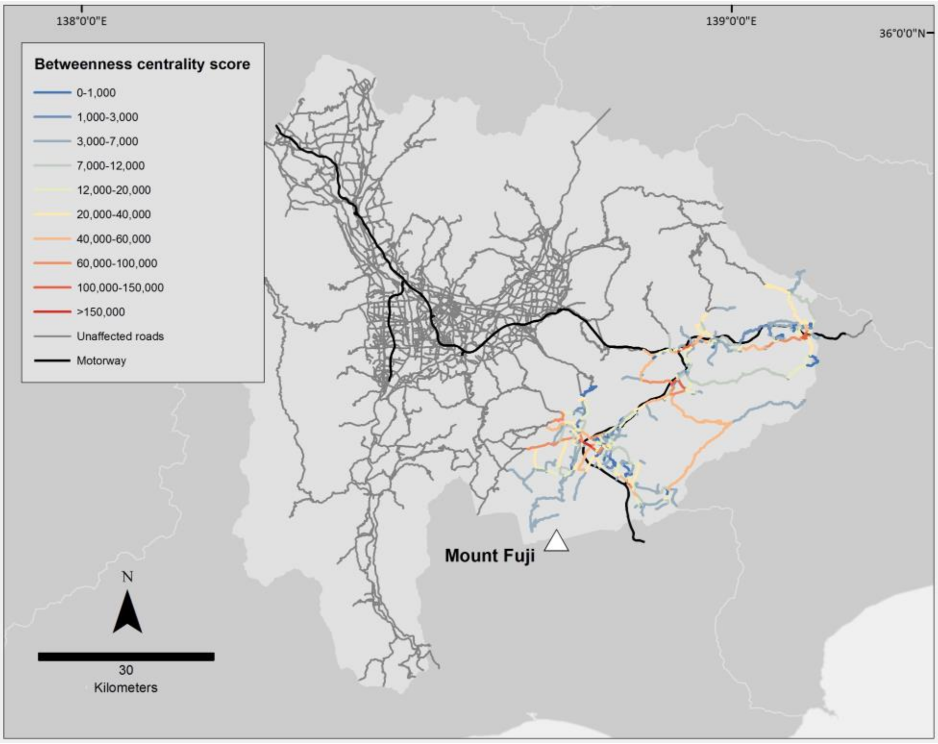


Figure 4.42: Road betweenness centrality with motorways omitted. Coloured as per Figure 4.41.

4.6 Discussion

This study used previously modelled ash fall simulations of the Hoei eruption and graph theory techniques to assess the impacts of volcanic ash fall on road infrastructure and to assess how road closures would affect current evacuation plans for Yamanashi Prefecture and resident return after the eruption. The eruption scenario was split into two parts. Part One looked at the ash fall conditions during the first 1.5 hours of the eruption (unit A), which coincides with the evacuation of residents in evacuation zone 2, outlined in the *Mt. Fuji Volcano Wide Evacuation Plan*. Part Two used the combined ash fall accumulation of all 17 units of the Hoei eruption to simulate the conditions Yamanashi Prefecture could face after the cessation of the eruption. In both Part One and Two of this scenario various ash fall thresholds were used to simulate road closures.

Ash induced road closures, at either 0.2, 1 or 10 mm, in Part One of this scenario would impact the evacuation plans for Oshino and Yamanakako cities by isolating a number of evacuation centres and creating necessary detours for others. This shows that ash fall accumulation, only after a couple of hours from the onset of an eruption, may inhibit the ability of residents to evacuate safely or unassisted. In this case it is advised that impacted areas in Oshino and Yamanakako cities evacuate well before the onset of the eruption, if possible, to avoid residents being impacted by volcanic ash fall and the hazards that ash can bring to road transportation. It is noted that this is only one potential scenario for a future eruption at Mt. Fuji and that other possible eruption scenarios and wind conditions should be explored. With more information and methods highlighted in Trindade et al. (2018), this work could go further to investigate evacuee arrival times at centres and to highlight potential congestion hotspots. This would be an interesting addition to this case study.

Part Two of this study looked at how ash induced road closures could impact resident return after the cessation of the eruption. Road closures due to ash fall accumulations of 0.2 mm would inhibit the return of residents in all six evacuated cities, with at least some, if not all, paths being blocked. If road closures occurred at ash fall accumulations of greater the 1 mm, road access to all cities, apart from Oshino and Yamanakako cities, would not be impacted. Oshino and Yamanakako cities would be impacted the most in this scenario, with road closures at any ash fall threshold impacting residents' return in some way. Those evacuees who are impacted by road closures after the cessation of the eruption will have to wait for roads to be cleared of ash before they can return home, extending their evacuation period and delaying their ability to attend to their properties, crops and/or livestock. It is noted that it is unlikely that roads with 100 mm or more of ash would remain open as roads would likely be impassable. It is important to ask whether, if ash fall depths of 100 mm or greater did not result in road closures, residents would want to return to their homes immediately. Residents located in Yamanakako City where ash loads were greater than 300 mm would also have to wait for roofs to be cleared of thick ash deposits and may face extensive damage and unliveable conditions on return.

In this scenario where wind conditions are predominantly westerly, the ash fall dispersal area of a future Hoei type eruption would also impact host cities to the west, especially Doshi, Otsuki and Uenohara Cities. Due to the potential disruptions caused by ash fall in this area it would be advised that, during these wind conditions, those that need to evacuate should relocate to host cities in the north or east instead. Evacuating residents into areas also impacted by ash fall will add additional pressure on those communities and could even result in further evacuations.

At the cessation of an eruption it is assumed here that a road would need to be cleaned if it received 0.2 mm or more of ash. Using ash loads and road areas, this study estimated that 2.29×10^5 m^3 of ash would need to be cleared from 769 km of roads. With NEXCO being responsible for the maintenance of the motorways, this would leave Yamanashi Prefecture with 0.75×10^5 m^3 of ash to clear from 674 km of roads. It is likely that roads will need repeated cleaning due to the remobilisation of ash from other areas by wind and vehicles. More information and work is needed in this area to determine prefecture equipment capacities, limits and a clean-up plan. Recent work by Hayes et al. (2017) provides a model to assess ash clean-up requirements in urban environments. The scalable clean-up response framework was tested on a number of eruption scenarios in Auckland, New Zealand, and the methods could be adapted for use in Japan. In looking at the impact of a series of eruption scenarios in Auckland, New Zealand, Blake et al. (2017b) noted that evacuation zones themselves can impact transportation networks, not only volcanic hazards. This is something that should be considered in this case study. Evacuation zones can inhibit road clean-up due to worker safety, potentially delaying clean-up operations. Moreover other transport services such as rail, although not physically damaged, may not be able to continue to run through evacuation zones, which can disrupt services outside of the hazard area.

Real-time ash modelling coupled with graph theory could be used to highlight where roads are likely to be impacted by certain ash fall thicknesses. This would be valuable for authorities especially if evacuating during the onset of the eruption cannot be avoided. For Yamanashi Prefecture, with set evacuation plans, it would enable authorities to plan where driving speeds should be reduced or where resources might be needed to help with a safe evacuation, such as in the clearing of thicker ash or fallen trees. Of concern in this scenario is a situation where residents are required to evacuate during the initial stages of an eruption (i.e. evacuation zone 2), when the eruption behaviour is unknown. Depending on the capacity of roads, it would be recommended to consider merging zone 2 with zone 1, which is to evacuate before the onset of an eruption and therefore less likely to be impacted by eruption products. However, it is acknowledged that evacuating residents when an eruption does not eventuate could impact on residents' willingness to evacuate again in the future (Tobin and Whiteford 2002).

Another concern is a situation where residents outside of the immediate evacuation zone for lava or pyroclastic flows are impacted by large amounts of ash fall. At first these residents are to shelter in place until over 300 mm of ash fall is reached. However, at this point it is likely that evacuation routes will be cut off by ash. Moreover, ash fall of less than 300 mm can damage lifelines that allow buildings to continue to be functional, such as electricity, gas, and water supply. Also, roof collapse can occur at ash fall depths less than 300 mm, especially if wet or if roof spans are large; therefore I would recommend that this threshold be re-evaluated and based on weight rather than depth. Perhaps ash fall thresholds for roof collapse should not be the determinant for evacuation at all, but instead ash fall thresholds required to disrupt critical lifeline services. This would reduce the risk of communities being cut off by blocked roads and/or refuging in place without essential amenities.

This scenario utilised simulations of eruption unit A and the combined units of the Hoei eruption. Methods used in this case study could be extended to include conditions likely to be faced during all evacuation categories outlined in the *Mt. Fuji Volcano Wide Evacuation Plan*, beyond zone 2 (3 hours – 40 days). This scenario also only assessed the impact of ash fall in westerly wind conditions. Areas impacted by volcanic ash will vary with different wind conditions and therefore these methods should be used to assess impacts during other wind directions.

Graph theory measures such as betweenness centrality can be used to determine important components of a network and were utilised here to provide a method for assigning clean-up priorities. Apart from motorways, roads that connect the cities and villages within Yamanashi Prefecture were found to be the most important and it was the loss of these roads that hindered evacuation plans and resident return. High betweenness scores were given to all types of roads (trunk, primary, secondary and tertiary), which shows that road type might not give the best representation of importance in terms of use. In this case, road edges were weighted by length and shortest paths were determined by the shortest distance. Other weights such as road widths, speed limits or time could also be added to the network to make modelling more robust. These parameters might uncover a different priority pattern, such as the ability of roads to transport more vehicles at the same time, which could be deemed more important than overall distance. This case study only looked at the evacuation of residents within Yamanashi Prefecture and not to or from other prefectures, which is a limitation of this study. Another limitation was not including road and intersection capacities, which were not available in the road data obtained.

Clean-up priority is an area that Yamanashi Prefecture has yet to look into in detail. Graph theory measures could be used as an initial step to map out potential areas of importance. Prefecture Governments can easily assign their own priority weights to network components. With private, national and locally owned roads, clean-up operations will need a collaborative effort between all parties. The availability of clean-up machinery and personal, and locations for ash collection is also not known at this stage. To help with a more collaborative approach it is advised to extend this scenario to include all prefecture government areas exposed to ash fall hazards.

Although great work has been done to mitigate against other life threatening volcanic hazards, from the interviews conducted in this study, it was noted that in Japan, at a national level, evacuation due to ash fall and its clean-up has not been fully addressed. Methods developed in this study can be transferred to other eruptive scenarios and to other volcanoes throughout Japan. Future scenarios could also include all eruptive products and potentially other lifelines. In particular, secondary mudflows and flooding impacted the area around Mount Fuji for years after the eruption. The study area could be extended beyond the immediate hazard event to look at the impact of these secondary hazards, which could have potential long-term impacts for road transportation.

This study provided the opportunity to test graph theory in natural hazard risk assessment and for post event recovery in a real world scenario, and to explore areas not yet addressed by Yamanashi Prefecture and the *Mt. Fuji Volcano Wide Evacuation Plan*. The results of this study have the potential to better inform Prefecture Governments of the feasibility of their planning and to provide them with methods for further assessment. This scenario also showed that the use of graph theory techniques alongside hazard modelling, with an understanding of the use of the lifeline impacted, helped to envisage the potential problems that could result from lifeline failure and that methods developed may aid in recovery.

4.7 Supplementary material

4.7.1 General interview questions

- Is anyone in your organisation currently studying the impact of ash on infrastructure networks around Mount Fuji?
- Which organisations are responsible for the management of particular infrastructure/networks?
- Which organisations would be responsible for ash clean-up following an eruption? What planning has been undertaken, and what are the clean-up methods and capacities?
- What are the ash clean-up priorities (if any)?
- What are the organisations current emergency response procedures for an eruption at Mount Fuji with regards to evacuation and ash clean-up?
- When would residents be advised to evacuate and how would that be carried out (private vehicles or emergency services)? Note this was only discussed with the prefectures.
- Where are evacuation centres located and what is their capacity? Note this was only discussed with the prefectures.
- How could my research help lifeline organisations, government and emergency management in Japan?

4.7.2 Yamanashi evacuation centres

4.7.2.1 Evacuee centres

Table 4.12: Evacuation centre locations in evacuating cities. These locations were used as start locations for calculating shortest paths.

City	Evacuation point	Lat_N	Long_E
Fujikawaguchiko	Fuji-Toyoshige Primary School	35.41666000	138.61713200
	Fujigamine Public Hall car park	35.41581400	138.61975600
	Old Kamikuishiki Junior High School	35.46842100	138.60658600
	Motosu Camp Field Car Park	35.46090800	138.60230900
	Motosuko Prefectural Car Park	35.46497200	138.60198900
	Motosuko Prefectural Youth Sports Centre Ground	35.45492800	138.59981600
	Saiko Minami Sports Ground	35.47924600	138.65899900
	Old Shoji Primary School	35.47835000	138.61336600
	Saiko Nishi Sports Ground	35.48898100	138.67643000
	Shoji Indoor Gateball Ground	35.49586000	138.60886900
	Residents' Sports Ground	35.48220100	138.75992200
	Oarashi Primary School	35.49631900	138.73255300
	Shojiko Prefectural Car Park	35.48610800	138.61556900
	Shototsudo Sports Ground	35.49693000	138.77690000
	Funatsu Primary School	35.50018400	138.76764800

	Kawaguchiko Minami Junior High School	35.50043000	138.75942500
	Kodachi Primary School	35.50518500	138.75065500
	Katsuyama Primary and Junior High Schools	35.50409200	138.74038000
	Saiko-Mukaihama river bank	35.50499200	138.69973500
	Yagisaki Park multi-purpose ground	35.51210100	138.75499800
	Nishihama Primary and Junior High Schools	35.50637600	138.70984100
	Nagahama-Shimojohama river bank	35.50812800	138.71602600
	Oishi Primary School	35.52437900	138.74566100
	Kawaguchiko Kita Junior High School	35.52095700	138.76943600
	Kawaguchi Primary School	35.53071300	138.76914000
Fujiyoshida	Kamiyoshida Community Centre	35.47877400	138.793679
	Shimoyoshida-Minami Community Centre	35.48602500	138.80643200
	Myoken Community Centre	35.49118400	138.81804600
	Shimoyoshida Community Centre	35.49518500	138.79546400
	Kamikurechi Community Centre	35.51650800	138.83142400
Narusawa	Keio Second Holiday House Tennis Court	35.45336600	138.71113200
	Keio First Holiday House Tennis Court	35.45654400	138.74119100
	Fuji-kan Third holiday House Tennis Court	35.45074200	138.73630800
	Marubeni Holiday House Park	35.45522600	138.73444800
	Momijidai "Century Villa" Holiday House Admin Office	35.47087900	138.67841900
	Narusawa Primary School	35.48216900	138.70721300
	Narusawa Road-side station	35.47833200	138.69203400
	Otawa Public Hall	35.48813700	138.72650500
	Narusawa Village Centre	35.48331700	138.71257900
Nishikatsura	Nishikatsura Primary School	35.51915800	138.84274600
	Nishikatsura Junior High School	35.52278200	138.841765
	Nishikatsura Child-care Centre	35.52413200	138.843584
	YLO Hall	35.52432600	138.84430300
	Health and Welfare Centre	35.52367100	138.84290600
Oshino	Yanagihara Park	35.44944600	138.84179400
	Museum car park	35.45735900	138.81938400
	Uchino-area office car park	35.45822100	138.85830500
	Shoten Temple	35.45925100	138.85419700
	Tengu Shrine	35.45605500	138.862274
	Oshino Primary School	35.46115900	138.84742300
	Shibokusa Community Centre car park	35.45794400	138.83610700
Yamanakako	Yamanakako-mura Public Gym	35.40805900	138.85734000
	Yamanakako Creative Information Centre	35.40718000	138.86891000
	Nagaike Community Centre	35.40761900	138.87523100
	Yamanakako Junior High School	35.40848400	138.85712500
	Asahigaoka Public Hall	35.40808400	138.88550300
	Yamanakako-mura Public Hall	35.42030300	138.84924500
	Yamanaka Primary School	35.42533000	138.84682200
	Yamanakako-mura residents' & kids' gym	35.42507800	138.84622900

	Yamanakako-mura Community Centre	35.42583500	138.90925600
	Yamanakako-Hirano-Onsen Ishiwari Spa	35.43510200	138.90871800
	Yamanaka Child-care Centre	35.42881900	138.84924200
	Yamanakako Communication Plaza 'Kirara'	35.41957700	138.90134200
	Hirano Child-care Centre	35.42953900	138.89890500
	Higashi Primary School	35.42332500	138.89184400
	Yamanakako-Onsen Beni-Fuji Spa	35.43014300	138.84247000

4.7.2.2 Host centres

Table 4.13: Evacuation centre locations in host cities. These locations were used as stop locations for calculating shortest paths.

City	Evacuation point	Lat_N	Long_E
Kofu	Yuda Primary School	35.64948200	138.57510800
	Higashi Primary School	35.65199200	138.582707
	Maizuru Primary School	35.66323200	138.565047
	Old Anagiri Primary School (City Office West Building)	35.66319500	138.55972800
	Kita Junior High School	35.67956600	138.55725200
Nirasaki	Nirasaki High School	35.71538500	138.45004500
Minami-Arupusu	Shirane High School	35.64310000	138.49409100
	Kushigata Junior High School	35.61612900	138.46054100
	Koma High School	35.61603700	138.46876300
Hokuto	Akeno Junior High School Gymnasium	35.77020300	138.44346900
	Sutama Primary School Gymnasium	35.79435300	138.42535500
	Takane Gymnasium	35.84209500	138.42713500
	Nagasaka General Sports Park Gateball Field	35.84128200	138.37007600
	Oizumi Gymnasium	35.85819900	138.378776
	Kobuchisawa Junior High School Gymnasium	35.86694800	138.32130500
	Hakushu Gymnasium	35.82670100	138.31039500
	Mukawa Junior High School Gymnasium	35.78461300	138.37325200
Kai	Ryuo-kita Junior high School	35.67016200	138.50476500
	Shikishima-kita Primary School	35.69481100	138.52484900
	Futaba-higashi Primary School	35.69261200	138.49853900
Chou	Tatomi-kita Primary School	35.60338000	138.51358300
	Mimura Primary School	35.60425100	138.54455700
	Toyotomi Primary School	35.57060000	138.55748800
Showa	Saijo Primary School Gymnasium	35.63775500	138.53927400
Otsuki	Old Sasago Primary School	35.60520200	138.83135800
	Hatsukari Primary School	35.59862600	138.88467600
	Otsuki College	35.61283200	138.94664300
	Old Kowaze Primary School	35.61580600	138.95664700
	Nanaho Primary School	35.63181700	138.95547900

	Saruhashi Junior High School	35.61696600	138.98044900
	Torisawa Primary School	35.61011000	139.00513800
	Shizen-Gakuen High School (Old Yanagawa Primary School)	35.60031500	139.042944
Uenohara	Uenohara-nishi Junior High School Gymnasium	35.61841600	139.089409
	Uenohara-nishi Primary School Gymnasium	35.61560900	139.07894600
	Uenohara high School Gymnasium	35.62356900	139.100700
	Ome Branch Office	35.62093900	139.06002900
	Old Heiwa Junior High School Gymnasium	35.63258100	139.06108300
	Koto Branch Office	35.63636700	139.06389100
	Uenohara-nishi Primary School Wami Branch School	35.65905500	139.05767600
	Akiyama Junior High School Gymnasium	35.56836600	139.08597700
	Nishihara Branch Office	35.70204400	139.02253900
	Furusato Choju Hall	35.66993900	139.08954800
	Uenohara City Culture Hall	35.63012600	139.10822900
	Shimada Primary School Gymnasium	35.61485000	139.118802
	Old Otsuru Primary School Gymnasium	35.63637500	139.09354600
Doshi	Doshi Junior High School	35.52002000	139.02203300
Koshu	Enzan High School Gymnasium	35.71943400	138.72750300
Minobu	Simobe District Residents' Gymnasium	35.46320100	138.48389300
	Hara Primary School Gymnasium	35.44453500	138.43913700
Nanbu	Arcadia Manbu Sports Centre	35.27918700	138.45655600
Yamanashi	Kanoiwa Primary School	35.68223400	138.68553900
	Kusakabe Primary School	35.69760200	138.69958000
	Yawata Primary School	35.70667000	138.68404800
	Yamanashi Primary School	35.68457100	138.665639
	Higawa Primary School	35.66562400	138.69030400
	Goyashiki Primary School	35.68933000	138.70416800
	Iwade Primary School	35.71573000	138.697350
	Hanakage-no-Yu	35.73645000	138.71376100
	Fuekawa Junior High School	35.74406700	138.71401300
	Makioka-Daiichi Primary School	35.74656300	138.713252
	Makioka-Daini Primary School	35.74761800	138.69530100
	Makioka-Daisan Primary School	35.74553100	138.65210900
	Mitomi Primary School	35.78150800	138.73883700
Fuefuki	Fuefuki High School	35.64516300	138.64592600
Ichikawa-Misato	Ichikawa Primary School	35.55908800	138.50128200
Fujikawa-	Masuho Primary School	35.56329500	138.45758600

4.7.3 Impacts to evacuation routes with regards to resident evacuation and return

Tables 4.14 to 4.24 show the detailed disruption caused by road closures at various ash fall thresholds (0.2 mm – 300 mm). These tables were created by calculating the difference between the original shortest paths between evacuee and host centres and the recalculated shortest paths after road closures, for both Part One (evacuation) and Part Two (resident return) of the eruption scenario. In some cases multiple ash fall thresholds resulted in the same situation. In these cases they were combined into one table to avoid repetition. To which ash fall scenario and threshold the table refers to is stated in the caption.

Table 4.14: Impact to Oshino evacuation plans. Situation for Part One ash fall thresholds 1 mm and 10 mm, and Part Two ash fall thresholds 100 mm and 300 mm. Evacuee locations are in the left hand column and the host locations are across the top.

To ->	**D**	**O1**	**O2**	**O3**	**O4**	**O5**	**O6**	**O7**	**O8**	**U1**	**U2**	**U3**	**U4**	**U5**	**U6**	**U7**	**U8**	**U9**	**U10**
Oshino 1	Detour + 14919 m	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Oshino 2	Detour + 8299 m	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Oshino 3	Detour + 12160 m	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Oshino 4	Detour + 11125 m	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Oshino 5	Detour + 10891 m	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

*D = Doshi, O = Otsuki, U = Uenohara, - = shortest path unchanged

Table 4.15: Impact to Oshino evacuation plans. Situation for Part One ash fall threshold 0.2 mm. Evacuee locations are in the left hand column and the host locations are across the top.

To ->	D	O1	O2	O3	O4	O5	O6	O7	O8	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
Oshino 1	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked
Oshino 2	Blocked	-	-	-	-	-	-	-	-	Blocked	-	-	-	-	-	-	-	-	-
Oshino 3	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked
Oshino 4	Blocked	-	-	-	-	-	-	-	-	Blocked	-	-	-	-	-	-	-	-	-
Oshino 5	Blocked	-	-	-	-	-	-	-	-	Blocked	-	-	-	-	-	-	-	-	-

*D = Doshi, O = Otsuki, U = Uenohara, - = shortest path unchanged

Table 4.16: Impact to Oshino evacuation plans. Situation for Part Two ash fall thresholds 0.2 mm and 1 mm. Evacuee locations are in the left hand column and the host locations are across the top.

To ->	D	O1	O2	O3	O4	O5	O6	O7	O8	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
Oshino 1	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked
Oshino 2	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked
Oshino 3	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked
Oshino 4	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked
Oshino 5	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked

*D = Doshi, O = Otsuki, U = Uenohara, - = shortest path unchanged

Table 4.17: Impact to Oshino evacuation plans. Situation for Part Two ash fall threshold 10 mm. Evacuee locations are in the left hand column and the host locations are across the top.

To ->	D	O1	O2	O3	O4	O5	O6	O7	O8	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
Oshino 1	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked
Oshino 2	Blocked	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Oshino 3	Blocked	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Oshino 4	Blocked	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Oshino 5	Blocked	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

*D = Doshi, O = Otsuki, U = Uenohara, - = shortest path unchanged

Table 4.18: Impact to Yamanakako evacuation plans. Situation for Part One ash fall thresholds 0.2 mm and 1 mm, and Part Two ash fall thresholds 0.2 mm, 1 mm and 10 mm. Evacuee locations are in the left hand column and the host locations are across the top.

To ->	**Koshu**
Yamanakako 1	Blocked
Yamanakako 2	Blocked
Yamanakako 3	Blocked
Yamanakako 4	Blocked
Yamanakako 5	Blocked
Yamanakako 6	Blocked
Yamanakako 7	Blocked
Yamanakako 8	Blocked
Yamanakako 9	Blocked
Yamanakako 10	Blocked
Yamanakako 11	Blocked

Table 4.19: Impact to Yamanakako evacuation plans. Situation for Part Two ash fall threshold 100 mm. Evacuee locations are in the left hand column and the host locations are across the top.

To ->	**Koshu**
Yamanakako 1	Blocked
Yamanakako 2	Blocked
Yamanakako 3	Blocked
Yamanakako 4	Blocked
Yamanakako 5	Blocked
Yamanakako 6	Blocked
Yamanakako 7	Blocked
Yamanakako 8	Blocked
Yamanakako 9	Blocked
Yamanakako 10	Blocked
Yamanakako 11	-

- = shortest path unchanged

Table 4.20: Impact to Yamanakako evacuation plans. Situation for Part One ash fall threshold 10 mm. Evacuee locations are in the left hand column and the host locations are across the top.

To ->	Koshu
Yamanakako 1	Blocked
Yamanakako 2	Blocked
Yamanakako 3	Blocked
Yamanakako 4	Blocked
Yamanakako 5	Blocked
Yamanakako 6	-
Yamanakako 7	Blocked
Yamanakako 8	Blocked
Yamanakako 9	-
Yamanakako 10	Blocked
Yamanakako 11	-

- = shortest path unchanged

Table 4.21: Impact to Yamanakako evacuation plans. Situation for Part Two ash fall threshold 300 mm. Evacuee locations are in the left hand column and the host locations are across the top.

To ->	Koshu
Yamanakako 1	Blocked
Yamanakako 2	Blocked
Yamanakako 3	Blocked
Yamanakako 4	Blocked
Yamanakako 5	-
Yamanakako 6	-
Yamanakako 7	Blocked
Yamanakako 8	Blocked
Yamanakako 9	-
Yamanakako 10	Blocked
Yamanakako 11	-

- = shortest path unchanged

Table 4.22: Impact to Fujiyoshida evacuation plans. Situation for Part Two ash fall threshold 0.2 mm. Evacuee locations are in the left hand column and the host locations are across the top.

To ->	H1	H2	H3	H4	H5	H6	H7	Ka1	Ka2	Ka3	Ko1	Ko2	Ko3	Ko4	Ko5	M1	M2	M3	N1
Fujiyoshida 1	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked
Fujiyoshida 2	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked
Fujiyoshida 3	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked
Fujiyoshida 4	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked
Fujiyoshida 5	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked

*H = Hokuto, Ka = Kai, Ko = Kofu, M = Minami-Arupusu, N = Nirasaki, - = shortest path unchanged

Table 4.23: Impact to Fujiyoshida evacuation plans. Situation for Part Two ash fall threshold 1 mm. Evacuee locations are in the left hand column and the host locations are across the top.

To ->	H1	H2	H3	H4	H5	H6	H7	Ka1	Ka2	Ka3	Ko1	Ko2	Ko3	Ko4	Ko5	M1	M2	M3	N1
Fujiyoshida 1	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked
Fujiyoshida 2	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked
Fujiyoshida 3	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked
Fujiyoshida 4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fujiyoshida 5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

*H = Hokuto, Ka = Kai, Ko = Kofu, M = Minami-Arupusu, N = Nirasaki, - = shortest path unchanged

Table 4.24: Impact to Fujikawaguchiko evacuation plans. Situation for Part Two ash fall threshold 0.2 mm. Evacuee locations are in the left hand column and the host locations are across the top.

To ->	Ff	Fj	I	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10	Y11	Y12
Fujikawaguchiko 1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fujikawaguchiko 2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fujikawaguchiko 3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fujikawaguchiko 4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fujikawaguchiko 5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fujikawaguchiko 6	Detour + 2278 m	-	-	Detour + 5248 m	Detour + 2041 m	Detour + 4343 m	Detour + 4765 m	Detour + 4343 m	Detour + 3749 m	Detour + 3894 m	Detour + 3894 m	Detour + 3894 m	Detour + 3894 m	Detour + 3894 m	Detour + 4174 m
Fujikawaguchiko 7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fujikawaguchiko 8	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked
Fujikawaguchiko 9	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked

Fujikawaguchiko 10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fujikawaguchiko 11	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked
Fujikawaguchiko 12	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked
Fujikawaguchiko 13	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked
Fujikawaguchiko 14	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked
Fujikawaguchiko 15	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked
Fujikawaguchiko 16	Detour + 10910 m	-	-	Detour + 13880 m	Detour + 10673 m	Detour + 12975 m	Detour + 13397 m	Detour + 12975 m	Detour + 12381 m	Detour + 12526 m	Detour + 12526 m	Detour + 12526 m	Detour + 12526 m	Detour + 12526 m	Detour + 12806 m
Fujikawaguchiko 17	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked
Fujikawaguchiko 18	Detour + 14652 m	Detour + 591 m	Detour + 591 m	Detour + 17622 m	Detour + 14415 m	Detour + 16717 m	Detour + 17139 m	Detour + 16717 m	Detour + 16123 m	Detour + 16268 m	Detour + 16268 m	Detour + 16268 m	Detour + 16268 m	Detour + 16268 m	Detour + 16548 m
Fujikawaguchiko 19	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked
Fujikawaguchiko 20	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked

Fujikawaguchiko 21	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked	Blocked

*Ff = Fuefuki, Fj = Fujikawa, I = Ichikawa-Misato, Y = Yamanashi, - = shortest path unchanged

Table 4.25: Impact to Narusawa evacuation plans. Situation for Part Two ash fall threshold 0.2 mm. Evacuee locations are in the left hand column and the host locations are across the top.

To ->	M1	M2	N
Narusawa 2	Blocked	Blocked	Blocked
Narusawa 2	Blocked	Blocked	Blocked
Narusawa 2	Blocked	Blocked	Blocked
Narusawa 2	-	-	-
Narusawa 2	Blocked	Blocked	Blocked
Narusawa 2	Blocked	Blocked	Blocked

*M = Minobu, N = Nanbu, - = shortest path unchanged

Table 4.26: Impact to Nishikatsura evacuation plans. Situation for Part Two ash fall threshold 0.2 mm. Evacuee locations are in the left hand column and the host locations are across the top.

To ->	C1	C2	C3	S
Nishikatsura 1	Blocked	Blocked	Blocked	Blocked
Nishikatsura 2	Blocked	Blocked	Blocked	Blocked

*C = Chou, S = Showa, - = shortest path unchanged

Chapter 5 Discussion

The aim of this thesis was to provide a better understanding of the impacts of lifeline failure during natural hazard events, with graph theory being the proposed tool to help achieve this. This thesis sought to go beyond natural hazard exposure and vulnerability and to model lifeline disruption in order to investigate how the loss of essential services can impact disaster response and recovery. This chapter first summarises and evaluates the contribution of individual chapters towards the thesis aim, then discusses the implications of research findings, limitations of the methods used and how this work can be expanded upon going forward.

5.1 Chapter summaries and contributions

The chapters in this thesis, although addressing distinct objectives, link together to address the main goal of modelling the impact of lifeline infrastructure failure during natural hazard events. Each chapter is therefore not only a standalone contribution to its specific topic area but also part of a body of work that, as a whole, contributes to the improvement of disaster management in a modern interconnected world. This section highlights the important points and findings of each chapter and the connections between them.

Chapter 1 introduced the importance of lifeline infrastructure in the modern world and the impacts that lifeline failure can have on all aspects of daily life. The chapter identified gaps in the preparedness for extensive lifeline failure, especially during natural hazard events, which often cause damage to multiple lifeline components. Chapter 1 also introduces the aims and objectives of this thesis and outlines the thesis structure, including research outputs and contributions to each chapter.

Chapter 2 looked to two past events – the 2009 south-eastern Australia heatwave and the 2010 Eyjafjallajökull eruption in Iceland – to understand how lifeline failure can compound the impacts of natural hazards. These events highlighted that the disruption of lifeline services (power and air transportation respectively) during natural hazard events has the potential to impact populations by exacerbating the hazard itself and/or hindering the ability to respond to or recover from the event. Lifeline failure can also propagate outside the reach of the hazard footprint, causing disruption in regions not directly impacted by the event, and potentially creating a disaster where, if it was not for the reliance on that network, there would not be one.

The two case studies also highlighted that, in the natural hazard space, there is an unpreparedness for the loss of lifeline services. This sparked the need for further investigation on why such events were not anticipated. The cascading nature of lifeline failures represents an emergent risk, in that natural hazard events can now have complex and far-reaching impacts due to our reliance on interdependent and interconnected systems. Although not entirely unforeseen, lifeline failure during disasters has yet to be fully incorporated into disaster plans.

A review of relevant literature showed improved preparedness at higher levels of industry and government in terms of lifeline resilience but there was a gap at the local government level and especially a disconnect at the community level. The barriers which appeared to limit the extent of the inclusion of and preparedness for lifeline failure were:

- Inadequate community education and engagement about lifeline failure in a disaster.
- Limitations of local government to strengthen lifeline infrastructure and mitigate service failure.
- Inaccessibility of sensitive lifeline information.
- A lack of holistic disaster scenarios.

Chapter 2 addressed the first objective of this thesis by identifying current gaps in emergency management and disaster mitigation with regards to shocks to lifeline infrastructure from natural hazards, and the flow on effects of lifeline failure. The findings of this review found that most efforts have concentrated on upgrading lifeline infrastructure to avoid future failures but have given little attention to preparing communities to better cope with inevitable future outages; reiterating the need for a better understanding of lifeline systems and the incorporation of all aspects of the built environment in planning for future disasters.

Chapter 3 set out to address the second objective of this thesis by assessing the usefulness of mathematical graph theory tools in aiding disaster mitigation, emergency response and community recovery. This chapter explored how graph theory could be used to analyse and predict service disruption during network failure in a natural hazard context. For exploratory purposes the Tokyo Subway network was subjected to a hypothetical inundation scenario, mimicking a sudden sea level rise of seven metres. The stations and tracks that coincided with the inundation footprint were removed from the network and a number of graph theory measures were used to assess the networks functionally. The network was weighted by travel times and passenger numbers to help determine the possible extent and magnitude of the simulated disruption. The hypothetical inundation scenario resulted in 26% of the network being deemed non-operational. Graph theory based tools allowed alternative routes to be determined, where possible, and helped to explain how station importance and influence in the network changed after network disruption. It was concluded that graph theory has the potential to be of great assistance in preparing for and responding to lifeline disruption caused by natural hazards if enough information is available on the network and the population who relies on its operation.

Chapter 4 built on the findings of both chapters 2 and 3 to incorporate lifeline disruption into current natural hazard plans and to further examine the use of graph theory to assess the impact of lifeline failure on disaster response and recovery. Chapter 4 used the scenario of a future explosive volcanic eruption at Mount Fuji in Japan. This scenario was used primarily due to the availability of information and the willingness of various sectors to participate. A number of representatives from prefecture governments, research centres and lifeline companies were engaged to better understand the reliance on lifelines in this scenario and the potential gaps that this study could help fill. Field visits uncovered that the potential disruption of road transportation from volcanic ash fall and its clean up were under investigated. Using both ash fall dispersal modelling and graph theory techniques this chapter assessed the impacts that ash induced road closures would have on emergency response during, and recovery following, an eruption. In particular these techniques were used to assess the impacts of ash fall on the evacuation plans for Yamanashi Prefecture with regards to a future 1707 Hoei type eruption. In this scenario, with similar westerly wind conditions as at the time of the Hoei eruption, ash induced road closures would impact current evacuation plans for Yamanashi Prefecture and hinder event recovery. The initial eruption phase that resulted in the deposition of unit A exposed ~150 km of roads, to the east of the volcano, to 0.2 mm or more of volcanic ash. If road closures occurred at ash fall thicknesses between 0.2 to 10 mm, current evacuation plans for Oshino and Yamanakako cities (two of the six cities noted to evacuate) would be impacted by cutting off a number of evacuation centres and creating necessary detours for others. The entire ash fall accumulation of this eruption scenario resulted in 2.29 x 10^5 m^3 of ash being deposited on ~770 km of roads in Yamanashi prefecture. With ash fall clean-up likely to commence at accumulations as low as 0.2 mm a number of residents from all six evacuated cities may not be able to return home until roads reopen. Moreover, areas which are likely to receive high ash loads (≥ 300 mm), such as Yamanakako City, would also have to clean roofs of ash to avoid collapse and ensure resident safety. In this scenario host cities to the east, especially Doshi, Otsuki and Uenohara, would receive up to 10 mm of ash fall and be impacted themselves. Therefore these locations might not make the best environments to evacuate to. For this particular scenario the following recommendations were made:

- Ash fall accumulation, only after a couple of hours from the onset of an eruption, may inhibit the ability of residents to evacuate safely or unassisted. Therefore, locations potentially exposed to ash fall need to evacuate before the onset of an eruption to avoid the hazards that ash fall can bring to road transportation. However, this relies on adequate warning systems and fast decision-making processes to pre-emptively evacuate a population before an eruption starts. This is no easy feat and comes with its on problems. Such as being able to accurately predict eruptive events.
- Evacuees should plan for an elongated stay in host locations. Not only is the duration of a future eruption unknown but also it may take some time for roads to be cleared of ash and buildings to be assessed for damage.
- In a scenario where wind conditions are predominantly westerly it is advised to reassess the evacuation of residents to the north east where host cities could be impacted by ash fall themselves; adding additional pressure on these communities.

It is noted that the Hoei eruption itself is only one possible eruption scenario from Mount Fuji, leaving many potential scenarios unacknowledged. Perhaps for Yamanashi Prefecture a more devastating outcome would be one where the wind blows a little more to the north. This would lead to the deposition of volcanic ash in more densely populated regions of Yamanashi and therefore expose more of the prefecture's roads to ash fall, potentially resulting in greater disruption to current evacuation plans and requiring more extensive ash fall clean-up operations. Hence it is recommended to explore a variety of future scenarios, including the impacts from all eruptive products. Areas that may not be impacted by substantial ash fall could instead be impacted by other volcanic hazards such as such as pyroclastic flows or lahars.

However, this scenario provided the opportunity to test graph theory techniques for the use of natural hazard risk assessment and post event recovery in a real-world context and to explore potential situations that were yet to be addressed by Yamanashi Prefecture. With the *Mt. Fuji Wide Evacuation Plan* only completed in 2016, the prefecture government, at the time of my visit, had yet to test this plan and acknowledged there were areas that needed further attention; the impacts of ash fall being one of them. The results of this study have the potential to better inform the prefecture government of the feasibility of their evacuation plans with regards to volcanic ash fall and to provide them with methods for further risk assessment. This chapter will be disseminated to the Japanese collaborators and any journal articles resulting from this study will be submitted only after input and approval from these collaborators.

This scenario also showed that the use of graph theory techniques alongside GIS tools and hazard modelling, with an understanding of the use of the lifeline impacted, can help to envisage potential problems that could result from lifeline failure and aid in the process of recovery. This may include analysis of the impact of disruption of transportation systems on emergency response operations and determination of which routes to open first for optimal network recovery. With the impact of ash fall and its clean up still not fully addressed at a national level in Japan there is a need to further explore this hazard in other prefectures around Mount Fuji and other volcanoes throughout the country. Methods developed in this scenario could be transferable to other eruptive scenarios throughout Japan. Moreover these methods could be used to address the exposure and risk to lifelines from other natural hazard events or even to compare between them.

Additional outputs produced during my candidature included magazine articles and conference papers and posters (see Appendices). Some summarised past and present work and others explored new areas of research that ultimately did not develop further. Although these additional pieces of work (Appendix B and C) did not find their place in the final thesis, they influenced and guided the direction of my PhD overall. Initially I strived to include an Australian case study into this thesis but was not able to acquire the necessary information and data to adequately model lifeline failures in Australia. Although lifeline infrastructure vulnerability and resilience is an area of interest for the Australian Government and emergency managers, information to truly assess either is difficult to come by. A number of representatives of the Australian lifeline sector and the Attorney Generals Department were approached about lifeline data accessibility for this thesis. Although they were supportive of the study, they either did not have the information to give, such as geolocations of assets or estimates of infrastructure vulnerabilities, or were unable to do so due to security concerns and/or market sensitivities. Therefore initial plans for an Australian scenario had to be abandoned. Australia is not alone in being dogged by these problems that inhibit lifeline research. However, other locations, such as New Zealand, have been able to overcome them. New Zealand has made significant progress in this area over the last couple of decades with the creation of regional lifeline groups and a national lifelines committee (http://www.nzlifelines.org.nz/). A recent extensive study on the impact of a future eruption in the Auckland Volcanic Field, New Zealand, which is includes the impact to lifelines (Deligne et al. 2017, Blake et al. 2017b) shows what can be achieved with interagency collaboration and information sharing.

I am happy to report that things in Australia are also slowly changing. Over the course of this thesis, the interest in lifeline impacts has grown in the Australian emergency management space and I was invited by the Bushfire and Natural Hazard CRC to contribute to a workshop in August 2018 with the electricity sector to discuss current gaps in their preparedness for natural hazard events and to outline key areas for future research in this area. I hope this thesis highlights the need for further work on lifeline impacts during natural hazard events and that Australia continues progressing in this area. Although most of the case studies and scenarios in this thesis are from afar, the learnings can be implemented here in Australia.

A portion of chapter 2 was also submitted as a chapter, entitled: '*Disruption from disaster or disasters from disruption? Compounding impacts from lifeline infrastructure failure during natural hazard events*', to the book '*The demography of disasters*'. With the publication of this work I hope to encourage and add to the global conversation on the impact of lifeline failure during disasters.

Chapter 4 is currently being prepared for publication and the results of the Hoei scenario will be shared with the Yamanashi Prefecture and the other representatives that participated in interviews.

5.2 Implementation

With a combined understanding of lifeline networks, natural hazards and the community natural hazard events and their impacts can be better prepared for. When combined with hazard modelling and GIS tools, graph theory measures can be useful for both understanding and visualising lifeline failure in a natural hazard context. Methods outlined in this study can be of use throughout the entire disaster management process, from mitigation to response and recovery.

Mitigation: Knowing the current exposure and vulnerability of lifelines to disruption from natural hazards can help local governments or councils to prioritise infrastructure upgrades, make better development choices and help target community outreach. Development of disaster scenarios, incorporating potential lifeline failure, can help inform emergency services of likely areas to be without lifeline services. Knowing which areas could be cut off from utilities such as power or water would enable populations to pre-empt any aid needed, such as generators or sanitation solutions, and assess their ability to combat the hazard. This could create a clearer picture of an event and allow residents and emergency managers to decide whether exposed populations should leave early or shelter in place.

Response: Natural hazard events can wreak havoc on the built environment and surrounding landscape. Provided with adequate input information, the methods outlined in this thesis could help emergency services to visualise and assess the situation. Graph theory techniques could help determine road access for evacuation and/or emergency response or the availability of lifeline services that first responders rely on to do their jobs such as power, communications and water. The remaining components of a damaged network could be assessed for importance and therefore prioritised for protection to help prevent further service outage.

Recovery: In the aftermath of a natural hazard event, techniques utilised in this thesis could be useful for optimising recovery. What parts of a lifeline network should be repaired first to allow for optimal operation? Overlaid with social and economic data graph representations of lifelines could help decide what areas need to be reconnected first or what areas need temporary solutions in the meantime. Learnings from an event or any changes to demographics that may influence exposure and vulnerability can be built into future scenarios, disaster mitigation and land use planning.

Referring back to the two case studies in Chapter 2 – the 2009 south-eastern Australia heatwave and the 2010 Eyjafjallajökull eruption in Iceland – we can ask whether the use of these methods would have aided in the preparedness or recovery of these events. In the case of the south-eastern Australian heatwave, the electricity network was the most vulnerable. However, it would have been difficult to foresee which component would fail first in the high heat due to the widespread nature of the phenomenon. Pre-event modelling of network failure in this case would have been useful for collaborative operational purposes but any imagined scenario would have unlikely captured the exact flow of events in 2009. However, sharing the knowledge of how fragile the power network is to disruption during heatwave events and what to do in the case of power failure could have better prepared communities for service outage and potentially lessened the reliance on emergency services. Where graph theory and a holistic approach to emergency management would help in this case is in understanding the impacts of scheduled rolling blackouts on the community and other lifelines, such as transportation and communication networks, and where to prioritise reconnection during recovery.

For the Icelandic eruption, which shut down the European airspace, there was an overall lack of preparedness for this event. This event highlighted that there is a need to plan for emergent or pear-shaped events, not just the most probable. If this event was investigated and the risk of extensive airspace closure highlighted and communicated across all sectors, perhaps the result would have been different. Policies and insurances could have been pre-developed rather than being assembled hastily during the crisis, such as determining aircraft ash tolerance levels and changes to airlines' business interruption insurance to include non-material damage. Modelling various catastrophic disruptions of air transportation in this case could have better prepared not just the airline industry itself but also other sectors that rely on its operation. Graph theory could have also been used to determine alternative routes for the movement of goods and people, both within the air network itself and on-land and sea-based transport networks.

5.3 Limitations

Understanding the true impacts of natural hazards involves an intimate understanding of natural, built and social systems and their interconnectedness. This thesis integrated a number of tools and techniques to provide a holistic approach to disaster management. Each model used had its own simplifications and assumptions; the integration of which inherently presents limitations and errors in any result. Although efforts were made to make case studies as authentic and realistic as possible, the results and conclusions in this study should be used as a guide only and act as a starting point to be built upon. Specific limitations for each model and tool used is expanded on in the methods and discussion sections in chapters 3 and 4. This section looks at the broader limitations of this approach as a whole, potential barriers to implementation and ways these barriers may be overcome.

One limitation that was met up front was data availability and sensitivity. Although critical infrastructure vulnerability and resilience is an area of interest for government and emergency managers, the information to truly assess either was hard to come by. For example, the Australian Government established a national Critical Infrastructure Strategy for Australia (Commonwealth of Australia 2010). This Strategy provides a foundation on which governments and owner and operators of critical infrastructure can prepare for, and response to, a range of significant disruptive events. This thesis aligned with a number of Outcomes of the Strategy and Outcome 3 of the Critical Infrastructure Resilience Strategy Policy Statement specifically stated:

"The Australian Government will continue to work closely with The Trusted Information Sharing Network (TISN) groups, international partners, government agencies and academia to examine strategic issues and trends affecting critical infrastructure, and will facilitate cross-sectional collaboration and information sharing on these issues, including through exercises and workshops" (Commonwealth of Australia 2015 page 12).

However, the TISN has a deed that prohibits confidential and sensitive information from being shared beyond this group (Commonwealth of Australia 2018), challenging the statement above. Although commercial and security sensitivities around critical infrastructure vulnerabilities are appreciated the inability to access vital information is a large barrier for the implementation of the methods outlined in this thesis and for better preparedness for lifeline failure on the whole. A solution could be that organisations use these methods to assess their own vulnerabilities and aggregate the information they share publically to avoid releasing sensitive information. For example, collectively the group could release maps of general areas likely to experience service outages for various situations and provide information on likely recovery times.

A limitation of graph theory techniques as a tool for disaster management is that when large portions of lifeline infrastructure components are exposed to disruption from a natural phenomenon, graph theory techniques would not provide much insight during the event itself. For example graph theory techniques for determining alternative paths, changes in component importance and highlighting areas of isolation become redundant when there is no network left to analyse. However, in such cases, these techniques can still be of use in recovery. Another limitation of network modelling is that data collection and network construction can be time consuming. Data often need to be gathered and aggregated from numerous sources. Data then needs to be extensively reformatted into usable network components to enable the construction of a graph representation. Understanding network vulnerabilities, thresholds for failure and the reliance on the network needs consultation with government, private and community sectors. The creation of network models cannot be created rapidly at the onset of a natural hazard event, instead this process would have to occur beforehand during disaster planning and mitigation. However, once created, graphed networks can be easily adjusted though coded scripts. A natural hazard event can change rapidly and automation of a network model would enable it to adapt to changes in the hazard footprint. This may be particularly important in the case of volcanic eruption where the hazard may occur over an extended duration. A pre-established graphed lifeline network – such as the Yamanashi road network created in Chapter 4 – could be incorporated into the outputs of the real-time ash modelling done by Japan Metrological

Agency, not only providing daily simulations for all volcanoes but also the likely resulting network disruption from the eruptive products. This would also be useful in other hazards such as earthquakes. Although an initial earthquake cannot be predicted, subsequent aftershock locations can be estimated. This may include a situation such as the series of aftershocks that impacted the Canterbury region of New Zealand after the initial 2010 earthquake. Once lifeline network models are established, estimated aftershock locations and intensity footprints could be overlaid to predict future damage.

The hazard scenario in chapter 4 was based on the 1707 Hoei eruption of Mount Fuji, Japan. This event was chosen partly due to the amount of information on the event and current exposure, but also due to the threat Mount Fuji poses for large urban areas in Japan, including Tokyo. However, it is appreciated that the Hoei eruption is just one feasible outcome for the next eruption of Mount Fuji and that an exact repeat is very unlikely to eventuate. Woo (2011) expressed his apprehension of highly detailed model depictions that may bear little relation to reality. However, Pieke (2015) states that "*we are only surprised when we fail to think about a possibility that actually occurs; there is little consequence to considering possibilities that go unrealised*". The point of scenarios is not to perfectly predict the future but to explore possible outcomes and the ramifications of them. It is hoped that some adaptive capacity would enable stakeholders to apply learnings from practiced scenarios to other situations. Scenarios are important components of emergency management and are useful when investigating specific operational capacities and potential impacts at a finer scale. Collaborative constructions of future scenarios can also strengthen social ties, trust and legitimacy among different actors (Sanderson and Sharma 2016). This thesis advocates for the incorporation of human/infrastructure interactions in disaster planning; however, this requires a high amount of computational time and a lot of information with inherent uncertainties (Solano 2010). It is also acknowledged that creating holistic and collaborative disaster scenarios can be difficult to achieve with contradicting interests, political discontinuity and limited budgets and time (Sanderson and Sharma 2016). Complex disaster scenarios also lose their value if the results of which cannot be communicated or shared with all levels of society.

5.4 Future directions

Through this thesis, graph theory proved to be a useful tool for understanding the impact of lifeline disruption in the case of natural hazard events. The scenarios in this thesis all looked at just a single lifeline in isolation. There is scope to take this research further in order to include analysis of interconnected lifelines and to model the potential propagation of services failure between lifeline networks (Buldyrev et al. 2010, Gao et al. 2012, Fu et al. 2014). For example, this may include the impact of the loss of power on telecommunication systems or electric powered train transportation. Research such as Buldyrev et al. (2010), who modelled cascading failures between power stations and Internet communication networks, could be incorporated into the methods of this thesis. Dependences or connections between lifelines can also be mapped in graph form, creating a network or networks, which would allow failure to propagate not just through, but between lifeline networks.

These techniques could also be extended to all hazards in a specific location, where exposure and disruption to lifelines can be compared and ranked. For example, bushfires could pose a greater risk to infrastructure than riverine flooding in a particular area and with this knowledge investments for mitigation could be optimally appointed. There is also scope to add in economic data to allow for a monetary value to be placed on lifeline disruption, such as losses due to impacts to local or global supply chain networks. Cost-benefit analysis would help in determining optimal disaster recovery or targeted mitigation. Of concern, however, is that economic preservation could be deemed a priority over the return of services to those most vulnerable, or that the 'reopening' of a network too soon due to political or industry over eagerness, may put populations in danger for the sake of financial gain or politically saving face, i.e. reopening airspace in case of volcanic ash when an eruption is still ongoing.

To further analyse the impact of lifeline failure, particularly transportation systems, on population mobility in natural hazard events, graph theory techniques could be married with methods developed to monitor and predict people's movements using mobile GPS data (Horanont et al. 2013, Dobra et al. 2015, Ogawa et al. 2016, Duan et al. 2017 and Wang et al. 2018). A critical factor in managing disaster response is uncertainty in people's movement and real-time knowledge of large shifts in population would enhance the effectiveness of emergency response and help improve decision-making (Horanont et al. 2013). Moving from static population data sourced from national census' to mobile GPS data would provide fast access to more reliable information on population movements (Ogawa et al. 2016). This is assuming that everyone has a mobile device and will carry it with them in a disaster. Nevertheless this data could be used to help gain information about the normal flow of people during different situations (e.g. work days, night-time and public holidays), which could help provide estimates on population disruption for a number of temporal and spatial disaster scenarios. In particular, this research is useful to understand how transportation networks are used, the impact of network disruption to passenger flow and to better inform emergency management, such as evacuation planning, with regards to resident relocation and transport capacity and identification of services needed.

GNS Science (alternatively the Institute of Geological and Nuclear Sciences Limited) - New Zealand's leading provider of Earth, geoscience and isotope research and consultancy services – has a platform (GeoNet) where the public can share their experiences and impacts of recent earthquakes (GNS Science 2018). A platform, such as this, where both the public and emergency services can visualise the situation and add to the intelligence in near real time is a promising concept. Adding network features to this Google Map type application would help create a database of impacts, not only hazard characteristics but also any loss of lifeline services, such as roadblocks or loss of water. If such a tool was available for portable devices and was accessible to both the general population and emergency responders, it would allow both to log their experiences at a convenient time before physical impacts disappeared and resident's memories of the event fade. This would help preserve the learning from an event and save time and resources when mapping the extent of the event. If such a platform could be updated in near real time, such as within a command centre at state emergency or civil defence headquarters, it could enable residents to make more informed decisions. As described in Phillips et al. (2013), the South Illawarra Coast of New South Wales, Australia, experienced a flash flood in early 2011. The flood occurred at the end of a weekday when commuters were heading home and parents were picking up their children from school. Many residents came across flooded roads. Some drivers chose to drive through flood waters to access children or to get home, a number of which were washed off the road and needed assistance. Others turned around to find an alternative route only to be meet again with floodwaters. After the event, during interviews with residents, it was stated that most would not have tried to head home if they knew there was no safe route available. Others felt they were not going to be impacted because warnings were not specific enough to their area. If road blocks were noted at the time and available to view, residents may have behaved differently, lightening the load for the emergency services.

Lifeline network modelling could also be incorporated into multi-hazard risk assessment platforms such as RiskScape (https://www.riskscape.org.nz/) and Hazus (https://www.fema.gov/hazus), which are used to estimate the impacts and losses for assets. These tools incorporate exposure and damage estimates for people, buildings and infrastructure and ultimately determine an estimation of economic loss. However, indirect disruption and loss from lifeline failure is currently not accounted for. A case where this has been accounted for is MERIT (Measuring the Economics of Resilient Infrastructure https://www.merit.org.nz/merit/) in New Zealand. MERIT is an integrated spatial decision support system used to estimate economic consequences associated with disruption events. Lifeline network modelling could be added to this decision support tool, especially in future development areas such as service producing dynamic service outage maps.

Shared responsibility is a common direction in emergency management to increase awareness and resilience to the impacts of natural hazards. However, in the case of lifeline resilience, shared responsibility does not always equate to shared information. The sensitivity of lifeline vulnerabilities can be appreciated, especially in the current global climate, which is focused (sometimes disproportionately) on the risk of terror related activity. It is also noteworthy that parties across lifeline sectors have endeavoured, in some places, come together along with governments to increase the resilience of critical infrastructure in the face of all hazards to ensure the continual operation of essential services for all. However, it has been seen that these systems can and do fail, and will likely continue to do so into the future. Some cases are likely to be unforeseen or underestimated. Societies are becoming ever more disconnected with their environment and ever more expectant on government and emergency services to deal with the consequences of natural hazards. To become truly resilient to disruption from natural hazard events it is not just about mitigating disruption but also being more robust when it does happen. For true shared responsibility to occur, local governments and communities need to be better informed and prepared so they can cope with the absence of lifelines during a disaster.

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Appendix A. Conference Paper

Phillips, E., Bird, D., Haynes, K., Van den Honert, R., Morgan, M. and Davies, B. (2013) Experience, attitudes and behaviour. Residents in response to warnings during the March 2011 flash flooding in Shellharbour, Kiama and Jamberoo, NSW. *AFAC13 (Bushfire and Natural Hazards CRC, 2013), Melbourne, Australia, September 2013*

Experience, Attitudes and Behaviour

Residents in Response to Warnings During the March 2011 Flash Flooding in Shellharbour, Kiama and Jamberoo, NSW

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Risk Frontiers, NSW SES

AFAC13
Shaping Tomorrow Together
melbourne 2-5 september

ABSTRACT:

On 21st March 2011 heavy rainfall fell along the Illawarra South Coast region of New South Wales (NSW) resulting in severe flash flooding. As a result, one person lost their life in Warilla. Flooding caused the closure of major roads and railway lines and the destruction of numerous bridges, isolating hundreds of people. A number of Local Government Areas (LGA) were declared Natural Disaster areas. The NSW State Emergency Services (NSW SES) received over 800 requests for assistance for the Illawarra area alone, including 51 flood rescues between 19th and 23rd March 2011.

Risk Frontiers, in collaboration with the NSW SES, undertook a community-based study in three heavily impacted locations (Shellharbour, Kiama and Jamberoo). The aim was to examine the public's experience, attitudes and behaviours before, during and after the March flash flood event. The study also documented how people received flood warnings and the usefulness of the information broadcasted. The survey included a questionnaire distributed to residents door-to-door and online, and face-to-face semi-structured interviews with various members of each community. The results show that the majority of those surveyed were not aware that flooding was going to impact their area before 21st March. Therefore people that were impacted by flooding took actions that were more reactive than proactive and often put themselves in danger by entering floodwaters. This information has been used to help review and update the NSW SES community engagement practices and gauge the community's expectations of the SES during future events.

Introduction

Heavy rainfall fell along the already wet catchments of the Illawarra South Coast region on the morning of 21st March 2011 and continued in some locations throughout 22nd. Table 1 below summaries the consequences of this event.

Table 1 – 21st March 2011 event overview.

	Shellharbour	Kiama / Jamberoo
Peak and total rainfall	210mm total daily rainfall. Peaked at midday with 85.5mm recorded in one hour.	169mm total daily rainfall. Peaked at 2:00pm with 45mm recorded in one hour.
Peak gauge heights	2m and 3m along the Macquarie Rivulet catchment. >4m at Mullet Creek.	The Minnamurra River near Browns Lane, Jamberoo, peaked at 4m.
Consequences	One life lost in Warilla	Over-the-floor flooding in 6 properties (residential, business and schools) in Kiama and 14 in Jamberoo.
	All but seven of the Surfrider Caravan Park's 180 homes were inundated by floodwaters.	Flooding impacted main roads out of Kiama and Jamberoo, isolating these communities. Flooded roads impeded parents collecting children from school and day care.
	Over-the-floor flooding in 45 properties (residential, business and schools) around Shellharbour.	Kiama Community Centre flooded 1m.
	Albion Park and Albion Park Rail were impacted by flooding with the Princes Highway, Illawarra Highway and parts of Tongarra Road cut off by floodwaters, halting busy afternoon traffic, in some cases for hours.	Allowrie Street in Jamberoo was inundated by floodwaters, impacting residential properties, local businesses and a pre-school.

In response to these events, the NSW SES commissioned Risk Frontiers – a natural hazard research centre based at Macquarie University– to compile a report of available data on the impacts in and around Shellharbour and Kiama. Risk Frontiers were also tasked with documenting the experience, attitudes and behaviour of each community, especially in response to warnings and to evacuation or shelter-in-place. A large amount of information was collected through local SES, councils and community engagement.

NSW SES routinely seeks information about the impacts of flooding on communities to review its flood intelligence and to update Local Flood Plans. Commissioning this work following significant flooding events also allows SES to evaluate warning and evacuation performance as well as community attitudes and behaviour in response to flooding.

Methods

Questionnaire

The questionnaire covered topics relating to the physical damage from 21st March flash flood; flood information and warnings received leading up to the event; actions taken that day; and, flood preparations put in place since. The questionnaire was advertised through fliers delivered by Australia Post to addresses in the Shellharbour and Kiama areas and by hand in Jamberoo. The fliers included a link to an online version of the questionnaire or alternative locations where a hardcopy could be collected. Posters were put up in schools, local stores and community centres around pre-identified flood impacted locations and the study was also advertised on local councils' websites. Over 450 responses were received from a widespread area.

Semi-structured interviews and site visits

Site visits involved meetings with local officials and observations of flood affected areas. Approximately 23 open and semi-structured interviews were conducted with SES and council personnel, police, schools and other community members to gain further detail.

Results and Discussion

Flood warnings

The results show that nearly 80% of respondents were caught by surprise by the event. The main factors hindering people's access to information or warnings at the time was a lack of mobile phone reception and power outages. Being on the roads or at work were also cited as barriers to receiving flood information and warnings due to limited access to media outlets like TV, radio or social media.

Only around 20% of respondents were aware that flooding was likely to occur in their area in the days leading up to the event. The majority of those who were aware received information from the radio (the next most common source of information was television then family/friends). The information broadcasted included severe weather warnings, high tides, and road closures. Although this information was cited as generic, most respondents found it to be sufficient to aid in their decision making.

Decision making and response

Overall, the majority of respondents did not act until they received warnings/cues from natural stimuli, e.g. water levels, rain etc. Others, however, were influenced by advice from emergency services. Some peopled acted out of concern for their belongings while others acted due to their responsibility for their children or other dependents.

Those that were at home before the onset of the flooding were reasonably active, moving things to higher locations, clearing drains and trying to sweep water back outside, with more concern for home and content than safety.

Interviewees who were on the roads or away from home were often caught by surprise by floodwaters, some immediately took action to reduce their risks while others compromised their safety by driving through floodwaters. The main reason for entering floodwaters was to get home or to collect children from school and day care. A number of respondents said in hindsight they would not go through the waters again as it was not worth the risk. Some parents now have a better response plan with the schools and their children in case of flood. Some respondents also stated that they would keep off the roads if they were told which roads were closed and there were no alternative routes available.

Public preparedness and expectations

The majority of respondents indicated that they search for flood information during bad weather or when flooding occurs in their area. That is, people do not search for flood information until an event occurs. Moreover, the results indicate that respondents only think about flood risk in their local area. Many respondents stated that the reason they have not made flood preparations was that their properties have not and never will be affected by flooding. However, people can be anywhere when a flood hits and in 2011 many people were trapped on the roads or at work, away from their properties.

A real barrier to preparedness is people's perception of their risk to flooding, which seems to be heavily biased by past experiences or the inability to comprehend situations they have yet to experience. For example, those who had previously experienced smaller floods only prepared themselves and their property for future events of a similar size.

Issues:

- Radio broadcasters lacked local knowledge and this devalued the information given, especially in relation to local road names and advice for alternative routes around flooded areas.
- Some respondents mentioned a lack of knowledge of what to do in a flood event. Some knew more about how to mitigate bushfire hazards as this information is presented to them every fire season.
- Many residents did not react to the dangers of flooding until they came across floodwaters or saw floodwaters approach their properties. They often left it too late to leave and were therefore cut off by flooded roads.
- Some residents said that they would wait until the SES told them in person to leave before they did so, suggesting there is a dependence on emergency services for direction. The issue here is that flash floods occur very fast and the SES cannot always oversee evacuations.
- There seemed to be a lack of communication between emergency services, schools and parents, leading to confusion and panic. Many parents drove through flood waters unnecessarily when their children were being cared for at school.
- There was also a lack of communication and collaboration between emergency services and transport providers.
- Fieldwork began a year and a half after 21st March 2011 event. Many residents had forgotten about the event or confused it with subsequent rain events in the area. Flood marks and flood damage were no longer preserved in many locations.

Recommendations and implications for the SES

- It was recommended by the public that a Roads and Maritime Services (RMS) or SES representative make road closure announcements on the radio rather than presenters with little local knowledge.
- A regular reminder of flood hazards and actions to reduce risks is needed. This information can be delivered to the community in the form of a pamphlet or media advertising as not many people actively search for this information. However, in order to understand the varied needs of each community, we recommend that the SES undertake community-based workshops and/or focus groups. Through these activities, the SES will gain a better understanding of what information each community needs in terms of recommended actions for preparedness and response, in addition to the best way to disseminate this information to those at risk.
- It is recommended that the SES work with frequently flood-impacted locations that may be cut off in times of flood and have to fend for themselves, like that of the Lake Windermere and Surfrider Caravan Parks. If these communities can be empowered by the knowledge of what to do or have their own emergency plans there may be less reliance on the SES.

- Schools, day care centres, and caravan parks need to have emergency plans that help them know what to do in the case of a flood. Principals, managers or directors need a system of obtaining warnings and relaying these messages onto parents or residents. If parents are assured of their children's safety, and if residents have an emergency plan to follow, the number of people taking risks and travelling through flood water may reduce in future. The SES have online tools to help residents and businesses prepare emergency plans.
- Future flood data collection and intelligence review projects are conducted closer to the event. This would likely improve the quality of data collected and increase community participation.
- The questionnaire created in this study should be used as a template for future post-flood community engagement projects, so results can be compared across time and location.
- The length of the questionnaire could remain as it is but it is strongly suggested that it is administered as soon as possible after the event. This will aid in the quality of information garnered from the survey as well as increase the response rate, as people would be more interested and knowledgeable of the event.
- Before the questionnaire is administered in future it would be very beneficial to hold a focus group meeting with SES personnel (and council, OEH officials etc) about the usefulness of the survey and to discuss which, if any, questions could be omitted.

Acknowledgements

We are indebted to the community members who took part in the survey and shared information, photos and stories. This project was funded by NSW State Emergency Service (NSW SES). Assistance and information was provided by the NSW SES at State, Regional and Local levels; Bega Valley Shire, Shellharbour City and Kiama Municipal Councils; NSW Office of Environment and Heritage.

Appendix B. Conference paper

Phillips, E., Dimer de Oliveira, F., Koschatzky, V. and Somerville, P. (2015). Disruption of critical infrastructure during prolonged natural disasters. *AFAC14 (Bushfire and Natural Hazards CRC, 2014), Wellington, New Zealand, September 2014*.

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DISRUPTION OF CRITICAL INFRASTRUCTURE DURING PROLONGED NATURAL DISASTERS

Proceedings of the Research Forum at the Bushfire and Natural Hazards CRC & AFAC conference
Wellington, 2 September 2014

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ABSTRACT

Recent events such as the 2010 and 2011 Canterbury earthquakes, New Zealand; 2009 Southeast Australia heatwave; 2010 eruption of Eyjafjallajökull volcano, Iceland; and the 2011 Tohoku earthquake, tsunami and nuclear disaster in Japan, have highlighted the vulnerability of infrastructure and essential services to long-term disruption from prolonged and complex natural disasters. Prolonged natural disasters can impact surrounding areas for weeks to months after the initial event, causing vast and on-going disruption to utility, transport and communication networks; infrastructure that is vitally important for everyday living, the economy and emergency response. The quake-stricken Canterbury region of New Zealand endured thousands of disruptive aftershocks that continued for over two years following the initial earthquake in 2010. These aftershocks contributed to delays in repair and rebuilding, and caused significant additional damage. Our growing reliance on infrastructure and technology, along with the strong interdependent nature of these critical services, can potentially turn one failure into a cascading disaster. Local impacts to critical infrastructure can also lead to the interruption of essential services in regions that were not directly impacted by the physical hazard event. It has never been more important to understand network vulnerabilities and to analyse the cost of long-term disruption, both social and economic. Whilst significant work has gone into understanding the direct impacts from natural hazards, less emphasis has been placed on understanding the vulnerability of critical infrastructure, including indirect and long-term disruption.

INTRODUCTION

Lifeline networks are the critical infrastructure and essential services that we rely on for day-to-day living, economic output and emergency response. These include, transportation, telecommunication, power and water networks. Continuing increases in population and urbanisation puts increasing pressure on these essential services. With this comes a growing reliance on infrastructure and technology, some of which has strong interdependencies, meaning one failure could potentially turn into a cascading disaster. Lifeline networks are particularly vulnerable to disruption from natural hazards and recent events around the world, including Australia and New Zealand, have highlighted this:

- In June 2014, Northland was hit by a severe storm; strong winds impacted the area and much of the North Island of New Zealand. At the height of the storm, there were over 90,000 power outages across Auckland and widespread power cuts in Tauranga, South Waikato and Coromandel; 30,000 residential and business customers lost power (NZ Newswire, 2014a). Most of the damage was caused by trees falling across lines, which the Electricity Networks Association (ENA) stated affected all suppliers (NZ Newswire, 2014b). Most power was restored the next day, but some residents were without hot water for up to a week (MediaWorks TV, 2014).
- In May 2014, Darwin airport was closed for around 24 hours after an ash cloud from Sangeang Api volcano in Indonesian blew over the Northern Territory. All flights in and out of Darwin were cancelled and flights around the country bound for Bail were also disrupted (Dmytryshchak, 2014).

Although disruptive, and not without cost, these events were relatively short lived and functionality was restored within days. However, this research project is particularly interested in prolonged and multi-hazard events.

A prolonged event is defined in this study as a natural hazard event with an extended duration (a week or more) or a series of events that occur in quick succession. The 2009 Southeast Australia heatwave and 2010 volcanic eruption in Iceland would therefore be classified as prolonged natural hazard events:

- The January/February 2009 southeast Australia heatwave caused localised power outages of various lengths throughout Adelaide and Melbourne over a period of 16 days (Australian Bureau of Statistics, 2013). On the 30th January nearly 500,000 residents in Melbourne City, northern suburbs, Geelong and western Victoria were without power (ABC, 2009). This loss of power resulted in evacuations from the Crown Casino and the Victorian Arts Centre, traffic light failures, and people requiring rescue from lifts. Train and tram services in Melbourne were cancelled not only due to the power outages, but also due to buckling of rail lines and air conditioner failures (McEvoy et al., 2012; ABC, 2009). As at 1 February 2009, the heatwave was estimated to have cost the Victorian economy $100 million (Houston and Reilly, 2009).
- The 2010 eruption of the Eyjafjallajökull volcano, Iceland, caused extensive air travel disruption due to a seven day closure of large areas of European airspace, affecting the travel arrangements of hundreds of thousands of people. This affected economic, political and cultural activities in Europe and across the world and resulted in an estimated total loss for the airline industry of US$1.7 billion (IATA, 2010).

A multi-hazard event is defined as an event that is associated with additional or secondary hazards (e.g. earthquakes causing liquefaction, landslides, fires and tsunami):

- The Canterbury region of New Zealand endured thousands of disruptive aftershocks that continued for more than two years following the initial 7.1 quake in 2010, including the M6.3 quake in February 2011 that killed over 180 people. Larger earthquakes in the sequence triggered soil liquefaction and rock falls, which caused widespread power outages, the disruption of wastewater services, the closure of the international airport and damage to roads and bridges. These additional hazards disrupted rescue and rebuilding efforts (Parker and Steenkamp, 2012). ANZ chief economist Cameron Bagrie estimated that it will take the New Zealand economy 50-100 years to fully recover (MediaWorks TV, 2013).

Prolonged and multi-hazard natural disasters are of interest as they can cause vast and on-going disruption to utility, transport and communication networks, which are critical services for rescue and recovery. While various network vulnerability models have been developed (Murray, 2013; Moon and Lee, 2012), most models were not created specifically to look at shocks from natural disasters, and certainly not prolonged and/or multi-hazard events. There is currently a lack of comprehensive modelling to investigate indirect and on-going lifeline network disruption from complex natural disasters. Therefore, the aim of this project is to describe and quantify the impacts of prolonged and multi-hazard natural hazard events on lifeline networks and to also understand the interconnectedness of these critical services. Key research questions include:

- How does the interconnectedness of critical services lead to a cascade of failures?
- What influences network recovery and how long can they take to rebuild?
- How long can impacts from a natural hazard event remain and what is the cost of long-term network disruption?
- What scenarios could generate a potentially catastrophic disruption in the future?

This project has been partially funded by the Bushfire and Natural Hazard Cooperative Research Centre and is linked with the project "Using realistic disaster scenario analysis to understand natural hazard impacts and emergency management requirements" in the "Scenario and Loss Analysis" cluster. This

project will develop realistic disaster scenarios utilising catastrophe loss models to identify vulnerable areas, utilities and assets within major Australian cities. As well as helping to create a better understanding of the implications of potential long-term lifeline network disruption, key outputs of this study will include:

- Review of key historical Australia, New Zealand and international natural disasters and the impact they had on lifeline networks
- Review of existing network vulnerability models
- Development of new approaches to quantify network vulnerability

PRELIMINARY STUDY – LATROBE VALLEY EARTHQUAKE

One example of a potential disaster that Australia could face is a damaging earthquake in the Latrobe Valley, Victoria, where ~80% of Victoria's energy is generated. The Latrobe Valley is located over the Morwell Hotspot earthquake source (Burbidge and Leonard, 2011) and is one of the more seismically active regions in Australia. Numerous historical earthquakes have been recorded in this region, the latest event being the Moe earthquake sequence that began with a 5.4 magnitude earthquake 10 km south of Moe, near Thorpdale, on 19th June 2012. Based on the earthquake source model defined in Burbidge and Leonard (2011), the most likely scenario for a damaging earthquake in the Latrobe Valley would be a magnitude 6 earthquake within the Morwell Hotspot.

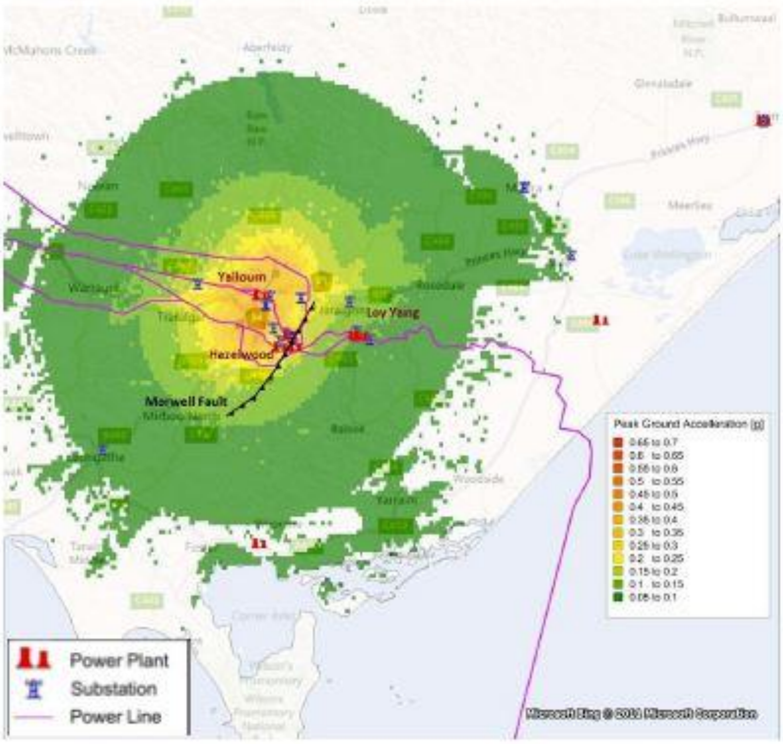

Figure 1: Peak ground acceleration in units of gravitational acceleration (g) for a M6.0 earthquake scenario along the Morwell Fault in the Latrobe Valley, VIC, and locations of main power infrastructure.

A preliminary scenario modelling exercise was commissioned by the Victorian Country Fire Authority (CFA) for emergency response planning purposes. The scenario we considered was a M6.0 earthquake occurring on the Morwell Fault (Figure 1). Loss and damage estimates were made from the ground shaking map shown in Figure 1, which was based on a ground motion prediction equations for bedrock conditions and took into account the quantifying efforts of the overlying soil. Losses to property and infrastructure were calculated using the methodology developed by the US Federal Emergency Management Agency (FEMA), through the HAZUS model. This methodology is based on deriving statistical models for a functional relationship between physical earthquake parameters such as peak ground acceleration (PGA), velocity (PGV), displacement (PGD) and response spectrum and a building's response to shaking.

Six power stations (Yallourn, Hazelwood, Jeeraland, Loy Yang A, Loy Yang B and Valley Power) could potentially be impacted by a M6.0 earthquake along the Morwell Fault. The HAZUS model defines four types of damage states (slight, moderate, extensive and complete damage) for generation plants and the probability of damage (Table 1). See Table 2 and Figure 2 for estimated PGA at each power station and the probability of damage.

If any number of these power stations, their substations and/or the power lines supplying the State were damaged, there would undoubtedly be major disruption and wide-spread impacts. A significant seismic event in this region could potentially impact infrastructure that is responsible for producing 90% of Victoria's required electricity. The true impact of a major power failure in Victoria cannot be fully described without understanding the ability of emergency services to conduct rescue operations with limited power supply; the length of time Victorian businesses will be able to operate without electricity; and the capacity of peaking facilities throughout the State to restore power to the grid in case of a major power failure.

Table 1: HAZUS definitions of damage states for generation plants

Damage state	Damage to generation plants
Slight/Minor Damage (ds_2)	ds_2 is defined by turbine tripping, or light damage to diesel generator, or by the building being in minor damage state
Moderate Damage (ds_3)	ds_3 is defined some by the chattering of instrument panels and racks, considerable damage to boilers and pressure vessels, or by the building being in moderate damage state
Extensive Damage (ds_4)	ds_4 is defined by considerable damage to motor driven pumps, or considerable damage to large vertical pumps, or by the building being in extensive damage state
Complete Damage (ds_5)	ds_5 is defined by extensive damage to large horizontal vessels beyond repair, extensive damage to large motor operated valves, or by the building being in complete damage state.

Table 2: Estimated PGA at power station site and each power station's contribution to power production.

Power station	PGA (g)	Power generation
Yallourn	0.36	supplies approximately 22 percent of Victoria's electricity needs and approximately eight percent of the National Electricity Market (NEM) (EnergyAustralia, 2014).
Hazelwood	0.26	supplies between 20 and 25 percent of Victoria's energy requirements and 5.4 percent of Australia's energy demand (GDF SVEZ Australian Energy, 2014a).
Jeeralang	0.21	The station is a peaking facility which is utilised only during periods of peak demand, it is also used as a black start facility to restore power to the grid in the event of major system failure.
Loy Yang A	0.1	Supplies approximately 30 percent of Victoria's power requirements (AGL, 2014).
Loy Yang B	0.09	supplies about 17 per cent of Victoria's energy needs (GDF SVEZ Australian Energy, 2014b).
Valley Power	0.09	Peaking facility

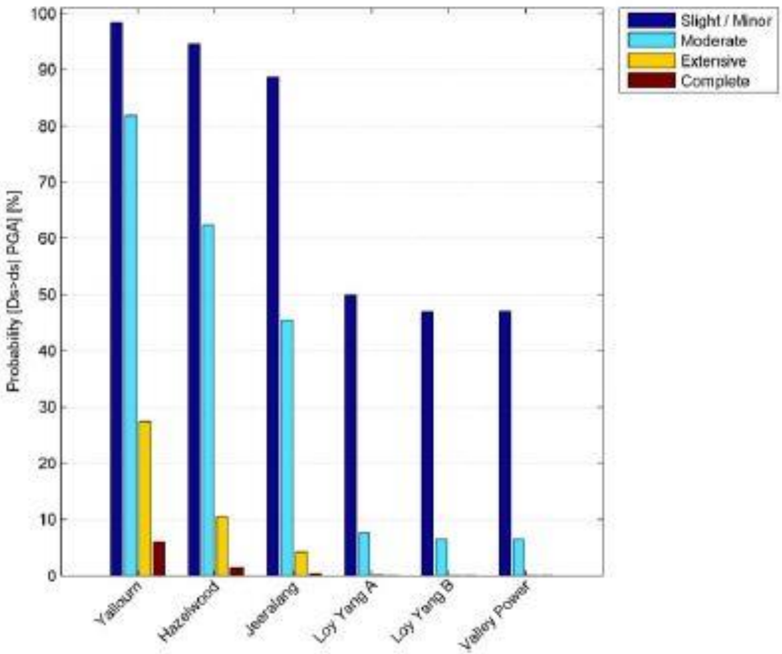

Figure 2: Probability of damage to power stations during at M6.0 earthquake on the Morwell Fault.

CONCLUDING REMARKS

In the preliminary work carried out for Victoria CFA, we considered losses and disruptions to lifelines in isolation, not taking into account the interactions between different elements, and only in a very general manner addressed the long-range/long-term impacts of natural disasters.

The current research project will create a model that can help answer questions such as:

- which areas of Victoria would most likely be blacked out? and
- which hospitals and fire stations would be most under-pressure?

This integrated analysis will also shed light on the increased costs and travel times of transportation; how this could affect emergency response, and what would be the economic impacts both state- and Australia-wide. To be able to do so, this project will require the following steps:

1. Collection of data describing infrastructure networks, such as roads, power and water
2. Modelling as a connected network considering the interactions between different lifeline elements
3. Overlaying this modelling with event hazard layers, and developing vulnerability functions to estimate losses to nodes and/or links between nodes
4. Analysing the post-event network to establish its efficiency, possible bottlenecks and impact to hubs

Such realism in modelled scenarios can help emergency and planning agencies better prepare and allocate resources more effectively.

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Appendix C. Magazine article

Phillips, E. (2015). Volcanic eruptions and disruptions. *Actuaries Digital*. https://www.actuaries.digital/2015/10/08/volcanic-eruptions-and-disruptions/.

Volcanic eruptions and disruptions

By Emma Phillips Posted on: October 8, 2015

Reading time: 7 mins

In recent years, volcanic eruptions have severely disrupted air travel, causing widespread havoc on economies, and losses for insurers. Emma Phillips of Risk Frontiers explores the direct and indirect impacts of volcanoes.

The insurance industry strives to estimate the cost and understand the impact of future natural hazard events. Insurers and reinsurers have been the key risk takers and, ultimately, the shock absorbers in today's modern world (Haueter, 2013). Through research in areas such as engineering, economics, earth sciences and geography, we have come to better understand the direct impact natural hazard events have on the built environment.

Indirect costs

However, it is becoming increasingly clear that direct damage only represents a portion of the total cost of natural hazard events. Indirect disruptions, both social and economic, contribute significant losses and in some cases these can be greater than the direct damage itself.

Supply chain disruption and accumulation of risk

In terms of business interruption the situation is further aggravated when multiple branches of industry are supplied by a small number of highly specialised manufacturers. When manufacturers are concentrated within a single geographical area, insurers face an accumulated exposure to a single loss event (Asia Insurance Review, 2014). The Thailand floods and Tohoku earthquake and tsunami in 2011 highlighted the enormous accumulation potential of supply chain disruptions and showed insurers and reinsurers how exposed they were to contingent business interruption (Asia Insurance Review, 2014, Greeley, 2012). The fact that many companies now see supply chain interruptions as one of their biggest risks shows just how deeply the global economy was shaken by the events of 2011 (Asia Insurance Review, 2014).

Impact on insurers

Can the insurance industry keep up with an increasingly interconnected and volatile world, where the cost and reach of disruptions will only increase? There is still debate within the industry over the future of contingent business interruption coverage and in some cases insurers have not responded to this challenge at all (Galey et al., 2002, Miller Insurance, 2012). On the other hand some sectors are making amendments and calling out for more transparency from their customers (Ladbury, 2014). In order to truly understand the price of indirect disruption, the industry needs to thoroughly examine each company's suppliers and the location of these suppliers, in order to identify vulnerabilities in their production and distribution process (Asia Insurance Review, 2014). Both direct suppliers and their subcontractors should be included in risk assessments (Asia Insurance Review, 2014). Secondly, underwriters should also identify as many threat scenarios as possible involving different hazard events and possible exposure accumulations (Galey et al., 2002). Just one example of a catastrophic natural hazard scenario could be the case of a large explosive volcanic eruption.

Historic volcanic eruptions

The largest volcanic eruptions on earth, greater than 450 km^3 of dense eruptive magma (or 1000 km^3 of fragmented volcanic ash deposits) (Self, 2006), have been described as the ultimate geologic hazard due to the immediate and devastating impacts from eruption products and potential longer-term climatic effects arising from loading the stratosphere with sulphur-rich gases (Miliier and Wark 2008; Self, 2006; Oppenheimer, 2002). However, the awareness of risks from volcanic eruptions remains low due to the infrequent nature of significant events in modern history. Consequently, commercial organisations are rarely prepared for the indirect impacts of a significant eruption, either locally or abroad.

Characterising eruptions

Volcanic eruptions are unique in that hazards may be very widespread and can persist over many weeks or months. Multiple volcanic hazards can occur simultaneously or consecutively, causing impacts over various distances and time scales (Wilson et al., 2014). Lateral forces, vertical loads, burial and exposure to high temperatures from lava flows, lahars, pyroclastic density currents and tephra falls can immediately damage buildings and infrastructure (Jenkins et al., 2014). Volcanic ash in particular is heavy, highly abrasive, corrosive and conductive and can spread far and wide; only millimetres are needed to disrupt essential services and critical infrastructure, such as electricity, water supply, waste systems, communications, roads and air transport (Wilson et al., 2014). Ejected into the atmosphere and carried by the wind, volcanic ash can potentially circulate the globe, causing international travel disruption.

Puyehue-Cordón Caulle (VEI 5 0.29km3 DRE, or 0.7km3 deposit volume)

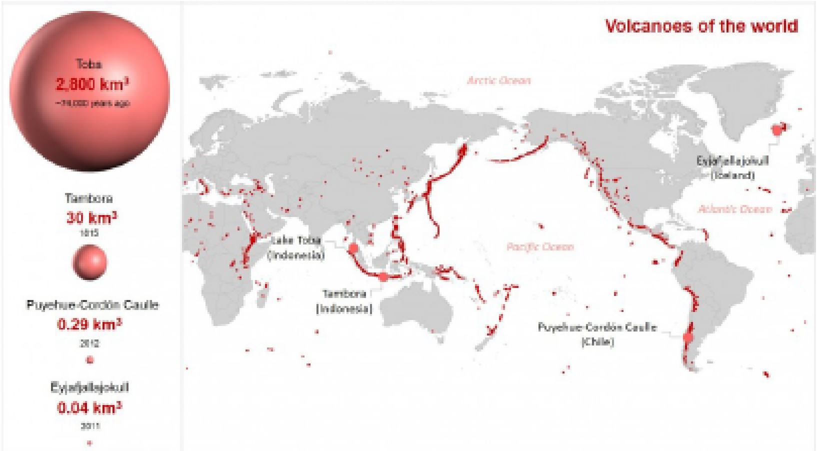
The Puyehue-Cordón Caulle eruption, Chile, sent ash right around the Southern hemisphere, forcing hundreds of international and domestic flights to be cancelled. The eruption began on 4 June 2011, and by the 18 June the ash cloud had completed its first circle of the globe. On the 11 June the ash cloud had reached the southern tip of New Zealand causing numerous cancellations of flights between Adelaide, Melbourne, Perth, Tasmania and New Zealand up until 22 June, and triggering substantial losses on travel insurance policies.

Eyjafjallajökull (VEI 4 0.04km3 or 0.1km3)

The 2010 eruption at Eyjafjallajökull volcano, Iceland, also highlighted the potential economic impacts from volcanic eruptions and exposed our reliance on air transport and its vulnerability to disruption from volcanic hazards. The April 2010 eruption caused extensive air travel disruption with the closure of large areas of European airspace for seven days. This disrupted the travel arrangements of hundreds of thousands of people; caused stock shortages and the spoilage of goods; affected sporting, political and cultural activities in Europe and across the world; and resulted in an estimated total loss of approximately US$1.7 billion for the airline industry alone (IATA, 2010; Oxford-Economics, 2010). Once again, there were substantial losses for insurers providing travel insurance.

Toba

Although disruptive, these events were relatively small compared to cataclysmic eruptions that have occurred around the world in the past. One of the largest eruptions on earth (involving 2800 km^3 of new magmatic material) occurred about 74,000 years ago at Toba, Indonesia. This eruption produced major pyroclastic flows that covered an area of 20,000 km^2; in some locations leaving deposits up to 200 metres thick (Self and Blake, 2008; Oppenheimer, 2002). Ash covered an area in excess of 20 million km^2, or 4% of the surface area of Earth, reaching over 3000 km from source to northern Indian (Self and Blake, 2008). A repeat of an event like this would be truly devastating



(http://www.actuaries.digital/wp-content/uploads/2015/10/Info-graph-for-Actuaries_Emma-Phillips.jpg)

Figure: The volume and location of mentioned eruptions plotted on the world map with the locations of the world's volcanoes. Eruption volumes sourced from the Volcano Global Risk Identification and Analysis Project (VOGRIPA) database (http://www.bgs.ac.uk/vogripa/ (http://www.bgs.ac.uk/vogripa/)) and volcano locations sourced from Smithsonian Institution National Museum of Nation History Global Volcanism Program database (http://volcano.si.edu/ (http://volcano.si.edu/)).

Slightly smaller eruptions still pose risk

Eruptions of this magnitude are, however, shown to be very rare. A survey conducted by Mason et al (2004) estimated the average frequency of these events to be 1 every 100,000-200,000 years. Slightly smaller eruptions of volumes greater than 40 km^3 of erupted magma (or 100 km^3 volcanic ash deposit) are much more frequent and still pose a considerable hazard to society (Self, 2006). In the Asia-Pacific region, eruptions of this size have an average recurrence interval of about 440 years (Mead and Magill, 2014). Compared to Toba like eruptions, eruption rates of this smaller magnitude can be sustained for longer and ash fall makes up a higher proportion of eruptive volume (Mason et al., 2004; Self, 2006), for that reason they should receive particular attention.

Tambora

In 1815, the Tambora volcano exploded with a dramatic eruption after more than three years of mild eruptive activity. This large explosion could easily have been taken as the conclusion of the eruptive phase. However, after a five day lull in activity, came the largest explosive eruption in recorded history of about 30 km^3 (Siebert et al., 2010; Self et al., 2004). The eruption sent ash 1,300 km from source, covering those within 500 km of the volcano in darkness for three days and impacting climate and food production in regions as far as China, Europe and North America. This in turn caused widespread sickness and hunger; an estimated 11,000 fatalities resulted from direct volcanic impacts and a further approximately 50,000 fatalities were due to post-eruption famine and epidemic diseases (Siebert et al., 2010). Tambora, which had an ejected volume less than 5% of the Toba eruption, still affected global climate and was the main cause for the 1816 'year without a summer', resulting in tens of thousands of deaths (Miller and Wark, 2008).

The future

What would be the impact and cost of an event such as Tambora in modern society today? To what extent would transportation systems, supply chains, and utility networks be disrupted and would affected business losses be insured? A future large, explosive and potentially prolonged volcanic eruption could lead to a global disaster and it is an event that will not elude us forever. If large natural hazard disaster scenarios are ignored, the next event will be a rather rude awakening. Potentially one the insurance industry would struggle to recover from.

"Of concern is a situation where a volcano that is presently unrecognized as a potential large-eruption site, or that is evolving towards its first super-eruption, or that is not monitored, becomes unrestful" (Self, 2006).

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Appendix D. Magazine article

Singh, E. (2017). Can graph theory techniques help with emergency response? *Asia Pacific Fire Magazine*. https://apfmag.mdmpublishing.com/can-graph-theory-techniques-help-with-emergency-response/.

Can graph theory techniques help with emergency response

To understand how components of our built environment and society will fare during a disaster, we first need to know the interconnectedness of network systems and the role each component plays.

Emma Singh

Emma Singh is a PhD student with Risk Frontiers and the Department of Environmental Sciences at Macquarie University in Sydney. Emma is investigating critical infrastructure disruption during natural hazard events, with a particular interest in the implications of network failure for emergency response during and community recovery after a disaster.

Disclaimer – This work has been submitted for publication and is currently under review. For more information and detailed references email emma.singh@gmail.com

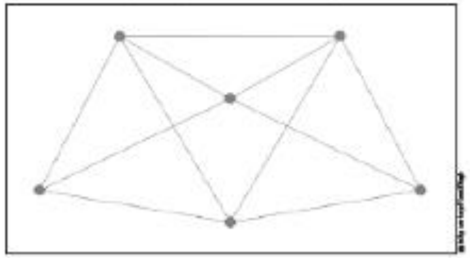
Transportation, communication, power, water and sewage are the infrastructure and services critical to modern societies for day-to-day living, the movement of goods and services, and disaster response and recovery. These lifeline networks are vulnerable to disruption from numerous shocks, including structural and technological failure, human error or targeted attack and, our interest here, natural hazard events.

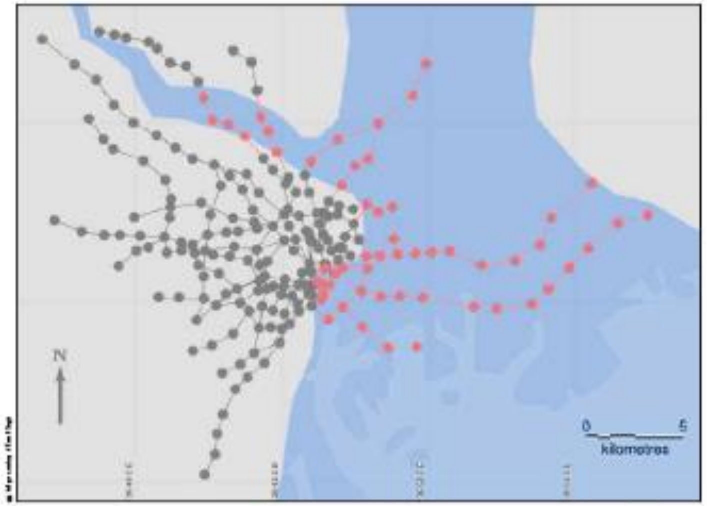
Lifelines comprise a large number of interconnected components, often spanning extensive geographic areas and, in some cases, multiple urban centres, states and international borders (Saltoma 2006). Feedback loops and complex topologies created by lifeline interdependencies can trigger and propagate disruptions in a variety of ways that are difficult to foresee (Rinaldi et al. 2001). Impacts may be felt not just locally but nationally or even globally.

Recent examples include the November 2016 7.8 magnitude Kaikoura earthquake in New Zealand, which triggered landslides that blocked the main highway, State Highway 1, and the South Island Main Trunk railway, isolating the popular tourist destination of Kaikoura for over a month. In September 2016, Southern Australian was hit by a severe storm that knocked over 22 transmission poles and damaged a number of generation facilities. This resulted in a statewide power outage, leaving 1.67 million South Australian residents without electricity for nearly 13 hours, disrupting businesses and affecting other lifelines operation such as communications and traffic signals. With more widespread consequences, the 2011 Thailand floods created problems for the global car and computer hardware industries.

Here we explore Graph Theory as a means of studying lifeline disruption using a hypothetical flooding incident on the Tokyo Subway network, Japan. The Tokyo Subway is used as an example because its configuration of stations and passenger numbers are well known. The subway is also located in a region susceptible to a range of natural perils.

▼ Fig. 1 Example of a graph with six nodes and eleven edges.





Graph theory simplifies complex systems into nodes and edges to identify network structure, and the processes within (Fig. 1). Its foundations go back to the mathematician Euler, who, in 1735, proved that it was impossible to take a walk through the medieval town of Königsberg, Russia, and visit each part of town by crossing each of its seven bridges only once (Barabási 2000). In recent decades graph theory has been used to investigate a wide range of systems from the World Wide Web to social networks. Current applications of graph theory for lifeline network analysis focus on network structure and robustness to random failure and targeted attack (Albert et al., 2004; Crucitti et al., 2004; Kog et al., 2014; Angeloudis and Fisk, 2006; Derrible and Kennedy, 2010; Cardillo et al., 2013).

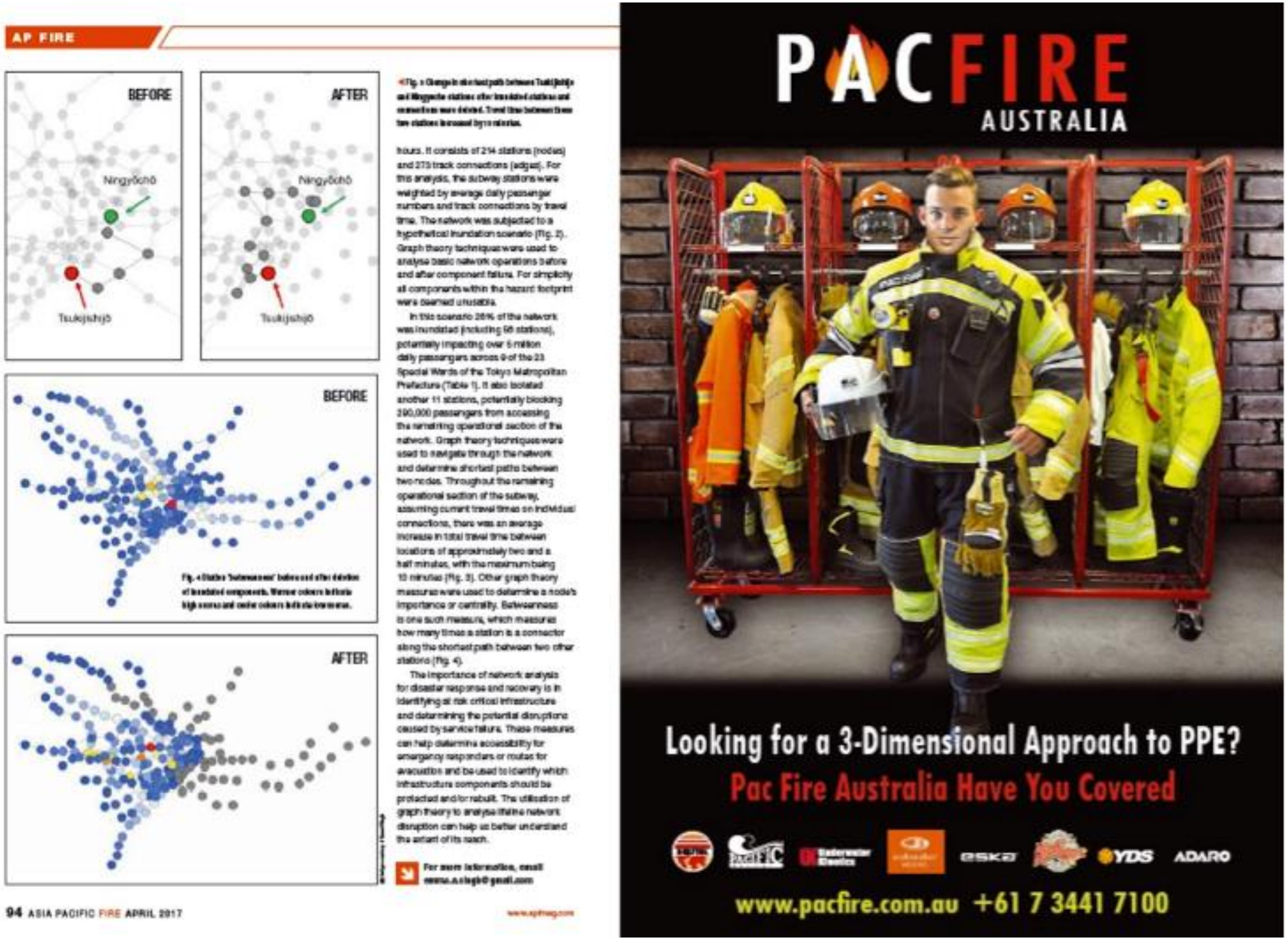
The Tokyo Subway (including Tokyo Metro and Toei Subway) services nearly nine million passengers daily. Despite its reputed reliability and punctuality, the Tokyo subway is still susceptible to failure and disruption, such as the Sarin attack in 1995 (Okumura et al. 1998), and suffers from congestion during peak commuting

▲ Fig. 2 Graph representation of the Tokyo Subway, Japan. Hypothetical inundation hazard footprint is indicated in blue and network components that coincide with the footprint are highlighted in red.

▶ Location of Tokyo Subway, Japan.

▼ Table 1 Impact of the theoretical inundation scenario on the Tokyo Subway network.

Impact	Count	% of network
Stations inundated	66	26
Track connections inundated	79	27
Shortest paths terminated	34,068	52
Shortest paths extended (by travel time)	1,704	4
Shortest paths unchanged	30,064	44
Number of daily average passengers impacted	5,186,065	37
Number of daily average passengers isolated from remaining operational section of network	216,751	2



AP FIRE

BEFORE

AFTER

Ningyōchō

Tsukijishijō

Fig. 3 Change in shortest path between Tsukijishijo and Ningyocho stations after inundated stations and connections were deleted. Travel time between these two stations increased by 10 minutes.

hours. It consists of 214 stations (nodes) and 273 track connections (edges). For this analysis, the subway stations were weighted by average daily passenger numbers and track connections by travel time. The network was subjected to a hypothetical inundation scenario (Fig. 2). Graph theory techniques were used to analyse basic network operations before and after component failure. For simplicity all components within the hazard footprint were deemed unusable.

In this scenario 26% of the network was inundated (including 56 stations), potentially impacting over 5 million daily passengers across 9 of the 23 Special Wards of the Tokyo Metropolitan Prefecture (Table 1). It also isolated another 11 stations, potentially blocking 290,000 passengers from accessing the remaining operational section of the network. Graph theory techniques were used to navigate through the network and determine shortest paths between two nodes. Throughout the remaining operational section of the subway, assuming current travel times on individual connections, there was an average increase in total travel time between locations of approximately two and a half minutes, with the maximum being 10 minutes (Fig. 3). Other graph theory measures were used to determine a node's importance or centrality. Betweenness is one such measure, which measures how many times a station is a connector along the shortest path between two other stations (Fig. 4).

The importance of network analysis for disaster response and recovery is in identifying at risk critical infrastructure and determining the potential disruptions caused by service failure. These measures can help determine accessibility for emergency responders or routes for evacuation and be used to identify which infrastructure components should be protected and/or rebuilt. The utilisation of graph theory to analyse lifeline network disruption can help us better understand the extent of its reach.

BEFORE

Fig. 4 Station 'betweenness' before and after deletion of inundated components. Warmer colours indicate high scores and cooler colours indicate low scores.

AFTER

For more information, email emma.s.singh@gmail.com

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Appendix E. Conference posters

Singh, E. (2016). Disruption of critical infrastructure during natural disasters. *AFAC16 (Bushfire and Natural Hazards CRC, 2016), Brisbane, Australia, August 2016*.

Singh, E. (2017). Disruption of critical infrastructure during natural disasters. *AFAC17 (Bushfire and Natural Hazards CRC, 2017), Sydney, Australia, September 2017*.

DISRUPTION OF CRITICAL INFRASTRUCTURE DURING NATURAL DISASTERS

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Supervisors: Dr Christina Magill and Prof John McAneney, Risk Frontiers, Macquarie University, NSW

CAN GRAPH THEORY TECHNIQUES HELP WITH EMERGENCY RESPONSE AND OPTIMAL LIFELINE NETWORK RECOVERY?

BACKGROUND

Critical infrastructure and essential services, such as: transportation, communication, power and water, are heavily relied upon by today's modern society for day-to-day living, the movement of goods and services, and disaster response and recovery. Currently there is limited quantitative research on the impact natural hazard events have on these systems and the flow on effects from their failure. To estimate the impact of lifeline network disruption during a disaster there is a need to better understand network behaviour and interconnectedness, as well as exposure and vulnerability to potential natural hazards.

PROJECT OBJECTIVES

- Utilising mathematical graph theory tools to analyse lifeline network behaviour and the impedance of services during network disruption.
- Overlaying natural hazard footprints onto network representations to simulate potential impacts of realistic disaster scenarios

GRAPH THEORY

Graph theory is the study of networks represented as graphs (Fig. 1). Graphs are mathematical structures consisting of nodes and edges that are used to describe the building blocks of many physical networks and other interactions (Van Steen, 2010). Current applications of graph theory looking at infrastructure networks focus on network structure and robustness to random failure and targeted attack (Albert et al., 2004; Crucitti et al., 2004; Koç et al., 2014; Angeloudis and Fisk, 2006; Derrible and Kennedy, 2010; Cardillo et al., 2013). This research aims to add to this work by looking at natural hazard shocks, cascading lifeline failures and dynamic flow through weighted networks.

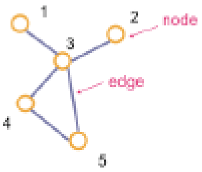

Fig. 1 Example of a graph with five nodes and five edges.

SIMULATED DISRUPTION TO THE TOKYO SUBWAY

The Tokyo Subway network was used as a case study example to show how graph theory techniques can be applied to assess transport system disruption during natural disasters. The subway network was subjected to a hypothetical inundation scenario based on an area prone to flooding. All components (56 stations) within the hazard footprint were deemed to have failed (Fig. 2). Over 5 million daily passengers across 9 of the 23 Special Wards of the Tokyo Metropolitan Prefecture would be impacted.

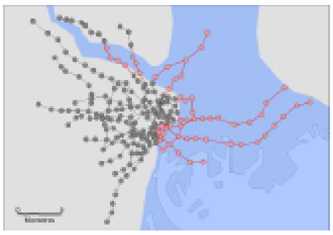

Fig. 2 Graph representation of the Tokyo Subway. Hypothetical inundation hazard footprint is indicated in blue (■) and network components that coincide with the footprint are highlighted in red (●).

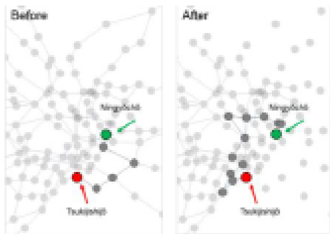

Fig. 3 Change in shortest path between Tsukijishijō and Ningyōchō stations after inundated stations and connections were deleted. Travel time between these two stations increased by 13 minutes.

Graph theory can be used to navigate networks and determine shortest paths between two nodes (Fig.3). This could help determine accessibility for emergency responders and routes for evacuation. Other common graph theory measures can determine a node's importance or centrality (Fig. 4). These could be used to identify which infrastructure components should be protected and/or rebuilt.

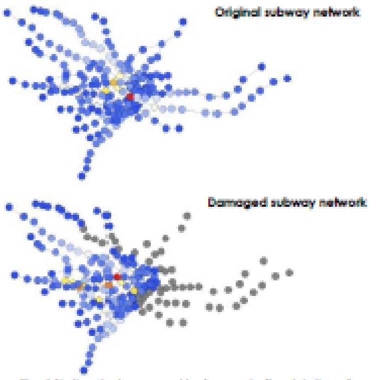

Fig. 4 Station 'betweenness' before and after deletion of inundated components. Betweenness is a measure of how many times a station is a connector along the shortest path between two other stations. Warmer colours indicate high scores and cooler colours indicate low scores.

FUTURE WORK

- Determine highway exposure to volcanic ashfall in Japan and identifying implications for evacuations and clean up
- Apply learnings to Australian case studies, contributing to the 'Using realistic disaster scenario analysis to understand natural hazard impacts and emergency management requirements' project, part of the BNHCRC 'Scenario and Loss Analysis' cluster

COMMENTS FROM THE END USERS

" Management of natural hazards, their impacts and their interactions in communities using structured mathematical and information system approaches is a critically important evolution of disaster management. Other sectors of industry and commerce use a variety of computational network and information modelling approaches to solve large and complex interconnected problems. These need to be applied to disasters. So the next few years will see disaster managers developing more formally adopted approaches to network, agent-based and least cost based methodologies and the research outlined in this poster will be part of the groundswell which will assist in understanding the adoption and innovation of these approaches to disasters." (NSW SES).

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DISRUPTION OF CRITICAL INFRASTRUCTURE DURING NATURAL DISASTERS

bushfire&natural HAZARDSCRC

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CAN GRAPH THEORY TECHNIQUES HELP WITH EMERGENCY RESPONSE AND OPTIMAL LIFELINE NETWORK RECOVERY?

1. Background

To better prepare for future hazard events, potential impacts on critical infrastructure need to be included in scenario development and vulnerability assessment. There is a need to understand the behaviour and interconnectedness of critical infrastructures and to identify populations and services that rely on their operation. Therefore, critical infrastructure vulnerability needs to be considered alongside social dimensions that take into account the ability of populations to adapt or cope with infrastructure disruption.

This study combines ash dispersal modelling and graph theory techniques to assess the exposure of major roads to volcanic ash from future eruptions at Fuji volcano, Japan, and to understand the impact road closures could have on emergency response and recovery.

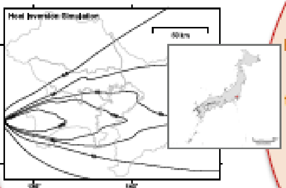

Figure 1: Inversion modeling results combining 17 phases describing the entire 1707 Hoei eruption sequence (Magill et al., 2015). Ashfall isopachs in millimetres.

2. Modelling ashfall from a future eruption at Mount Fuji

The 1707 Hoei eruption is one of the most violent eruptions that Fuji volcano has produced. The eruption produced wide-spread ashfalls covering most of the south Kanto plain to the east of the volcano. Ash from this eruption has also been found 280 km from source in deep sea cores in the Pacific Ocean (Miyaji et al 2011; Miyaji 2002). Although the 1707 eruption is maybe the worst-case scenario from Mount Fuji in terms of ashfall hazard, it would be inapt not to plan for the worst.

The 1707 Hoei eruption from Mount Fuji was replicated using *Tephra2*, an analytical tephra advection-diffusion model (Bonadonna et al., 2005), which calculates particle diffusion, transport and sedimentation. Magill et al. (2015) used high-resolution data describing 17 phases of the Hoei eruption (Miyaji et al., 2011) and inversion techniques to estimate the physical parameters of the Hoei eruption (Fig. 1).

3. Impact of volcanic ash on roads

The impact of volcanic ash on road transportation has been documented during recent eruptions such as Mount St Helens (1980), Pinatubo (1991), Sakurajima (1955 onwards), Pacaya (2010) and Shinmoedake (2011) (Fig. 2). Falling or remobilised ash has been found to significantly reduce driver visibility. Fine ash can make road surfaces slippery, especially if wet, and ash fall thicknesses of 0.5mm can obscure road markings. Fine ash can also abrade vehicle components and clog air and oil filters (Nairn 2002; Magill et al 2013; Wilson et al 2012; Wilson et al 2014; Hayes et al 2015).

The disruption of transport networks during a disaster can result in the isolation of populations, and hinder evacuation and rescue operations. After a disaster, road closures could dramatically increase travel time, disrupt supply chains and hamper recovery efforts such as stopping access to other critical infrastructure for maintenance.

Figure 2: Road closure during the 2011 Shinmoedake eruption in Japan (Magill et al., 2013).

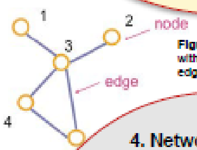

Figure 3: Example of a graph with five nodes and five edges.

4. Network analysis

Graph theory is the study of networks represented as graphs. Graphs are mathematical structures consisting of nodes and edges that are used to describe the building blocks of many physical networks and other interactions (Van Steen, 2010) (Fig. 3). In a road network, nodes represent road junctions and edges the road lengths.

Mathematical graph theory tools will be utilised to navigate highway and local road networks of Japan to determine the shortest paths, detours and optimal network recovery in the case of an eruption.

Table 1: Approximate road lengths impacted by various ranges of ashfall accumulation.

Ashfall (mm)	Length of highway (km)
0.5-10	369.9
10-50	379.6
50-100	200.1
100-300	181.1
>300	55.7

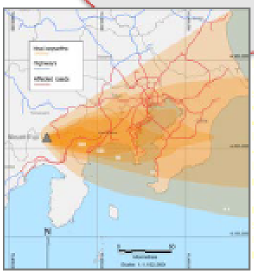

Figure 4: Inversion simulation of Hoei eruption sequence overlain onto the Nexco East and Central Nippon Expressway network. Impacted road segments marked in red.

5. Preliminary results

Isopachs from the Hoei inversion simulation (Fig. 2) were overlain onto expressway data (Fig. 4). In this scenario 20% (1186 km) of the combined Nexco East and Central Expressway networks would be impacted by 0.5 mm or greater of ash (Table 1). The minimum ashfall threshold of 0.5 mm represents the depth needed to cover road markings and therefore when road clean-up would need to commence.

6. Next steps

Graph theory techniques will be used to assess the impacts of ash fall on the evacuation plans for Yamanashi Prefecture with regards to a future 1707 Hoei type eruption at Mount Fuji.

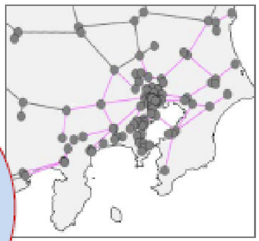

Figure 6: Graph representation of a portion of the highway system in Japan. The pink edges represent the sections of highway impacted by ≥0.5 mm of ashfall from the Hoei eruption from Mount Fuji

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Appendix F. Briefing Note

Phillips, E. (2014). March 2014 Darwin Blackout. *Risk Frontiers Briefing Note*. No. 269.

Risk Frontiers

briefing note
269
March, 2014

March 2014 Darwin Blackout

by Emma Phillips

Information for this briefing note was sourced from the Power and Water Corporation and the following online news sources: ABC, Sydney Morning Herald, Northern Territory News and Nine MSN.

On Wednesday 12th March 2014 Darwin experienced a blackout that affected over 130,000 residents, leaving some homes and businesses without power for more than 12 hours. The Power & Water Corporation (PWC) has apologised and stated that the fault was due to a tripped circuit at the Hudson Creek sub-station at Berrimah, in the city's east. This activated a protection switch, which also shut down the Channel Island station, the Northern Territory's main source of electricity. PWC announced that people inconvenienced by the power outage for 12 hours or more will be eligible for a Power & Water rebate. PWC will also consider claims for business compensation on a case-by-case basis.

The power went out at approximately 1:19am on Wednesday, impacting Darwin, Palmerston and as far south as Pine Creek and Katherine (Figure 1). The blackout was a System Black event and the Northern Territory Government stated that an inquiry will be held to review the power failure and response. Residents experienced a long hot night with the lowest temperature reaching just below 26 degrees. The blackout affected schools, public offices, public transport and traffic signals. Schools were ordered to close to care for the students. Some hotels in the area were evacuated resulting in a sleepless night for many guests. Court services were also disrupted. Business owners felt the cost of the outages with no trade, cold food storage issues, and still having to pay staff wages. One business owner stated that these losses were unlikely to be covered by insurance and that they were planning on requesting compensation from PWC. Three fires were attended to during the blackout, all said to be caused by faulty gas cooking equipment. PWC and emergency services told the public to remain calm and to be careful on roads. There were also public food safety concerns as household fridge and freezers lost power.

The Royal Darwin Hospital and airport were operating as normal through the use of backup generators and rubbish collection in the region also continued. Some businesses that managed to stay open benefited from the situation: the Caltex in Berrimah was the only working petrol station in Darwin, they had the busiest day they have ever had. People drove from far and wide to get their morning coffee there. The Deck bar in Darwin was the only pub to remain open, which was packed out by lunch time.

This type of event, complete failure of a main power station, has only occurred three times in the past 15 years. Arguing against the suggestion that the Northern Territory government had been cutting back funding of PWC with a view to its being split up and privatised, Chief Minister Adam Giles stated that $80 million was being spent on repairs and maintenance this year, compared to $61 million in 2010 after the last major blackout.

This event has brought the unavoidable problems facing utility networks sharply into focus. Maintaining a vast and expensive power network for a small and remote population is no easy feat.

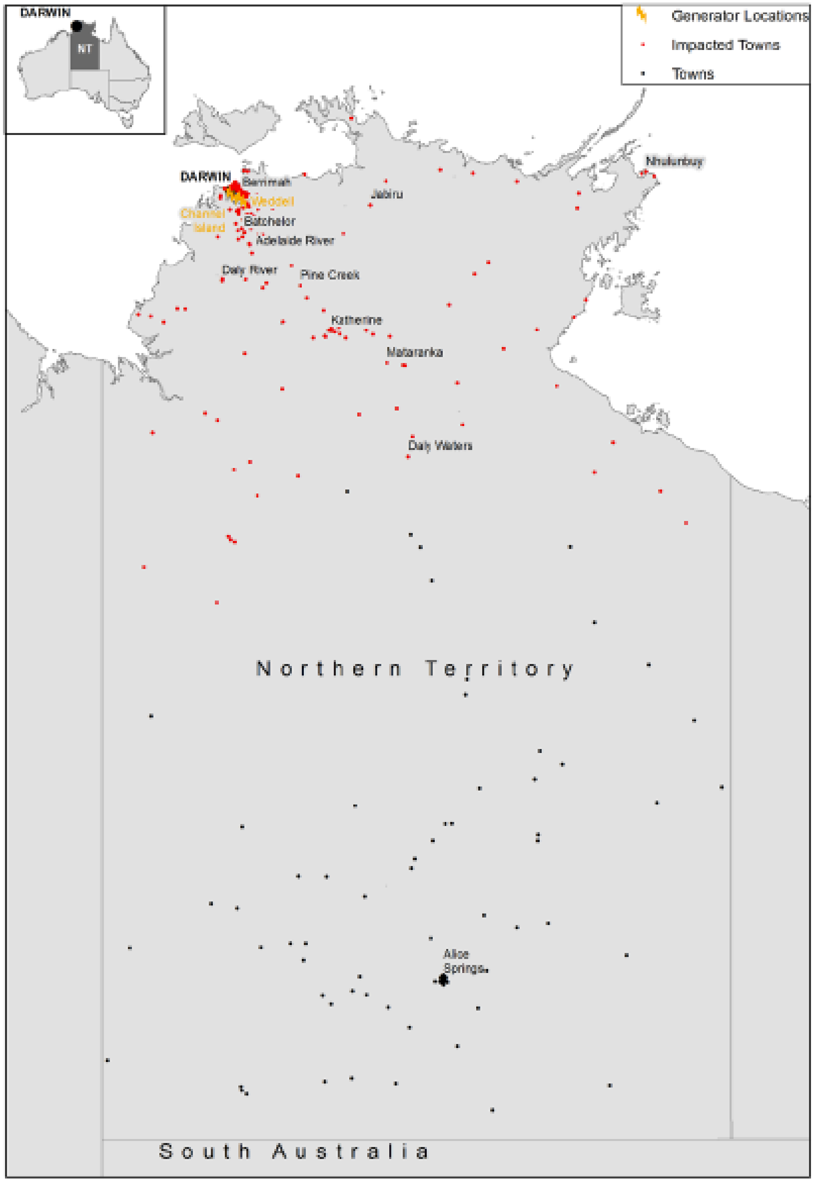

Figure 1: The extent of the 12th March 2014 Darwin blackout in the Northern Territory Australia.

Although the Darwin blackout was disruptive it was relatively small compared to historical power failures that have occurred around the world, for example, the 2003 Northeast blackout that affected over 55 million people across USA and Canada, some of whom went two days without power. The 31st July 2012 Indian blackout is the largest power outage in history affecting over 620 million people, the second blackout in two days. In mid February, 1998 the Auckland Central Business district suffered a power failure that left it with a minimal supply of power for five weeks and shortages and restrictions for another month or more. These situations show just how vulnerable critical infrastructure and services can be and how much society relies on these services for everyday living, the economy and emergency response.

It is worrying to think how vulnerable power networks are to future natural disasters. Prolonged natural disasters can impact surrounding areas weeks to months after the initial event; causing vast and on-going disruption to utility, transport and communication networks. Our growing reliance on infrastructure and technology, along with the strong interdependent nature of these critical services, can potentially turn one failure into a cascading disaster. Local impacts to critical infrastructure can also lead to the interruption of essential services in regions that were not directly impacted by the physical hazard event. It has never been more important to understand network vulnerabilities and to analyse the cost of long term disruption, both social and economic.

Whilst significant work has gone into understanding the direct impacts from natural hazards, less emphasis has been placed on understanding the vulnerability of lifeline networks, including indirect and long-term disruption. Current postgraduate research at Risk Frontiers aims to bridge this gap and will attempt to address some key research questions: What portion of contingent business interruption loss is caused by the disruption of lifeline networks? Can the interconnectedness of critical services lead to a cascade of failures? What influences network recovery and how long can it take to rebuild? How long can impacts of a natural hazard event last? What is the cost of long term network disruption?

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http://www.smh.com.au/national/darwin-in-the-grip-of-massive-power-blackout-20140312-34l98.html

Appendix G. Final ethics approval

Dear Dr Magill,

RE: Ethics project entitled: "Network disruptions during long-duration natural hazard events"

Ref number: 5201400284

The Faculty of Science Human Research Ethics Sub-Committee has reviewed your application and granted final approval, effective 3rd June 2014. You may now commence your research.

This research meets the requirements of the National Statement on Ethical Conduct in Human Research (2007). The National Statement is available at the following web site:

http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/e72.pdf.

The following personnel are authorised to conduct this research:

Dr Christina Magill
Miss Emma Anne Phillips

NB. STUDENTS: IT IS YOUR RESPONSIBILITY TO KEEP A COPY OF THIS APPROVAL EMAIL TO SUBMIT WITH YOUR THESIS.

Please note the following standard requirements of approval:

1. The approval of this project is conditional upon your continuing compliance with the National Statement on Ethical Conduct in Human Research (2007).

2. Approval will be for a period of five (5) years subject to the provision of annual reports.

Progress Report 1 Due: 3rd June 2015
Progress Report 2 Due: 3rd June 2016
Progress Report 3 Due: 3rd June 2017
Progress Report 4 Due: 3rd June 2018
Final Report Due: 3rd June 2019

NB. If you complete the work earlier than you had planned you must submit a Final Report as soon as the work is completed. If the project has been discontinued or not commenced for any reason, you are also required to submit a Final Report for the project.

Progress reports and Final Reports are available at the following website:

http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics/forms

3. If the project has run for more than five (5) years you cannot renew approval for the project. You will need to complete and submit a Final Report and submit a new application for the project. (The five year limit on renewal of approvals allows the Committee to fully re-

review research in an environment where legislation, guidelines and requirements are continually changing, for example, new child protection and privacy laws).

4. All amendments to the project must be reviewed and approved by the Committee before implementation. Please complete and submit a Request for Amendment Form available at the following website:

http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics/forms

5. Please notify the Committee immediately in the event of any adverse effects on participants or of any unforeseen events that affect the continued ethical acceptability of the project.

6. At all times you are responsible for the ethical conduct of your research in accordance with the guidelines established by the University. This information is available at the following websites:
http://www.mq.edu.au/policy/

http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics/policy

If you will be applying for or have applied for internal or external funding for the above project it is your responsibility to provide the Macquarie University's Research Grants Management Assistant with a copy of this email as soon as possible. Internal and External funding agencies will not be informed that you have final approval for your project and funds will not be released until the Research Grants Management Assistant has received a copy of this email.

If you need to provide a hard copy letter of Final Approval to an external organisation as evidence that you have Final Approval, please do not hesitate to contact the Ethics Secretariat at the address below.

Please retain a copy of this email as this is your official notification of final ethics approval.

Yours sincerely,
Richie Howitt, Chair
Faculty of Science Human Research Ethics Sub-Committee
Macquarie University
NSW 2109