Economics of Resilient Infrastructure Auckland Volcanic Field Scenario

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m.e market economics environment • spatial

RIKS research institute for knowledge systems

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Resilient ORGANISATIONS

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ABSTRACT

The Economics of Resilient Infrastructure (ERI) research programme is a four year project funded by the New Zealand Government. The final output of the programme is a software tool, MERIT (Modelling the Economics of Resilient Infrastructure Tool) which will quantify the economic consequences of infrastructure failure and explore various post disaster recovery strategies.

This report documents one of two multi-sector outage scenarios developed for the MERIT tool, a volcanic eruption in the Auckland Volcanic Field (AVF). The scenario is based on the all-of-nation 2008 Civil Defence Exercise Ruaumoko, which concerned the period of unrest leading to an AVF eruption. The Determining Volcanic Risk for Auckland (DEVORA) research programme recently produced a month long eruption scenario following Exercise Ruaumoko, which we have adapted here.

In this report we describe the geophysical scenario concerning the ‘Mt Ruaumoko eruption’, describe evacuation maps and a clean-up model, and then describe impacts and restoration times for the following infrastructure sectors: power, fuel, roads, rail, aviation, port, water supply, wastewater, stormwater, and telecommunications. For each sector we provide a ‘level of service’ time series map or a table, which detail how Auckland residents and businesses experience the service provided by each sector during the course of the eruption and its aftermath. We do not consider interdependencies between the sectors, as the MERIT tool will eventually provide various policy levers which may affect sector interdependencies.

In addition to providing an input for the MERIT tool, this report is a valuable contribution towards understanding the likely impacts of an AVF eruption.

KEYWORDS

Auckland Volcanic Field, aviation, clean-up, electricity distribution, electricity generation, electricity transmission, evacuation, fuel, infrastructure outage, level of service, MERIT, ports, rail, road, Ruaumoko, stormwater, telecommunications, transportation, volcanic eruption, volcanic impact, wastewater, water supply

1.0 INTRODUCTION

1.1 OVERVIEW OF ERI RESEARCH PROGRAMME

The Economics of Resilient Infrastructure (ERI) research programme is a four year project funded by the New Zealand Government. The programme aims are to study and quantify the impacts of natural hazards on infrastructure and to model the economic consequences of these impacts. To this end a new software tool called MERIT (Modelling the Economics of Resilient Infrastructure Tool) is being developed.

MERIT will be used to support government and infrastructure provider decision-making by enhancing understanding of the societal value of resilience improvements. MERIT consists of a suite of interlinked modules incorporating the spatial features of a region's infrastructure networks, economic activity, business behaviours, interdependencies, and policy options. These modules can be 'shocked' using scenarios (e.g., volcanic eruption, significant single infrastructure outage) to understand the impacts of such disruptions.

This report is an output of Research Aim (RA) 1 of the ERI project. RA 1 is focussed on developing 'Outage Scenarios' that can be used to better inform the MERIT approach. The other RAs consider business behaviours in response to infrastructure failure and economic modelling of the impacts of infrastructure failure.

Previous work on RA 1 focused on single infrastructure outages, specifically water supply, power, and transportation (e.g., Buxton et al., 2014). However, natural hazard events are likely to cause multi-sector outages with more complex economic impacts. RA 1 is now focused on developing multi-infrastructure failure scenarios – a volcanic eruption in the Auckland Volcanic Field (AVF; this report) and an earthquake on the Alpine Fault. Such events are likely to impact many sectors and have profound regional and national economic impacts.

ERI scenarios consist of an (optional) geophysical description of the event, (optional) maps showing the impact of the event for each sector of interest, time-stamped maps and/or tables detailing outages experienced by the user.

1.2 METHODOLOGY FOR OUTAGE MAP PREPARATION

The key output of the RA 1 scenario is a sequence of time-series maps that show infrastructure outages in terms of the change in level of service experienced by the end-user. Rather than just showing the damage or disruption to the infrastructure as a result of the hazard (impact maps), the consequences of the damage or disruption to end-users, in terms of changes in levels of service, needs to be shown on the maps. These maps are one of the core inputs into the MERIT economic model, which requires the level of service available to an end-user (business) at any point in time or space, in order for business behavioural responses to be modelled.

The methodology for preparing the final outage maps is:

1. Develop a geophysical hazard scenario;
2. Prepare hazard maps; this can be a single hazard map or a series of maps for an evolving situation;

3. Describe how the relevant infrastructure is impacted by the hazard(s); this can be a single impact map for each sector or a series of maps for an evolving situation;
4. Apply a user-focused metric scale to describe the altered experience of the infrastructure user, as a result of the impact states described in (3) above. This step is done in consultation with infrastructure providers;
5. Prepare time-series outage maps.

Consultation with infrastructure providers was a key part of the methodology of developing the outage maps. This consultation had two purposes: to validate the impact maps, and to understand what the impacts mean from an end-user point of view. Meetings and/or discussions were held with the following infrastructure providers:

- Watercare (water supply and wastewater infrastructure)
- Auckland Council (AC; stormwater infrastructure)
- New Zealand Transport Agency (NZTA) and Auckland Transport (AT; roading infrastructure)
- KiwiRail and AT (rail infrastructure)
- Transpower and Vector (power supply and distribution infrastructure)
- Spark (telecommunications infrastructure)
- Refining New Zealand (fuel infrastructure)
- Auckland Airport and Air New Zealand (aviation infrastructure).

Consultation with these providers has proved invaluable. It has allowed for the refinement of the impact maps, and a greater understanding of the effects of the impacts on end-users. The consultation process has also highlighted the depth of knowledge and information held by the providers, and the potential for much more detailed analysis of impacts and outages given more time and resources.

Consultation with Auckland Council Civil Defence Emergency Management Group (AC CDEM) was also undertaken. It became clear during discussions with the infrastructure providers that they would rely heavily on instructions and decisions taken by Civil Defence during the scenario, including the nature and extent of the evacuation zones. As such, understanding possible decision-making by Civil Defence during the scenario was critical for understanding the changes in levels of service experienced by end-users.

Another key aspect of the methodology of developing the outage maps was ongoing discussions with the RA 2 (business behaviour) and RA 3 (economic modelling) researchers. The purpose of this consultation was to ensure, to the extent possible, that the outage metrics used would be fit for purpose and provide the economic model with the information needed. While this process was quite straightforward for some outage metrics (e.g., water supply, wastewater) it was more complex for others (e.g., roads, telecommunications).

1.3 REPORT OVERVIEW

This report presents an Auckland Volcanic Field (AVF) eruption scenario for the MERIT model. The AVF scenario is based on an existing scenario developed by the University of Canterbury (UC) as part of the Determining Volcanic Risk in Auckland (DEVORA) research programme. We describe the UC scenario, which continues the scenario worked with during Exercise Ruaumoko, and explain its ERI adaptation (Section 2). We then provide snapshots of hazard extent and severity at relevant time steps for the edifice, pyroclastic surge and deposit, tephra fall, ballistics, and lava flows (Section 3), together with the New Zealand Volcano Alert Level (VAL) over the course of the scenario. Next we designate evacuation zones on the basis of the hazard extents and VAL (Section 4) and provide a clean-up model (Section 5). The main body of the report is derivation of impact and level of service maps for the power (Section 6), fuel (Section 7), road (Section 8), rail (Section 9), aviation (Section 10), ports (Section 11), water supply (Section 12), wastewater (Section 13), stormwater (Section 14) and telecommunications (Section 15) sectors. Each of Sections 6–15 provides comments on likely interdependencies with other sectors; interdependencies are generally not incorporated into outage maps. We finish with conclusions (Section 16).

1.4 CONTRIBUTORS AND DISCLAIMER

This report is a joint effort of the UC volcanic impacts research and the ERI RA 1 teams, with generous insights provided by members of the Auckland Lifelines Group (ALG) and Auckland Council (Appendix A1). This report should not be used as a prediction of future volcanic activity, impacts, and ramifications, nor should it be viewed as a recommendation or endorsement of present or future policy.

2.0 AUCKLAND VOLCANIC FIELD ERUPTION SCENARIO

2.1 AUCKLAND AND THE AUCKLAND VOLCANIC FIELD (AVF)

Auckland, New Zealand, is home to over a third of New Zealand's population – 1.4 million people – and accounts for ~35% of New Zealand's GDP (Statistics New Zealand, 2014). The city is built on top of the AVF, which covers 360 km2, has over 50 eruptive centres (vents), and has erupted over 55 times in the past 250,000 years, producing a cumulative volume of ~2 km3 of tephra, lava, and other volcanic deposits (Kermode, 1992; Kereszturi et al., 2013; Figure 2.1). The field is likely to erupt again: the most recent eruption, Rangitoto, was only 550 years ago (Lindsay et al., 2011). Most AVF vents are monogenetic, i.e., they only erupt once. This means that it is very likely that the next vent will erupt in a new location within the field. Despite considerable scientific efforts (e.g., Bebbington & Cronin, 2011), no spatial or temporal patterns have been identified; indeed, the oldest (Pupuke Volcano) and the youngest (Rangitoto) vents are located next to each other. However, it is almost certain that there will be a future eruption, although it is wholly unknown where or when the next eruption will be. The size of the next eruption is also difficult to address, as the last eruption, Rangitoto, accounts for nearly half of the erupted volume of the field, and it is unclear whether this eruption is an anomaly or signals a change in the eruptive behaviour of the field.

Presently, GeoNet monitors the AVF, and Auckland Council has developed an AVF Contingency Plan (Auckland Council, 2015) which will be followed should unrest and/or an eruption occur. Since 2008, there has been a multi-agency effort to better understand and prepare for an AVF eruption through the DEVORA research programme. DEVORA has focused on the geologic context of the AVF, AVF hazards, and more recently, AVF risk to Auckland. The scenario presented here has been developed with DEVORA researchers and will be further used for AVF risk evaluation and quantification.

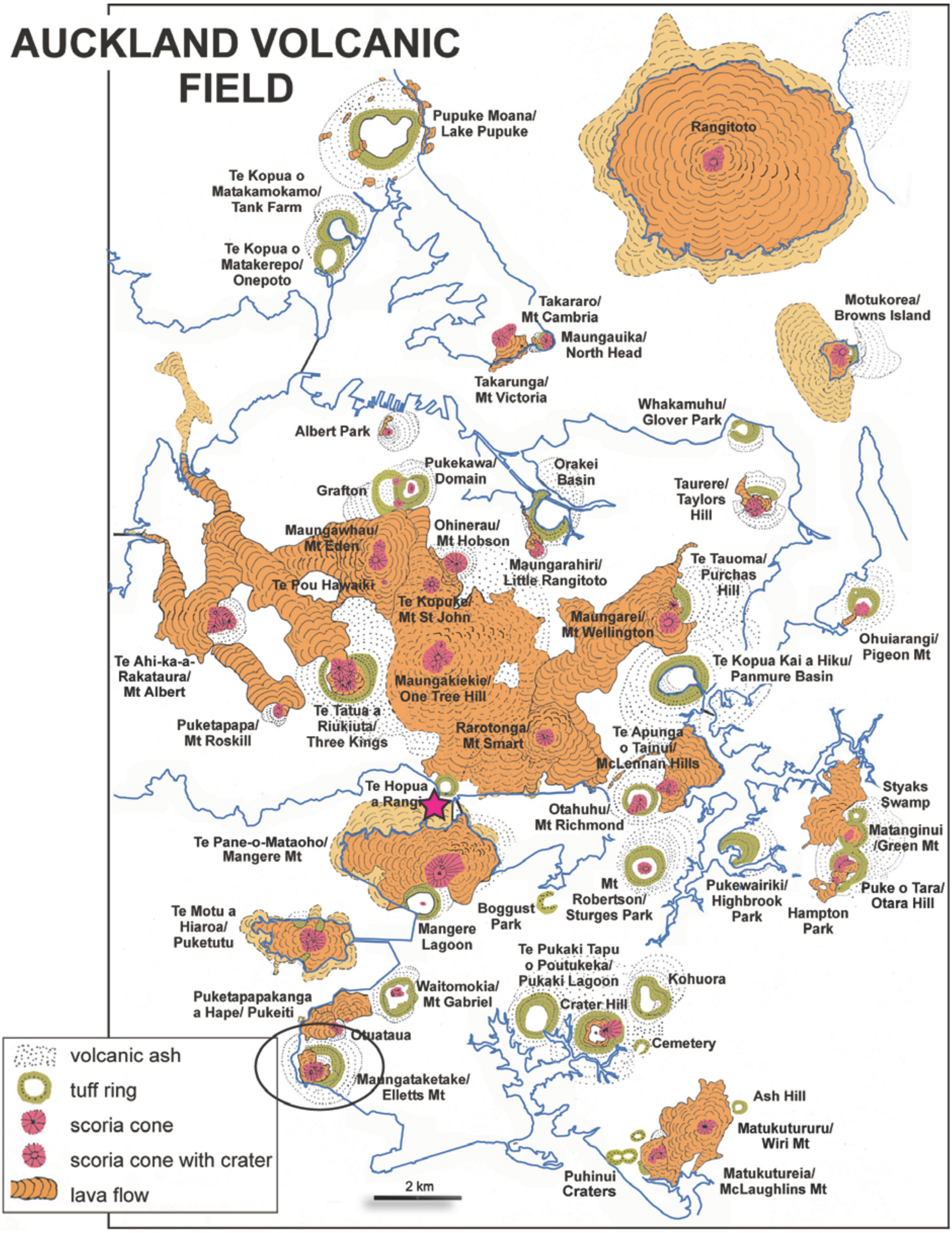


Figure 2.1 Map of the AVF after Kermode (1992). Scoria cones are in pink, tuff rings are green, lava flows are in orange, and volcanic ash extent is dotted. The shoreline is a blue line. The ERI Mt Ruaumoko scenario vent is indicated with a pink star, and the Maungataketake deposits are circled.

2.1.1 Maungataketake eruption

As will be discussed in Section 2.3, the UC AVF scenario is inspired by historic analogue eruptions from around the world. As the UC scenario was developed for educational purposes with aims different from ERI's, information important for ERI (e.g., hazard severity) had to be developed, and in many cases the Maungataketake eruption (Figure 2.1) is used as inspiration for the ERI scenario.

DEVORA research has identified several factors that influence the style of eruptive activity at a particular site; important ones are the thickness of the soft-sediment capping the landscape, distance from faults, and elevation above sea level (e.g., Kereszturi et al., 2014). The location of the UC scenario, 'Mt Ruaumoko' (see Sections 2.3, 2.4, and 3) is in the Turanga Group (soft sediment), very close to the contact with the Waitemata Group (coherent rock; Edbrooke 2001). While the Waitemata Group underlays the Turanga Group, it is the immediate subsurface which is important for influencing the style of eruption.

Maungataketake is one of the best-characterised eruptions of the AVF and is situated within the Turanga Group, ~6 km SSW of the Mt Ruaumoko site. At the time of the Maungataketake eruption (~85–89 ka), sea level was similar to today (Agustín-Flores et al., 2014) so eruption occurred close to sea level. The groundwater table is thought to be similar to today: 2–6 meters below the surface.

Although the Mt Ruaumoko eruption begins in shallow water, the water depth is too shallow (particularly given the shallow water table during the Maungataketake eruption) for the most likely eruption style to be different from Maungataketake. There are some volcanoes that are closer to 'Mt Ruaumoko' than Mangutaketake, but none have been studied in as much detail (Agustín-Flores et al., 2014, Brand et al., 2014), particularly regarding the base surges. As such, Maungataketake is heavily used as an analogue for Mt Ruaumoko to fill in details that are not provided in the UC scenario.

2.2 EXERCISE RUAUMOKO

The UC scenario is based on work done as part of Exercise Ruaumoko. Exercise Ruaumoko was a national disaster exercise run from November 2007 to March 2008. Its aim was to test New Zealand's all-of-nation arrangements for responding to a major disaster resulting from a volcanic eruption in Auckland. More than 1,500 participants from approximately 125 organisations were directly involved, including local and central government agencies and private companies, making it the largest Civil Defence and Emergency Management (CDEM) exercise held in New Zealand (MCDEM, 2008).

The exercise was based on the scenario of a volcanic eruption located in the wider Auckland metropolitan area. The exercise focused on the lead-in to a volcanic eruption, stopping shortly after the eruption itself started. The location of the eruption was not known by any of the participants until the simulated eruption occurred.

Initially, the scenario involved the identification of precursor activity in the form of unfelt earthquakes in the Auckland region in November 2007. After 48 hours the earthquakes ceased. Seismic activity resumed in early March 2008. As the activity continued, the depth of the source of the activity started to shallow, increasing the likelihood of a volcanic eruption. On the morning of 13 March the epicentral clustering became constrained to an area centred on the Mangere Inlet in the Manukau Harbour. At 1:50pm on Friday 14 March, a simulated eruption began in this location (MCDEM, 2008).

Several restrictions were provided to the 'volcano' prior to Exercise Ruaumoko, which account for the scenario having less severe consequences than it might in another location within the AVF (Sherburn, personal communications 25 Feb 2015):

- The eruption site could not force the closure of both State Highway 1 and the Western Motorway given an anticipated 3 km evacuation radius (closure of one of the two permitted);
- The eruption should be in an area with a range of socio-economic groups (e.g., not in a predominantly poor or wealthy area);
- The eruption should start in shallow water to introduce a range of possible eruption types;
- The heightened unrest had to evolve in 'real time' over the course of the exercise, i.e., heightened unrest started on Monday with an eruption Friday afternoon.

2.3 MT RUAUMOKO SCENARIO DEVELOPED BY UC

UC, through the DEVORA research programme, has developed an AVF eruption scenario that takes Exercise Ruaumoko and continues it through an eruption. The 'Mt Ruaumoko' scenario was developed for an educational simulation exercise where tertiary students respond to a volcanic crisis (Dohaney et al., 2015). The scenario spans 10 weeks (6 February–14 April), with two weeks of background AVF behaviour, four weeks of low to heightened unrest, and four weeks of eruptive activity. The UC Mt Ruaumoko scenario (Table 2.1 and Figure 2.2) is the basis for the ERI AVF scenario. A full description of the geophysical scenario, together with scientific justification for phenomena and severity parameters, is presented in Fitzgerald et al., (2015). The full educational scenario includes geophysical data (e.g., seismicity, deformation) for students to interpret. These data, along with general eruption characteristics, are based on loosely analogous historic eruptions from around the world, in particular eruptions at Hekla and Grímsvötn (Iceland), Kīlauea (Hawai'i), Stromboli and Etna (Italy), Parícutin (Mexico) and Spurr (Alaska).

Table 2.1 UC Mt Ruaumoko scenario (Fitzgerald et al., 2015).

Date	Monitoring 'Observation'	Eruptive Activity
6 February	'Normal'	
19 February	Small swarms of high frequency (non-volcanic) earthquakes	
22 February	Swarm of low frequency earthquakes at 39–45 km depth with magnitude 1.8–2.2	
1–5 March	125 mostly low frequency earthquakes at 34–45 km depth with magnitude 1.8–2.2	
7–11 March	Some high frequency earthquakes, increasing in magnitude and shallowing. Swarms with up to 300 quakes per day. Ground deformation detected.	
12–13 March	Volcanic gases detected. Some high frequency earthquakes, increasing in magnitude and shallowing. Swarms with up to 300 quakes per day. Ground deformation detected. Shallow (< 5 km) M4.4 and 4.5 earthquakes morning of 13 March.	

Date	Monitoring ‘Observation’	Eruptive Activity
14 March (early)	Tremor earthquakes, acceleration of deformation data. Visual observation of cracking near Mangere. Volcanic gases increase.	
14 March (AM)	M4.5 earthquake accompanies eruption.	Phreatic eruption
14 March (PM)	M4.8 earthquake accompanies eruption	Phreatomagmatic eruption with 3 km plume
15–17 March	Sudden decrease in gas levels	
18 March	Low levels of volcanic gas	Tuff ring visible underwater
19 March	Low levels of volcanic gas	
20 March	Low levels of volcanic gas. Measurable inflation (deformation).	
21 March	Several orders of magnitude spike in volcanic gas.	Phreatomagmatic eruption with 2.5 km plume.
22 March		Phreatomagmatic eruption with 1.5 km plume.
23 March		Tuff ring visible above water
25 March		Phreato- to magmatic eruption with fire fountaining with 500 m plume, ballistics to 350 m above the vent in the afternoon for 8 hours.
26 March		Strombolian eruption with 1 hour of fire fountaining with plume up to 300 m high
29–30 March		Magmatic eruption with plume up to 500 m high
1 April		Small cinder cone visible
2 April	Peak of deformation; decreases thereafter.	
3 April		Surface lava flows flowing south towards Kiwi Esplanade
4 April	Volcanic gas emissions low and stabilised.	Surface lava flows flowing south towards Kiwi Esplanade
5–13 April		Lava flows to west, reaching water. Littoral explosions at water contact. Plume of mostly steam, gas, and some ash from the lava – water contact.
14 April		Lava bench collapses, with plume height ranging from 40–100 m
15 April	*Eruption geologically over*	

TIMELINE

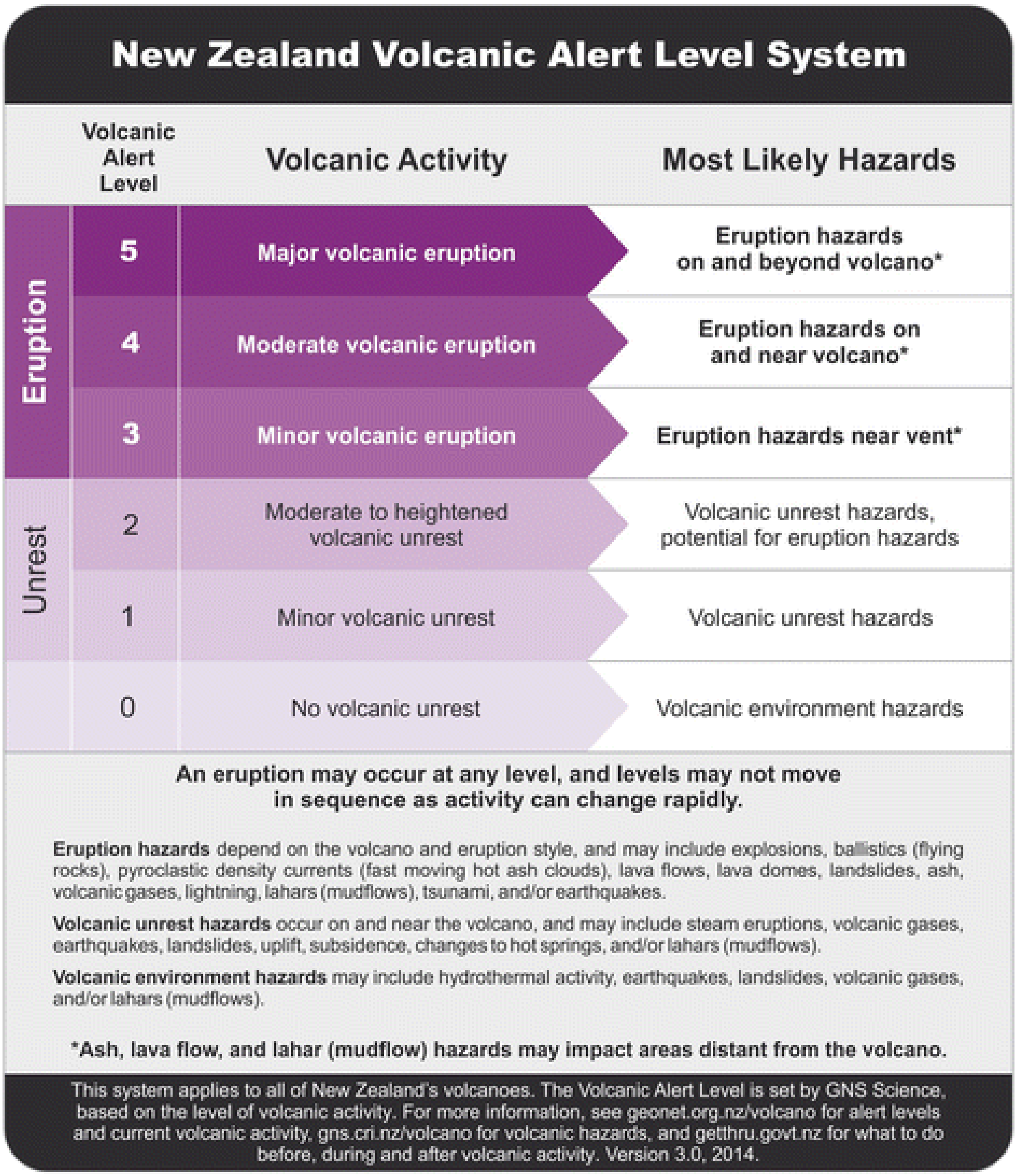
Precursors		Event	PAUSES
6-Feb	Background, no changes		
15-Feb	Background; Feb 19 - small HF earthquakes representing background seismicity		Feb 23rd 0:00 - PAUSE - 20 minutes to prepare for a 10 min Press Conference
1-Mar	Mar 6: LF quakes at depth, and shallowing. Mar 8: Magma reaches the brittle crust; Mar 8-13: Some HF quakes, with an increase in magnitude, and continuing to shallow. Swarms present now with up to 300 quakes per day.		March 8th 16:00 - PAUSE - 15 mins prepare for a 10 minute Interview between the Section Manager and a member of the EM team
10-Mar	Some HF quakes, swarms. Deformation data no longer background. March 12 - beginning of gas changes. March 14- Tremor quakes present now, with accelerating deformation data and visual observations of cracking near Mangere. Gas levels increase, with deflation of ground surface. March 15-20 sudden decrease in gas levels. March 18 - tuff ring visible below waters surface.	 March 14th AM first phreatic eruption (Mangere). March 14 PM phreatomagmatic eruption (3 km plume); March 18 - Tuff ring visible underwater.	March 14th @ 16:00 PAUSE, 10 min to prepare for a 15 min Joint GNS-EM Team Meeting to discuss the status of the Event
20-Mar	March 20 - inflation (deformation) measureable now. March 21 - huge spike gas content (by huge magnitudes). Steady decrease in gas content after this. Prior to most magmatic eruptions, inflation events occur, with deflation occuring afterwards.	 Mar 21 - Phreatomagmatic eruption (2.5 km plume) which continues sporadically over ~48 hours. March 22nd - 3rd phreatomagmatic eruption (1.5km), March 23rd -Tuff ring visible above water level. March 25 AM - Phreato to Magmatic eruption with fire-fountaining (500 m plume); March 25 PM - fire fountaining continues, ballistics are thrown 350 m high, continues for 8 hours; March 26th - Strombolian eruption (1 hr of fire fountaining; plume height of 300 m); March 29th - Magmatic eruption (max height of 500 m plume), intermitant eruptions over 2 days	March 25th - 4:00 PAUSE 5 minute break :)
April 1 to April 14	Tremor continues over the entire eruptive period. Gas levels fall off as the activity becomes more effusive. Levels stabilize around April 4th. Height of deformation around April 2nd. Deflation continues as activity becomes more effusive	 Small cinder cone is now visible. April 3rd - surface lava flows are visible. Flows go south to Kiwi esplanade. April 5th - flows on the western part of the cone. Flows go west, and reach the water - forming littoral explosions. A plume is present at lava-water contact (mostly steam, gas, and some ash) - that is present from April 5-13th. Lava bench collapse on April 14th (height of plume ranges from 40 -100 m)	April 3rd PAUSE 10 minutes to prepare for a 15 minute press conference

Figure 2.2 Figure of UC Mt Ruaumoko scenario from Fitzgerald et al. (2015). Table 2.1 provides greater detail of the scenario.

2.4 ERI Mt Ruaumoko Scenario

The ERI Mt Ruaumoko scenario is based on the UC scenario, adapted for ERI usage. There are several major modifications:

1. Volcano Alert Levels (VAL) are provided, using New Zealand VAL version 3.0 (Potter et al., 2014; Figure 2.3). For the educational scenario, the 'GNS Science' student team set volcanic alert levels. For the ERI adaptation, N. Deligne circulated the timeline provided in Table 2.1 to members of the GeoNet volcano monitoring team and requested that team members 'vote' (privately, over email) on how they would set the VAL through the course of the scenario. 7 team members participated, and the scenario VAL was set following GeoNet monitoring meeting voting procedures. The VAL is important as several Auckland Council and infrastructure policies and procedures (e.g., evacuation) are triggered by various VAL levels.
2. Hazard layer extents and severity are provided.
3. A base surge accompanies the phreatic and phreatomagmatic eruptions on 14 March and the phreatomagmatic eruption on 21 March. Work on Maungataketake is used to describe surge extent and severity, as one would expect similar initial eruption characteristics given substrate location (see Section 2.1.1; Agustín-Flores et al., 2014; Brand et al., 2014). Following Brand et al. (2014), a 'worst-case' damage footprint is adopted for the first phreatic eruption and an 'average' damage footprint is used for the 14 and 21 March phreatomagmatic eruptions. The base surge is most severe when there is considerable water in the system, so the latter two eruptions, although larger in terms of magmatic contribution, would likely have smaller surges.
4. Rainfall, typical for the season, is added, using rainfall data from NIWA Cliflo database for the Auckland Aeordrome for the scenario dates for 2014 (i.e., March–May 2014). This is important regarding impacts to electricity networks and potential ingress into stormwater networks. Additionally, this is important for clean-up purposes, as rain, once it is on the ground, can move/remove thin ash deposits.



New Zealand Volcanic Alert Level System

	Volcanic Alert Level	Volcanic Activity	Most Likely Hazards
Eruption	5	Major volcanic eruption	Eruption hazards on and beyond volcano*
Eruption	4	Moderate volcanic eruption	Eruption hazards on and near volcano*
Eruption	3	Minor volcanic eruption	Eruption hazards near vent*
Unrest	2	Moderate to heightened volcanic unrest	Volcanic unrest hazards, potential for eruption hazards
Unrest	1	Minor volcanic unrest	Volcanic unrest hazards
	0	No volcanic unrest	Volcanic environment hazards

An eruption may occur at any level, and levels may not move in sequence as activity can change rapidly.

Eruption hazards depend on the volcano and eruption style, and may include explosions, ballistics (flying rocks), pyroclastic density currents (fast moving hot ash clouds), lava flows, lava domes, landslides, ash, volcanic gases, lightning, lahars (mudflows), tsunami, and/or earthquakes.

Volcanic unrest hazards occur on and near the volcano, and may include steam eruptions, volcanic gases, earthquakes, landslides, uplift, subsidence, changes to hot springs, and/or lahars (mudflows).

Volcanic environment hazards may include hydrothermal activity, earthquakes, landslides, volcanic gases, and/or lahars (mudflows).

***Ash, lava flow, and lahar (mudflow) hazards may impact areas distant from the volcano.**

This system applies to all of New Zealand's volcanoes. The Volcanic Alert Level is set by GNS Science, based on the level of volcanic activity. For more information, see geonet.org.nz/volcano for alert levels and current volcanic activity, gns.cri.nz/volcano for volcanic hazards, and getthru.govt.nz for what to do before, during and after volcanic activity. Version 3.0, 2014.

Figure 2.3 New Zealand Volcanic Alert Level (VAL) version 3.0 (Potter et al., 2014).

Table 2.2 details the ERI Mt Ruaumoko scenario, indicating VAL, what (new) hazards are present at each time slice, and what sectors are likely to be directly impacted (interdependencies are not considered here). Pre-eruption VALs are provided as they indicate the amount of warning or lead time available to take and/or implement mitigative measures. The emphasis on new hazards reflects reality that some hazards produce removable material (i.e., ash fall, surges). This material is disruptive to infrastructure, but once it's cleaned (e.g., the material is removed), infrastructure functionality is restored (Wilson et al., 2012; Wilson et al., 2014). Although initial implementation of the Mt Ruaumoko scenario will assume cleaning directives, policy levers in the future may consider how much and what cleaning is undertaken at what time. Thus, if a new hazard produces 20 mm of tephra in a location, it will be 20 mm of tephra or 20 mm of tephra on top of an existing eruption deposit.

Table 2.2 ERI Mt Ruaumoko scenario indicating date, VAL, and new hazards; italicised text indicates volcanic unrest or rainfall. 'Figure' indicates relevant hazard map in Section 3.

Date	Volcano Alert Level	New hazards	Figure
6 February	VAL 0		
22 February	VAL 1		
8 March	VAL 2		
12–13 March	VAL 2	*Volcanic gases detected; robust confirmation of high eruption likelihood*	
14 March (AM)	VAL 3	Edifice Surge (worst case)	Figure 3.3
14 March (PM)	VAL 4	Edifice Ash Surge (average)	Figure 3.4
15 March	VAL 3	-	
16–17 March	VAL 2	-	
15–17 March		*17 mm total rainfall*	
18–20 March	VAL 3	-	
21 March	VAL 4	Ash Surge (average)	Figure 3.5
22 March	VAL 3	Ash	Figure 3.6
23–24 March	VAL 3	-	
25–30 March	VAL 3	Edifice Ash Ballistics	Figure 3.7
25–26 March		*3 mm total rainfall*	

Date	Volcano Alert Level	New hazards	Figure
3–14 April	VAL 3	Lava Mini-tsunami Edifice (Ash too minor to account for)	Figure 3.8
4 April		*21 mm total rainfall*	
16 April	VAL 2		Figure 3.9
11–30 April		*87 mm total rainfall*	
1 May	VAL 1[1]		
1 June	VAL 0[1]		

[1] Not voted on by the GeoNet volcano monitoring team (arbitrarily set by report authors).

There are several volcanic hazards that will not be considered:

1. Volcanic gases. Volcanic gases can be corrosive and exacerbate respiratory problems. However, volcanic gases are likely to cause negligible (if any) impacts to infrastructure, and so will be ignored in the ERI scenario.
2. Earthquakes. Volcanic eruptions cause earthquakes and tremor. However, these tend to be quite localised. It is extremely unlikely that earthquake activity related to an AVF eruption would cause damage in an area outside the area impacted by the edifice. As the edifice footprint will correspond to complete devastation, it is unnecessary to consider additional damage from earthquakes. We do note however three of the largest earthquakes due to KiwiRail protocols requiring rail line checks, and possible minor disruption to road transport, following moderate to large earthquakes.
3. Lahars (volcaniclastic debris flows) and landslides. There is nothing in the Auckland geologic record or from analogous historic eruptions from around the world to suggest that lahars are a concern for Auckland.
4. Ground deformation. We account for the most severe ground deformation by stating that everything underneath the edifice (which is larger than the actual vent conduit) is destroyed, but have not considered medium or far field ground deformation which may impact buried infrastructure.

3.0 SCENARIO HAZARD MAPS

This section provides a series of hazard maps tracking the evolution of the ERI Mt Ruaumoko scenario. Refer to Section 2 for scenario description. We adopt a vent location of NZTM E1758370 N5910750 to be compatible with the DEVORA research programme.

3.1 HAZARD MAP DEVELOPMENT

The following data sources, software programs, and assumptions/simplifications were used to develop the hazard maps in this section, discussed hazard by hazard. The nearby Maungataketake eruption is used in several places as a basis, given that it erupted in a similar substrate and has been the subject of thorough geologic study (see Agustín-Flores et al., 2014 and Brand et al., 2014).

3.1.1 Edifice

The vent size is informed by the Maungataketake eruption. The final Maungataketake edifice (tuff ring and now-quarried cone) is roughly an ellipse of dimensions 1100 m x 1300 m (Agustín-Flores et al., 2014). The initial vent was slightly smaller, so here we start with a smaller vent area (800 m diameter) and expand it over the course of the eruption. The final tuff ring is 1200 m diameter with a nested cinder cone of 900 m diameter.

3.1.2 Pyroclastic surges

We use ‘average’ and ‘worst-case’ scenarios developed for the AVF for substrate similar to Maungataketake by Brand et al. (2014) shown in Table 3.1. We ignore the effect of directionality or topography, which could be important for this type of eruption. Therefore, it is likely our models overestimate hazard severity and resulting damage.

Table 3.1 Pyroclastic surge physical characteristics from modelling by Brand et al. (2014) following work on the Maungataketake eruption.

Scenario	Distance (km)	Dynamic Pressure (kPa)	Damage
Average	< 0.5	Up to 160	Complete destruction
	0.5–2	< 12	Heavy structural damage most buildings, near total destruction for weaker structures
	2–4	< 5	Damage to weaker structures
Worst-Case	< 2.5	> 35	Complete destruction
	2.5–4	> 15	Heavy structural damage most buildings, near total destruction for weaker structures
	4–6	< 5	Damage to weaker structures

There is little available data on surge deposit thickness, so again we use Maungataketake as a starting point, although the geologic work by Agustín-Flores et al. (2014) and Brand et al. (2014) is too specific and precise, and too geographically constrained (focused on distance no more than 1.16 km from presumed vent) for ERI needs. We use the initial vent clearing phase (PH1 in Agustín-Flores et al., 2014 and Brand et al., 2014; Table 3.2) as a reasonable approximation for the first phreatic eruption, and a compilation of the remaining phases of the eruption (PH2, 3, and 4 in Agustín-Flores et al., 2014; Table 3.3) for the subsequent two Mt Ruaumoko surges. We use the same isopach contours as for tephra deposition (see Section 3.1.3).

Table 3.2 Deposit thicknesses for Phase 1 (units U1 and U2) of the Maungataketake eruption.

Site[1]	Distance from presumed vent (km)	Deposit thickness (m) (Brand et al., 2014)	Deposit thickness (m) (Agustín-Flores et al., 2014)
S1/M1	0.30	> 0.3	
S2/M2	0.33	> 0.75	
S3/M3	0.87	3.5	2
S4/M4	0.94	1.8	1 (grouped with site M5)
S5/M5	1.08	> 1	1 (grouped with site M4)
S6	1.16	> 0.75	

[1] Sites are called ‘S1’, ‘S2’, etc. in Brand et al. (2014) and ‘M1’, ‘M2’, etc. in Agustín-Flores et al. (2014).

Table 3.3 Deposit thickness for Phases 2, 3, and 4 of the Maungataketake eruption (after Agustín-Flores et al. (2014)).

Phase	Description	Thickness (m) at M1/M2 (~0.3 km from presumed vent)	Thickness (m) at M3 (~0.9 km from presumed vent)	Thickness (m) at M4/M5 (~1 km from presumed vent)
PH2	Deeper excavation	< 0.8	0.7	<0.7
PH3 (two units, U4 and U5)	Shallow seated explosions	~1.5	~1.2	<0.8
PH4	Vent stabilisation and waning	<1.5	<0.5	1.5

3.1.3 Tephra airfall

For tephra airfall, one option would be not do any modelling and instead take the ash footprint of a previous eruption and break it up into several ash events. However, given that past eruptions may have occurred in different prevailing wind conditions, and the fact that it is generally the larger eruptions that are best preserved (i.e., not ‘typical’), we are modelling tephra airfall.

We use the advection-diffusion model TEPHRA2 (Bonadonna et al., 2005) release 149 to model tephra airfall. Although undoubtedly imprecise, we adopt the physical characteristics, including grainsize distribution, of the 1992 Cerro Negro eruption provided by the TEPHRA2 team (Bonadonna et al., 2010; Table 3.4) – this was an explosive basaltic eruption with a sustained ash column 7 km high (Roggensack et al., 1997). Note that ‘plume model’ of 0

indicates that the grain size distribution of particles released is the same at all elevations, and 'plume ratio' indicates where the particles are in the plume: a plume ratio of 0 means particles are released from all levels, while a plume ratio of 0.2 means all the particles are released from the top 80% of the plume (the highest permissible plume ratio is 0.99). We ignore the effect of topography (likely a minor effect) – the vent elevation is 1 m, and the grid across which tephra is accumulated is at sea level.

Table 3.4 TEPHRA2 eruption parameter inputs used for all eruptions, based on the 1992 Cerro Negro eruption (Bonadonna et al., 2010).

Parameter	Value
Maximum grain size (ϕ[1])	-4.0
Minimum grain size (ϕ)	4.0
Median grain size (ϕ)	0
Standard deviation grain size (ϕ)	1.5
Eddy constant	0.04
Diffusion coefficient (m^2/s)	568
Fall time threshold (s)	100,000
Lithic density (kg/m^3)	2600
Pumice density (kg/m^3)	1000
Column steps	100
Plume model	0
Plume ratio	0.2

[1]A ϕ of x corresponds to a particle diameter of 2^{-x} mm.

Tephra airfall mass 'eruption mass' in TEPHRA2) is difficult to evaluate, as there is no robust dataset for the AVF that catalogues strictly tephra airfall. Allen and Smith (1994) and Kereszturi et al. (2013) document total eruption volume orders of magnitudes ranging from 10^4 to 10^9 m^3 (all volcanic products; volume and not dense rock equivalent), with most in the 10^6–10^7 range. We are arbitrarily assigning a total tephra airfall volume for Mt Ruaumoko of 1×10^7 m^3. TEPHRA2 requires eruption mass in kg. The median mass for a TEPHRA2 particle per Table 3.3 is 1800 kg/m^3, which is on the dense side for tephra but within range of historic basaltic and basaltic andesite eruptions (e.g., Pioli et al., 2008); this means our volume corresponds to 1.8×10^{10} kg. Tephra airfall is modelled four times (14 March PM, and 21, 22, and 29 March); we arbitrarily divide the total tephra airfall mass between these, in chronological order, as 0.5, 0.5, 0.5, and 0.3×10^{10} kg.

All wind data comes from daily wind files provided by MetService to GeoNet Duty Volcanologists for the date in 2014 (year arbitrarily selected; Appendix 2); the preferred model of the day as designated by MetService (out of three) is used.

To convert from mass/area grid cell (kg/m2) (the TEPHRA2 output) to thickness we use a tephra density of 1000 kg/m^3 (Crosweller et al., 2012). All thicknesses below 0.1 mm are converted to 0 mm. As the smallest input grain size into the model (of which there are very few) is ϕ = 4.0, i.e., 0.0625 mm, our cutoff threshold thickness is less than two of the smallest grains stacked on top of each other. We use the following isopach contours: 1, 5, 10, 50, 100, 500, 1000, 2000, 5000, and 10,000 mm. 2000 mm is an isopach as that is about the height of a person.

3.1.4 Ballistics

Ballistics modelling is currently under development at the University of Canterbury. Here, we do not use any modelling but rather superimpose a detailed ballistics map produced for the combined 24 November 2009 and 21 January 2010 Stromboli eruptions (Gurioli et al., 2013). The Stromboli ballistics map is superimposed by taking a shapefile of the Stromboli ballistics field and aligning the Stromboli vent (UTM 33N E518362 N4293900) with Mt Ruaumoko (NZTM E1758370 N5910750). Gurioli et al. (2013) provide the short and long axis of each ballistic; to calculate the equivalent diameter the third dimension is required. As such, we take the average of the two axes as the ballistics size (cm), and provide this with as an attribute along with ballistics mass (kg).

3.1.5 Lava flows

At the time of writing, authors did not have access to bathymetric raster data for the Manukau Harbour, which would be required if credible lava flow modelling were undertaken. We use a flow depth of 10 m, a mid-range AVF thickness according to Kereszturi et al. (2012). Bathymetric charts (Figure 3.1) show that the area is relatively shallow such that a lava flow 10 m thick would be subaerial. We adopt a lava flow volume of 1 x 10^8 m^3 such that it is an order of magnitude more than the tephra volume and credible for 10 m thick AVF lavas (Kereszturi et al., 2012). This corresponds to an area of 10 x 10^7 m^2 or 10 km^2. We centre the lava flow about Mt Ruaumoko, 'stop' it in areas > 10 m a.s.l., and have it cut off the Manukau Inlet. As we are not undertaking proper lava flow modelling, we ignore effects of lava flow/water interactions, lava flow rheology, and finer scale topographic influences.

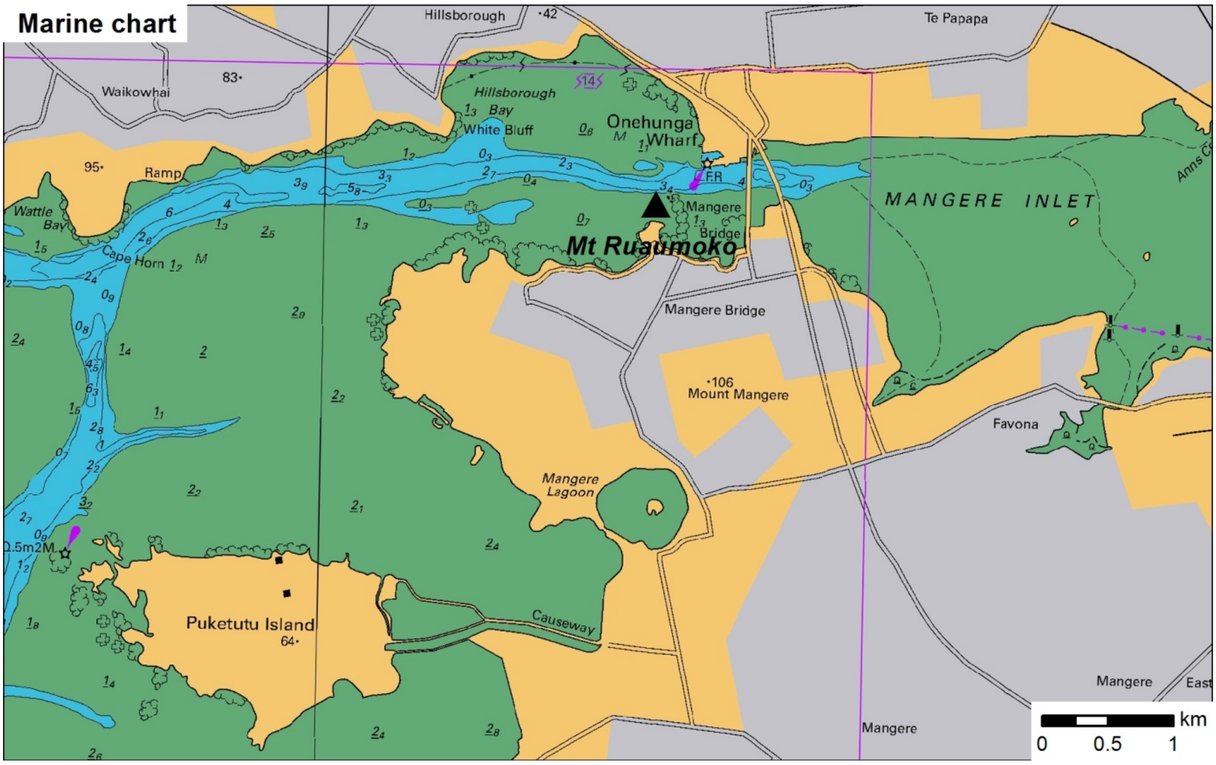


Figure 3.1 Marine chart for area around Mt Ruaumoko. A value of $\underline{1}_3$ indicates a water depth of 1.3 m.

3.1.6 'Mini-tsunami'

At the very end of the Mt Ruaumoko scenario there is a lava bench collapse with a resulting mini-tsunami propagating to the west. We have undertaken no modelling, but arbitrarily propose wave heights of 2 m for the Manukau harbour shoreline within 2 km of the lava flow front.

3.2 22 February – 13 March: Lead Up to Eruption

During Exercise Ruaumoko, GNS Science issued (fake) Science Alert Bulletins (now called Volcano Alert Bulletins). As the Mt Ruaumoko scenario is based on Exercise Ruaumoko, the pre-eruption bulletins are appropriate reflections of scientific information available which would inform evacuation and other decisions. Table 3.5 notes key spatial information detailed in the fake bulletins (Figure 3.2) supplemented by revisited VAL designations undertaken by the current GeoNet volcano monitoring team (Table 2.2).

Table 3.5 Summary of unrest leading to Mt Ruaumoko eruption per Science Alert Bulletins issued during Exercise Ruaumoko and VAL designations undertaken as part of this study.

Date	VAL	Source	Comment
22 February	0 to 1	Table 2.2	
3 March	1	AK-2008/01	Earthquakes in "a zone about 5 km wide and 15 km long that trends north-east from Mangere to St Heliers."
4 March	1	AK-2008/02	Earthquakes in "a zone about 5 km wide and 15 km long that trends north-east from Mangere to St Heliers."
5–7 March	1	AK-2008/03, AK-2008/04, AK-2008/05	Earthquakes "in a zone between Mt Mangere and Mt Wellington"; see Figure 3.2a
8 March	1 to 2	Table 2.2, AK-2008/06	Earthquakes near St Heliers and Onehunga
9 March	2	AK-2008/07	Earthquakes primarily near One Tree Hill and Onehunga area, some near St Heliers and Mt Wellington
10 March	2	AK-2008/08	"Seismicity continues in the One Tree Hill, Onehunga areas and has shifted northward as far as Newmarket and southward to Mangere"
11 March	2	AK-2008/09	Interpretation of an "intruding dyke oriented roughly north–south running through the Mangere area … uncertain as to the north-south extent of this feature but it likely extends at least as far south as Auckland International Airport and as far north as the central Auckland isthmus area towards One Tree Hill"; see Figure 3.2b
12 March	2	AK-2008/11	"Seismicity continues to be concentrated in an area south of One Tree Hill to Auckland International Airport"; see Figure 3.2c
13 March	2	AK-2008/13	Probable eruption zone constrained to "area 9 km long and 5 km wide centred just south of Mangere Mountain"; see Figure 3.2d

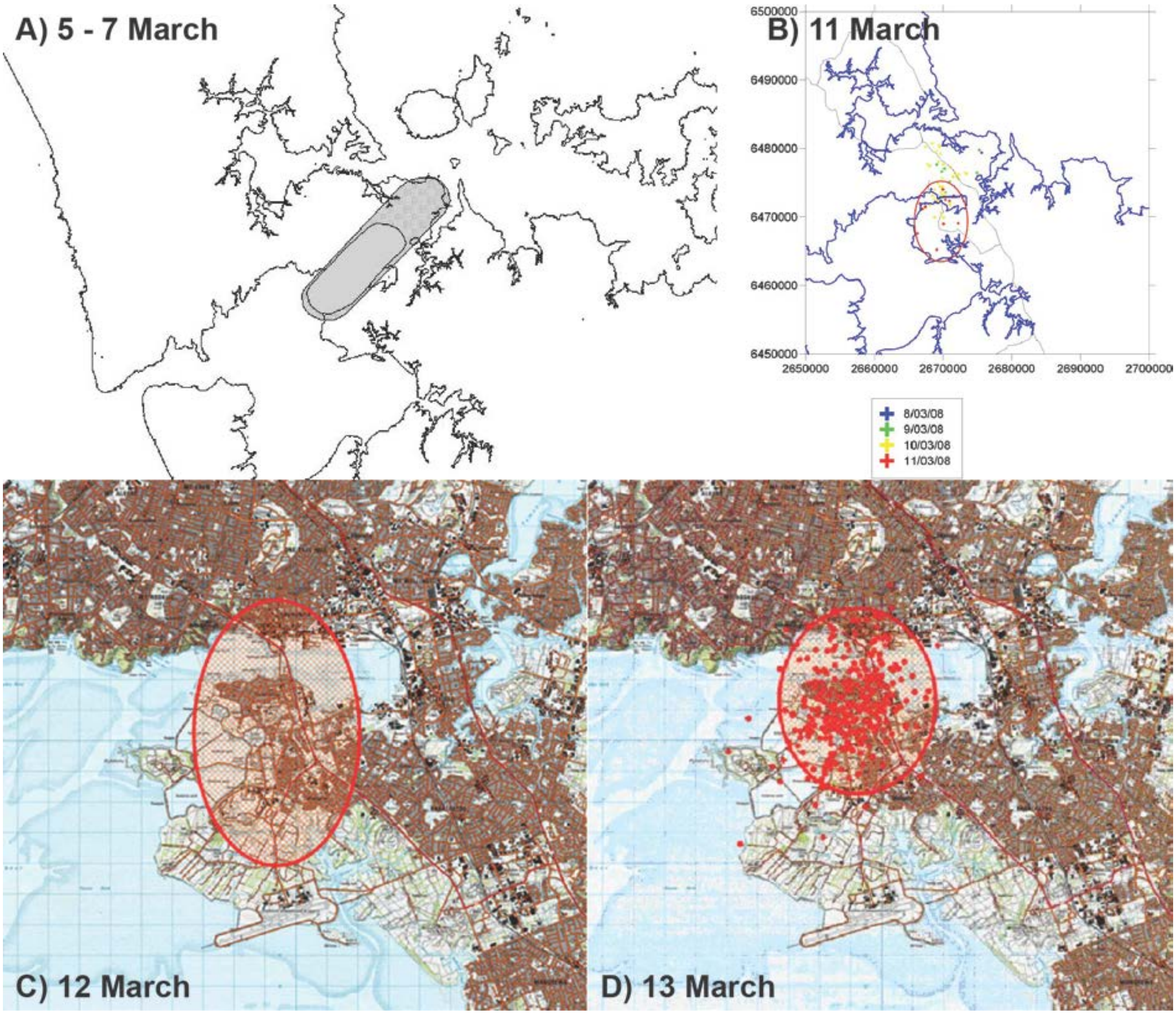


Figure 3.2 Maps from Exercise Ruaumoko Science Alert Bulletins. A) Map for 5–7 March, first issued in AK-2008/03, B) map for 11 March with earthquakes colour-coded by date issued in AK-2008/09, C) map for 12 March with initial probable vent location designated issued in AK-2008/11, and D) map for 13 March indicating revised probable eruption zone issued in AK-2008/13.
Source: http://info.geonet.org.nz/display/appdata/Exercise+Ruaumoko.

3.3 14 March AM: Phreatic Eruption

The first eruption is a phreatic eruption. The two direct hazards of concern are the vent, which will destroy everything it overlays (at and below the surface) and the base surge.

The vent size is modelled after Maungataketake eruption, with the initial vent slightly smaller than the final Maungataketake edifice: we assume the vent is 800 m diameter (i.e., radius of 400 m around the centre point).

The base surge causes surface damage as per the 'worst-case scenario' in Brand et al. (2014): complete destruction within 2.5 km of the vent, severe damage to most structures and destruction of weaker structures from 2.5–4 km, and some damage to weaker structures from 4–6 km. Figure 3.3a shows the edifice and base surge damage zones.

The surge leaves a deposit that requires some amount of removal/stabilization if the land is to be reoccupied. Deposit quantity inspired from phase 1 (PH1) of the Maungataketake eruption (Agustín-Flores et al., 2014; Brand et al., 2014; Table 3.2). We have adopted an "isopach" of 2 m within 1 km of the vent, 0.5 m from 1–1.5 km of the vent, 0.01 m from 1.5–2 km, and 0.001 m from 2–6 km. Figure 3.3b shows deposit isopachs.

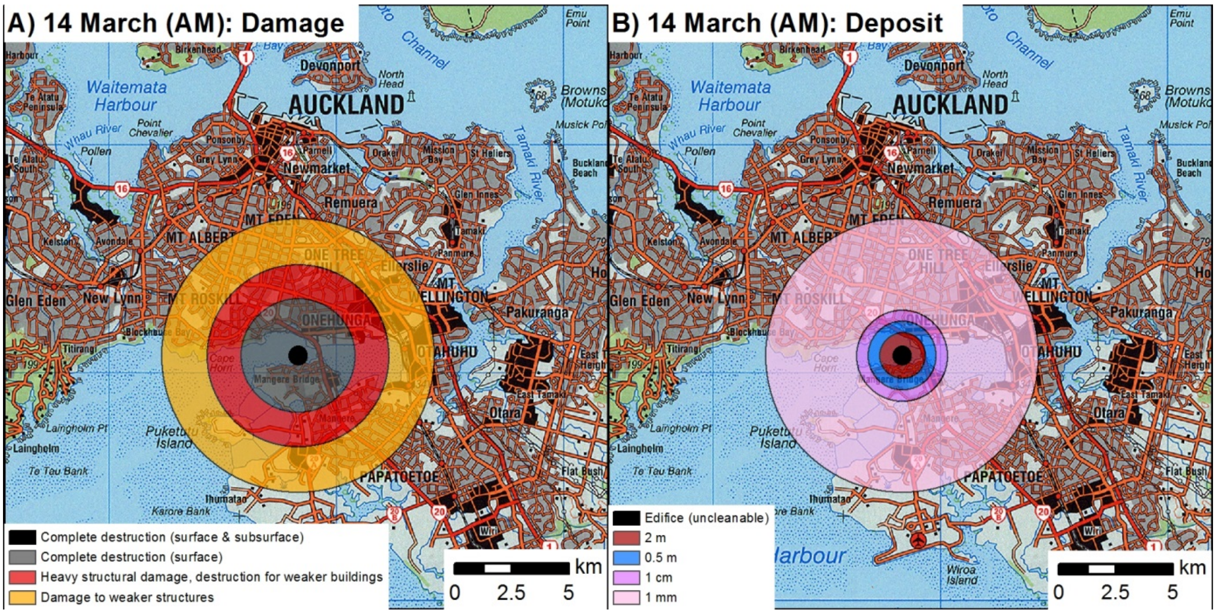


Figure 3.3 (A) Damage and (B) deposit maps for morning of 14 March (AM). The damage results from edifice building and a 'worst case' pyroclastic surge (Brand et al., 2014) and is classified as complete subsurface and surface destruction (black), complete surface destruction (grey), heavy structural damage most buildings and near total destruction for weaker structures (red), and damage to weaker structures (orange). The deposit map is based on work on Maungataketake (see text); colours correspond to deposit thickness (see legend). The edifice is shown in black.

3.4 14 MARCH PM: PHREATOMAGMATIC ERUPTION WITH 3 KM PLUME

The second eruption is a phreatomagmatic eruption with a 3 km plume height. The three hazards of concern are the vent, base surge, and tephra fallout.

The vent size remains unchanged from the first eruption: 800 m diameter.

The base surge causes surface damage per 'average scenario' in Brand et al. (2014): complete destruction within 1.5 km of the vent, severe damage to most structures and destruction of weaker structures from 1.5–2 km, and some damage to weaker structures from 2–3 km. Figure 3.4a shows the edifice and base surge damage zones.

The surge leaves a deposit that requires removal/stabilization if the land is to be reoccupied. Phases 2 and 3 (PH2 and PH3) of the Maungataketake eruption (Agustín-Flores et al., 2014; Table 3.2) provide the basis for deposit quantity. These two phases at Maungataketake correspond to deep excavation of the vent and deep shallow explosion. We have adopted an isopach of 2 m within 1 km of the vent, 0.5 m from 1–1.5 km of the vent, 0.01 m from 1.5–2 km, and 0.001 m from 2–3 km.

The tephra fall deposit can cause some damage and more importantly, functionality loss. We do not show damage zones as for surge because it is a very different mechanism. We used TEPHRA2 to model tephra dispersal as described in Section 3.1.3. Figure 3.4b provides the cumulative deposit thickness of the surge and tephra fall.

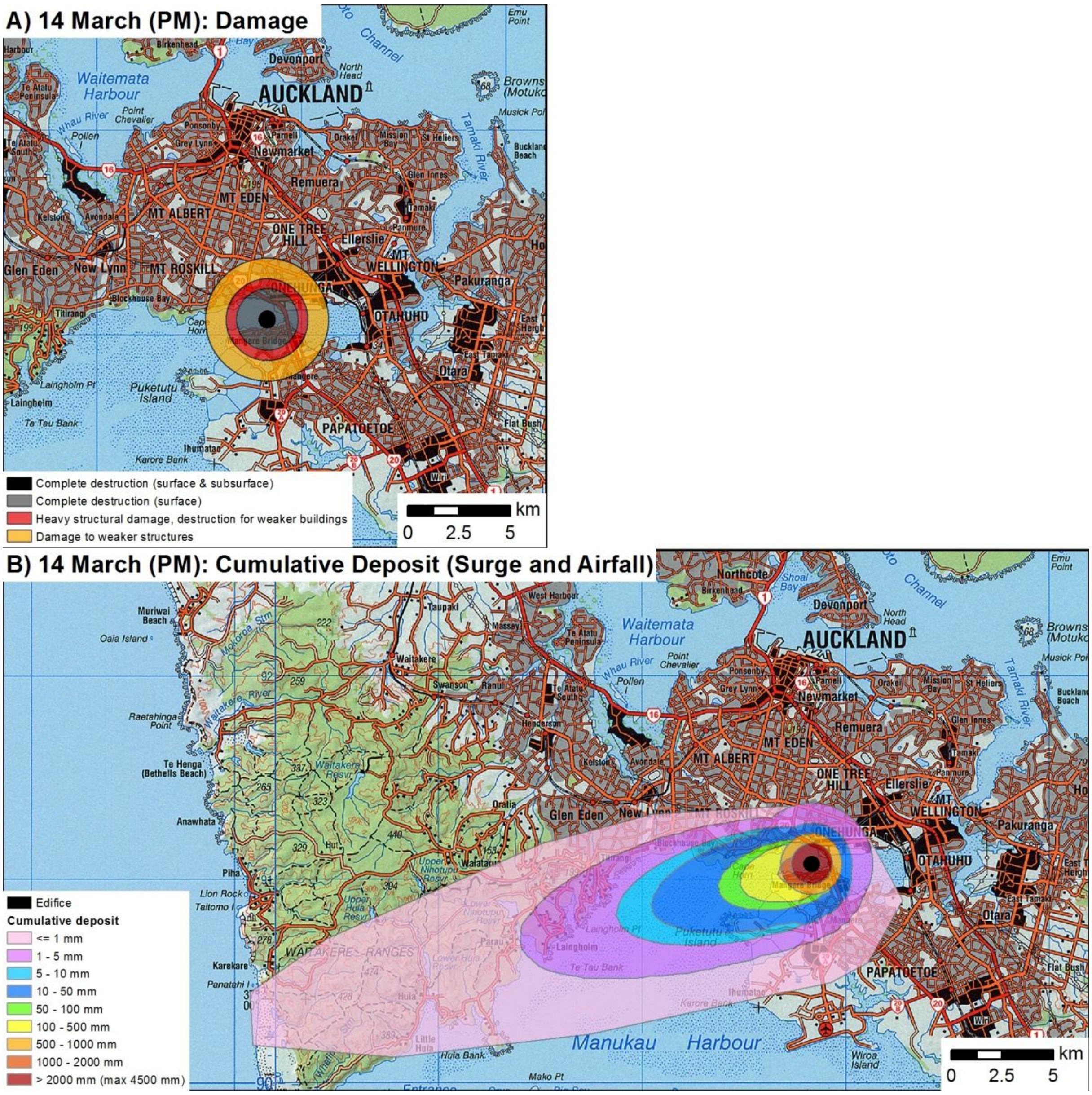


Figure 3.4 (A) Damage and (B) deposit maps for the afternoon of 14 March. The damage results from edifice building and an 'average' pyroclastic surge (Brand et al., 2014) and is classified as complete subsurface and surface destruction (black), complete surface destruction (grey), heavy structural damage most buildings and near total destruction for weaker structures (red), and damage to weaker structures (orange). The deposit map is based on TEPHRA2 modelling (tephra fall) and (loosely) the Maungataketake eruption (surge) and shows the cumulative thickness from both deposits; colours correspond to deposit thickness (see legend). The edifice is shown in black.

3.5 21 March: Phreatomagmatic Eruption with 2.5 km Plume

The third eruption is a phreatomagmatic eruption with a plume height of 2.5 km. The three hazards of concern are the vent, base surge, and tephra fallout.

The vent size remains unchanged from the first eruption: 800 m diameter.

The base surge causes surface damage per 'average scenario' in Brand et al. (2014): complete destruction within 1.5 km of the vent, severe damage to most structures and destruction of weaker structures from 1.5–2 km, and some damage to weaker structures from 2–3 km. Figure 3.5a shows the edifice and base surge damage zones.

The surge leaves a deposit that requires some amount of removal/stabilization if the land is to be reoccupied. Phase 4 (PH4) of the Maungataketake eruption (Agustín-Flores et al., 2014; Table 3.2) provides the basis for deposit quantity. This phase at Maungataketake corresponds to vent stabilisation and waning. We have adopted an isopach of 1 m within 1 km of the vent, 0.2 m from 1–1.5 km of the vent, 0.01 m from 1.5–2 km, and 0.001 m from 2–3 km.

The tephra fall deposit can cause some damage and more importantly, functionality loss. We do not show damage zones as for surge because it is a very different mechanism. We used TEPHRA2 to model tephra dispersal as described in Section 3.1.3. Figure 3.5b provides the cumulative deposit thickness of the surge and tephra fall.

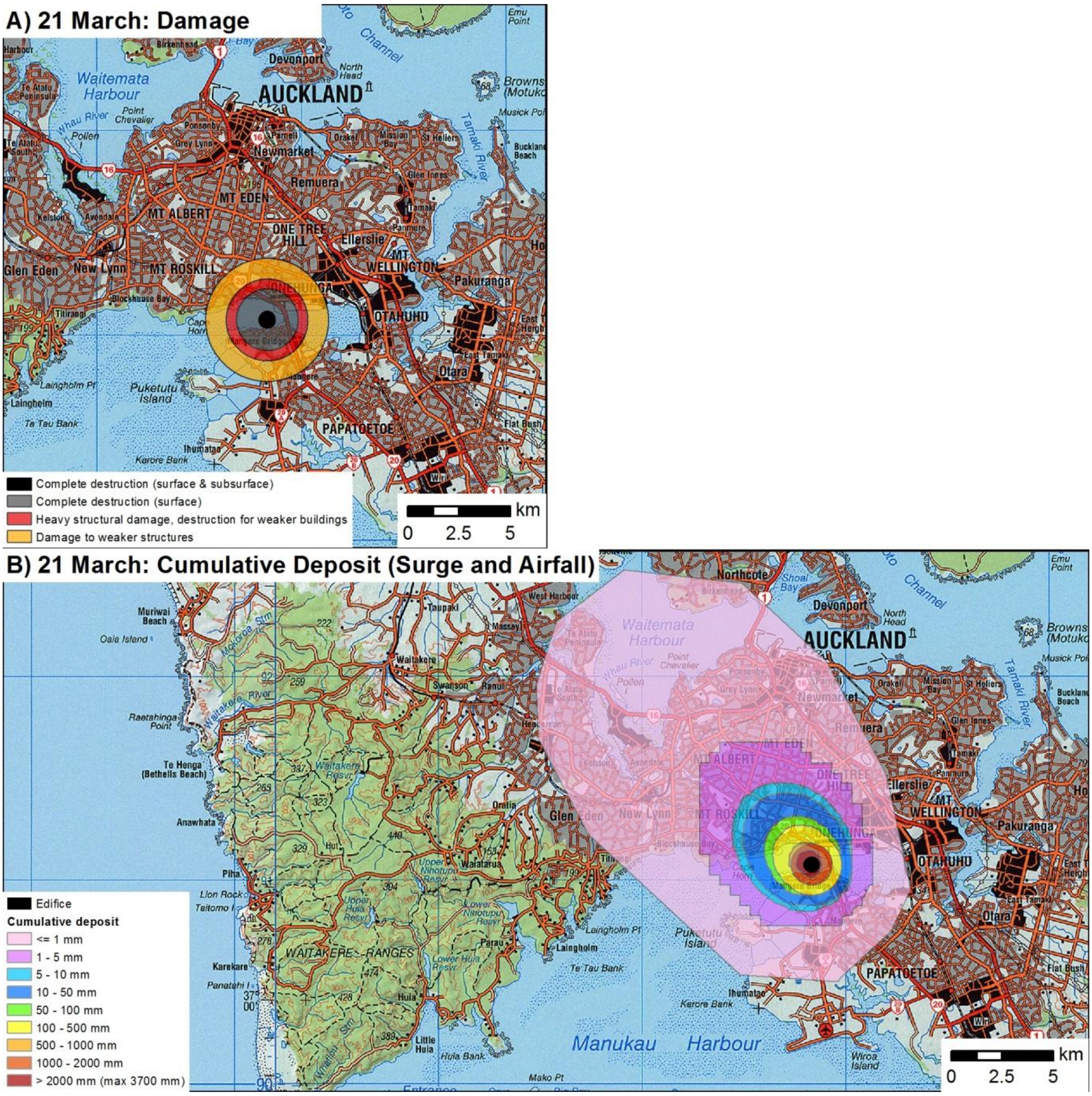


Figure 3.5 (A) Damage and (B) deposit maps for 21 March. The damage results from edifice building and an 'average' pyroclastic surge (Brand et al., 2014) and is classified as complete subsurface and surface destruction (black), complete surface destruction (grey), heavy structural damage most buildings and near total destruction for weaker structures (red), and damage to weaker structures (orange). The deposit map is based on TEPHRA2 modelling (tephra fall) and the Maungataketake eruption (surge) and shows the cumulative thickness from both deposits; colours correspond to deposit thickness (see legend). The edifice is shown in black.

3.6 22 March: Phreatomagmatic Eruption with 1.5 km Plume

The fourth eruption is a phreatomagmatic eruption with a plume height of 1.5 km. The two hazards of concern are the vent and tephra fallout.

The vent size remains unchanged from the first eruption: 800 m diameter.

The tephra fall deposit can cause some damage and more importantly, functionality loss. We used TEPHRA2 to model tephra dispersal as described in Section 3.1.3. Figure 3.6 provides the tephra fallout deposit thickness. The wind file comes from a remarkably low wind day, which results in a rather symmetric concentrated tephra deposit.

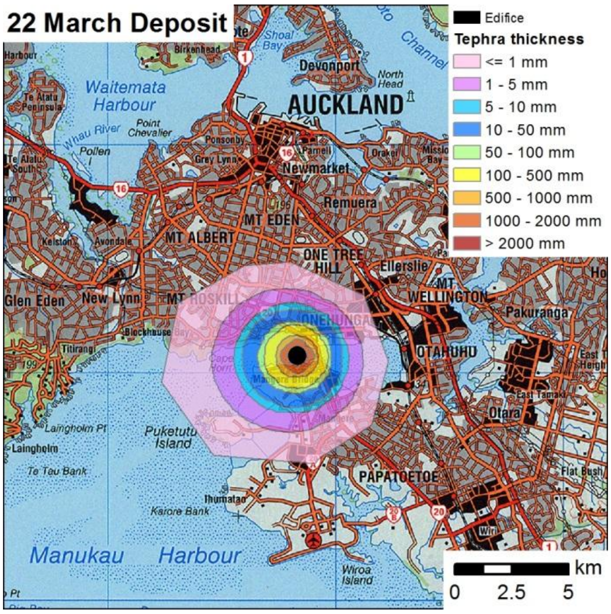


Figure 3.6 Tephra deposit map for 22 March based on TEPHRA2 modelling; colours correspond to deposit thickness (see legend). The edifice is shown in black.

3.7 25–30 March: Phreato- to Magmatic, Strombolian, and Magmatic Eruptions

The next stage of the eruption spans several days, featuring (1) a phreatomagmatic eruption with firefountaining up to 500 m high (2) ballistics, (3) Strombolian eruption with firefountaining up to 300 m high, and (4) a magmatic eruption with a 500 m high plume. The hazards of concern are the vent, ballistics, and tephra fall out.

The vent size increases to 1200 m diameter as the final size tuff ring. The ballistics come from the 2010 Stromboli eruption (see Section 3.1.4), and fall within the area described as ‘destroyed’ due to the tuff ring. Consequently, while we include ballistics for completeness, they do not cause damage to undamaged buildings and infrastructure. Figure 3.7a shows the complete ‘damage’ zone from the edifice and ballistics.

There are no good available models for fire fountaining deposits. Eruptions in Hawai’i and Mt Etna show material can be deposited a few kms to tens of kms from the source depending on wind conditions, although the majority of deposits will be close to the vent (e.g., Stovall et al., 2012, Andronico et al. (2008)). As such, we do not model fire fountaining separately but do model tephra fallout from the magmatic eruption on 29 March. We used TEPHRA2 to model tephra dispersal as described in Section 3.1.3. Figure 3.7b provides the tephra fallout deposit thickness.

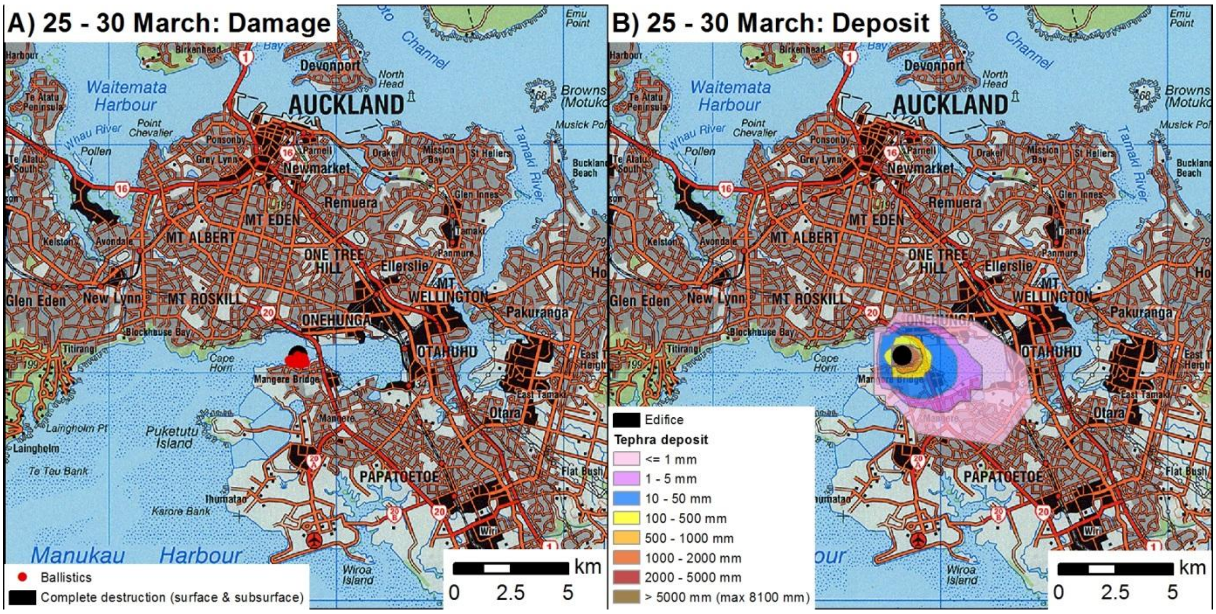


Figure 3.7 (A) Damage and (B) deposit maps for 25–30 March. The damage results from edifice building (black) and ballistics (red). Ballistics are based on the 2010 Stromboli eruption (Gurioli et al., 2013). The deposit map is based on TEPHRA2 modelling (tephra fall); colours correspond to deposit thickness (see legend). The edifice is shown in black.

3.8 3–14 April: Lava Flows and Mini-tsunami

The final stage of the eruption is primarily effusive (lava flows) with cinder cone building. As the cinder cone is within the tuff ring, there is no spatial lateral extension of the edifice. At the end of the lava flow emplacement part of the flow breaks off, causing a mini-tsunami to the west. The hazards of concern are the lava flow and the tsunami. We assume given the generation mechanism that there won't be a tsunami deposit, although surficial assets will be destroyed by it. However, given the steep cliffs that make the shoreline of much of the Manukau Harbour, using our criteria for a tsunami (2 m within 2 km of the lava flow front), the impact is considered negligible. Figure 3.8 shows the extent of lava flow damage. The lava flow damages everything at the surface, and underground infrastructure covered by the lava flow may be challenging to access.

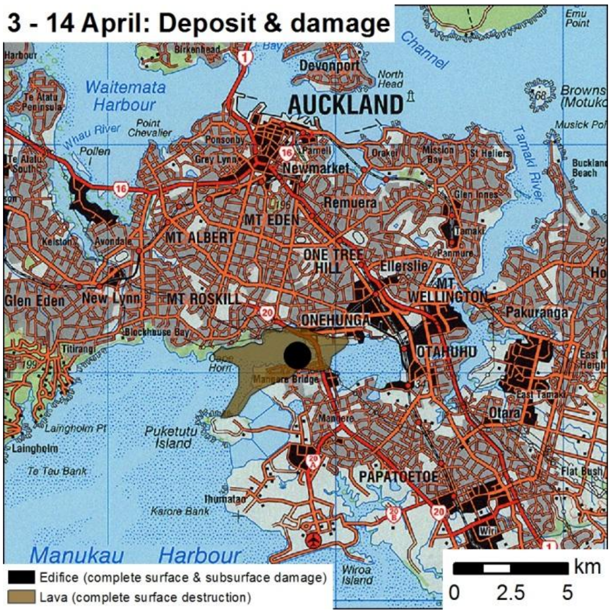


Figure 3.8 Lava flow extent is shown in brown for period from 3–14 April. The lava flow causes complete surface destruction. There is a tsunami in the scenario but its footprint is negligible. The edifice is shown in black.

3.9 16 APRIL: ERUPTION END (FINAL STATUS)

The eruption is over by 15 April, although it might take a few days or weeks for authorities to declare it over. Figure 3.9a shows the cumulative damage map from the edifice, lava flows, and surge. Tsunami damage is negligible in this instance. Figure 3.9b shows the cumulative deposit extent, with areas in black ‘uncleanable’ (lava and edifice) and the remainder the composite tephra and surge deposit thickness.

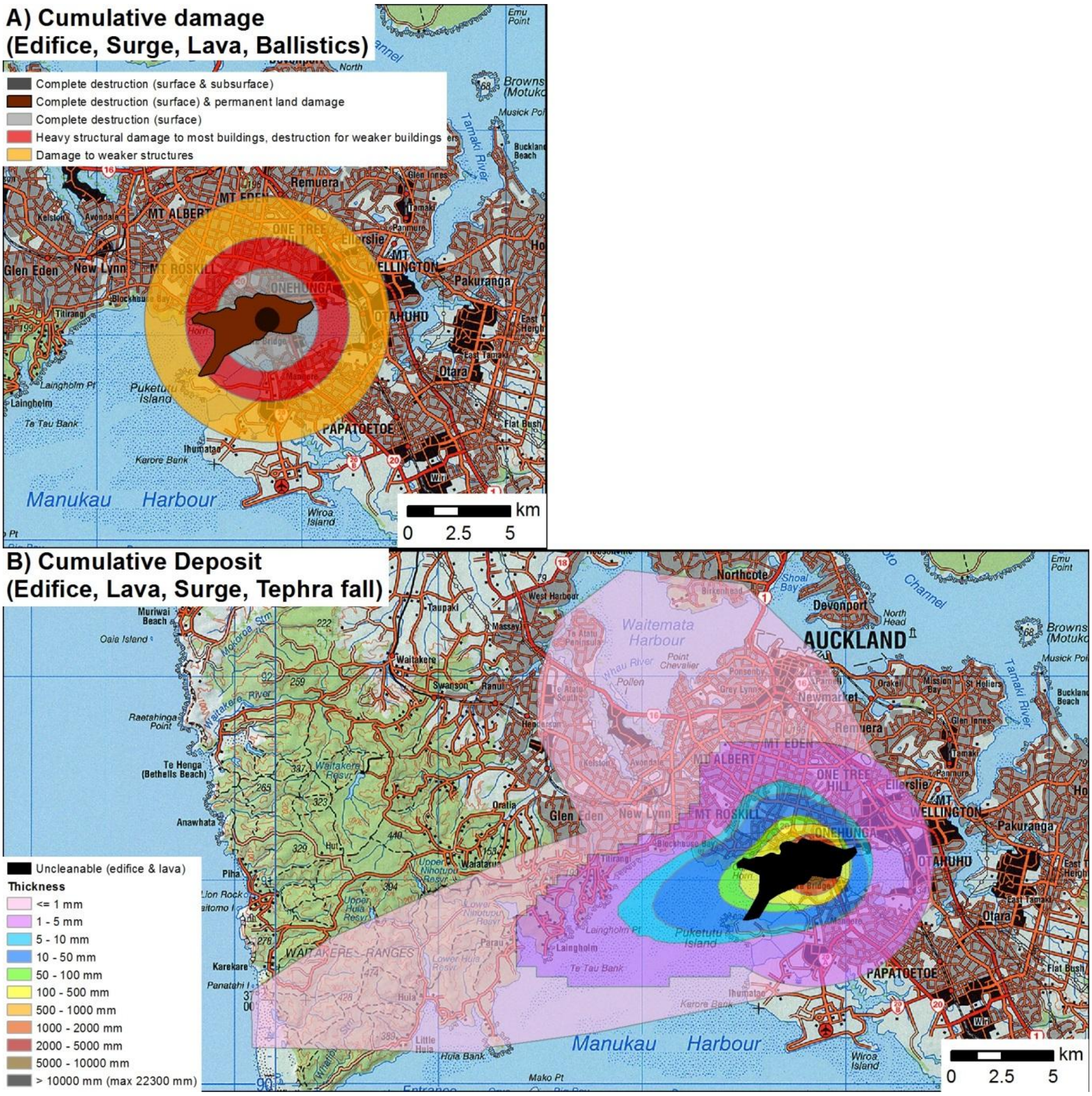


Figure 3.9 Final (A) damage and (B) deposit maps. The damage results from the edifice, surge, ballistics, lava flow, and tsunami and is classified as complete subsurface and surface destruction (black), complete surface destruction with permanent land 'damage' (brown), complete surface destruction (grey), heavy structural damage most buildings and near total destruction for weaker structures (red), and damage to weaker structures (orange). The deposit map is the cumulative surge, tephra, lava, and edifice deposit, with 'uncleanable' areas in black; colours correspond to deposit thickness (see legend).

4.0 CDEM RESPONSE AND EVACUATION MAPS

4.1 CDEM RESPONSE OVERVIEW

The lead up to the eruption in the Mt Ruaumoko scenario is based on what happened during Exercise Ruaumoko. However, CDEM practices and understanding of volcanic risk have changed since 2008, particularly given CDEM sector experience with the Christchurch earthquake sequence, improved understanding of the AVF through the DEVORA research programme, and changing public expectations given the rise of social media and other societal changes.

The Auckland Council (AC) CDEM Head of Emergency Management Planning indicated that when the VAL is raised from 0 to 1 CDEM would initiate meetings with infrastructure providers to draw specific plans for potential response and ensure coordination and prioritisation between the various sectors. Evacuations would be called when the VAL goes from 1 to 2 on 8 March, although at that stage the eruption location information is extremely uncertain (Table 3.5). Throughout the scenario, MCDEM and Auckland CDEM would be working with infrastructure providers to assess when cordoned areas can be entered for clean-up, repair, and maintenance. Thus, while evacuated areas are off limits to residents and businesses, infrastructure providers will sometimes be able to temporarily enter during lulls in volcanic activity. The Southern Motorway (SH1) would remain open when possible, albeit at limited capacity with access restrictions, even when it is within evacuated zones (Section 8).

4.2 AVF CONTINGENCY PLAN AND AUCKLAND EVACUATION PLAN

The 2015 Auckland Volcanic Field Contingency Plan (Auckland Council, 2015) details evacuation plans in the case of unrest or an AVF eruption. While at this stage evacuation zones are not an input parameter for MERIT, we include them as they may be in the future, and they have ramifications for the infrastructure outage maps and also businesses. During an AVF event, large zones may be evacuated, preventing businesses from accessing their sites. This can have cascading impacts on other businesses due to disruptions in the supply chain. Additionally, businesses can suffer when staff members are displaced or have uncertainty in their personal living situation. The AVF Contingency Plan also has specific infrastructure provisions, and so requires consideration here.

Our evacuation maps are based on the AVF Contingency Plan (Auckland Council, 2015), recently updated with the latest DEVORA findings. A sister document, the Auckland Evacuation Plan (Auckland Council, 2014), identifies five reasons to evacuate, including if personal safety is under threat and/or properties are unsafe or insanitary. In the case of AVF unrest, the AVF Contingency Plan states that an evacuation is needed if a hazard assessment indicates that an urban or strategic area may lie within 5 km of the inferred eruption centre and/or if there is a potential risk to life. When a suspected or actual eruption centre has been identified (this may be a polygon during unrest), two evacuation zones are established:

- Primary Evacuation Zone (PEZ), which corresponds to a high hazard area and is an:
  - Area encompassing both the inferred vent area and a 3 km zone extending radially from the vent area, and:
    - May be modified according to topography;
    - Radial boundary may be modified to include tsunami or other hazards for off-shore eruptions;
  - Area(s) with high population density within this zone may be further prioritised for evacuation.
- Secondary Evacuation Zone (SEZ), which corresponds to moderate hazard area and is:
  - An area extending 2 km radially from the PEZ boundary;
  - An area(s) which will or have become isolated due to the eruption hazard;
  - An area(s) where lifelines have been or are likely to be severed;
  - An area(s) which may be more adversely affected by wind or topography influences relating to volcanic hazards;
  - Any other area deemed to be at risk.

Additionally, the AVF Contingency Plan specifies that if it is safe to do so, lifelines operators may have access to evacuation zones.

The Auckland Evacuation Plan indicates that evacuated areas are reopened only when an 'all-clear' has been assessed. It is unclear how this would unfold during an eruption crisis, particularly during lulls in activity featured in the Mt Ruaumoko scenario. The Auckland Evacuation Plan in particular specifies that for evacuation to be lifted the:

- Threat to public safety from the original and other subsequent significant hazards has been eliminated;
- Service of required infrastructure should be restored, for example, power, water, and sewerage; the area should be rendered and identified as safe for return;
- Critical infrastructure facilities, for example, hospitals and fire stations should be re-established and returned to functional state prior to return of residents.

There are also other criteria listed, but those above are the most relevant.

Here we present estimated evacuation zones based when possible on the above criteria. We stress that these are not the authors' endorsement of what areas should or shouldn't be evacuated during a crisis, but rather the authors' attempt to interpret the AVF Contingency Plan and the Auckland Evacuation Plan given the Mt Ruaumoko scenario. Several sector outage/level of service maps (e.g., road and rail transportation) will be highly influenced by evacuation orders. At the moment the ERI interdependency module does not consider evacuation as an independent factor, but this may be introduced in the future. Likewise, evacuation considerations may be a policy lever in future versions of MERIT.

The number of people directly displaced by evacuation and exclusion zones has been calculated using the night-time resident population data collected in the 2013 Census (StatisticsNZ, 2013). Rather than an estimate of those who reside within the exact radial extent of the evacuation zones, we adopt census meshblock values using all meshblocks that fall within and intersect the zone boundaries and round to the nearest hundred. This is deemed to be a more accurate representation as the true extent of any evacuation or zone will likely reach beyond the initially designated radial extent in places due to features on the ground such as roads, potentially isolated neighbourhoods, and large property boundaries. For the final permanent exclusion zone, meshblocks to the south of Mt Roskill that are automatically selected as part of the processing are manually deselected as we suggest that the permanent exclusion zone boundary will run along the cliff edge and not intersect properties in this area. The majority of properties within the permanent exclusion zone are in Mangere Bridge and the south west of Onehunga.

4.3 PRE-ERUPTION EVACUATIONS

During Exercise Ruaumoko, the evacuation order was made at 10:00 AM and effective from 12 noon on 13 March (MCDEM, 2008). Essential services continued as possible, and evacuations continued into 14 March. Tomsen et al. (2014) suggest that an actual evacuation would take longer than estimated during Exercise Ruaumoko.

We have updated the pre-event evacuations undertaken in Exercise Ruaumoko based on the updated AVF Contingency Plan and a conversation with the AC CDEM Head of Emergency Management Planning. Evacuations begin when VAL goes from 1 to 2 – several days earlier than in Exercise Ruaumoko – and initially cover a wider region. We speculate that early evacuations (up to 12 March) focus on removing residents from high risk areas, but infrastructure providers and members of critical sectors (health, emergency services, GeoNet, etc.) have access to cordoned areas as needed. From 12 March to the start of the eruption however, the evacuation is comprehensive and applies to everyone – roads can only be used to exit the evacuation zones.

We expect some residents beyond the SEZ will also evacuate, causing a shadow evacuation effect. There is limited data available to suggest how many people will evacuate this area but we suggest that this number may be relatively high as very few people will have experienced such an eruption in their lifetime. Based on the night-time resident population within a 1 km buffer from the maximum extent of the 12 March evacuation zones, we suggest an additional 72,300 will evacuate. Therefore, we estimate that up to 434,400 people would seek alternative accommodation at times during the eruptive sequence.

4.3.1 22 February: Beginning of self-evacuations

On 22 February the VAL increases from 0 to 1 (Table 2.2). At this point there may be self-evacuation by some concerned residents. There will likely be progressive evacuation or redirection of long term or intensive care patients in major hospitals. However, no official evacuations are called and there is no reduction in infrastructure services to businesses.

4.3.2 8–10 March evacuation

On 8 March the VAL increases from 1 to 2 (Table 2.2), although there is limited information regarding where an eruption might be. The initial stage of an evacuation is called at this point. We arbitrarily took the oval of the zone of detected earthquakes in Exercise Ruaumoko Science Alert Bulletin AK-2008/03 (Table 3.5; Figure 3.2a) and added a 1 km buffer to designate the Primary Evacuation Zone (Figure 4.1). We have also extended the area to include all of Orakei and Ihumatao for ease of management. Given the huge uncertainty in vent location at this stage we are not including a secondary evacuation zone. This evacuation is to remove people from the designated zone, but we estimate that infrastructure providers, hospital staff, and emergency/response services can enter as needed. A total of 199,200 people reside in this area and are thus directly affected by the evacuation.

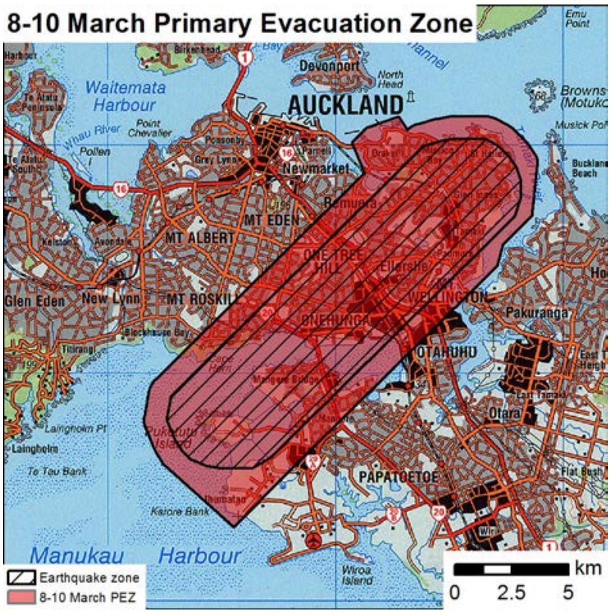


Figure 4.1 March 8–10 Primary Evacuation Zone (PEZ; in red) based on 1 km buffer around oval from the earthquake zone identified in Exercise Ruaumoko Science Alert Bulletin AK-2008/03 (hatched).

4.3.3 11 March evacuation

By 11 March unrest has started to focus in the Mangere area. We have added the zone indicated in Exercise Ruaumoko Science Alert Bulletin AK-2008/09 (Table 3.5; Figure 3.2b), with a 1 km buffer, to the Primary Evacuation Zone (Figure 4.2). Given the huge uncertainty in vent location at this stage we are not including a secondary evacuation zone. This evacuation continues to be geared to remove people from the designated zone, but we estimate that infrastructure providers, hospital staff, and emergency/response services can enter as needed. An additional 54,400 people are affected by the extended evacuation zone at this stage, bringing the total direct evacuees to 253,700.

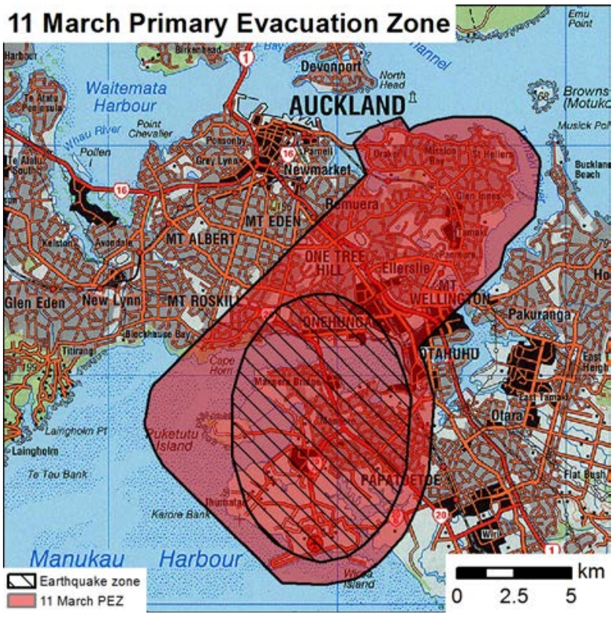


Figure 4.2 March 11 Primary Evacuation Zone (PEZ; in red) based on 8 March PEZ and 1 km buffer around oval from the earthquake zone identified in Exercise Ruaumoko Science Alert Bulletin AK-2008/09 (hatched).

4.3.4 12–15 March evacuation

On 12 March volcanic gas is detected (Table 2.1), which makes an eruption very likely, and Exercise Ruaumoko Science Alert Bulletin AK-2008/13 (2008) for the first time designates a probable vent location zone (Table 3.5, Figure 3.2c).

We base the Primary and Secondary Evacuation Zones (Figure 4.3) on the outer edge of the probable vent location zone following the AVF Contingency Plan. As the existing PEZ encompasses the area within 3 km of the probable vent location (Section 4.2), we keep the PEZ as is. The SEZ results from drawing a 5 km buffer from the probable vent location zone. We envisage that at this stage the evacuation impacts everyone in that area, including those who previously had access to cordoned areas. There are 362,100 evacuees from the PEZ and SEZ during this time. However, we suggest an additional 72,800 will evacuate beyond the PEZ and SEZ extents based on the night-time population within 1 km of the maximum extent of the evacuation zones. Total evacuees are therefore estimated at 434,400 people, which is the maximum number encountered during the scenario.

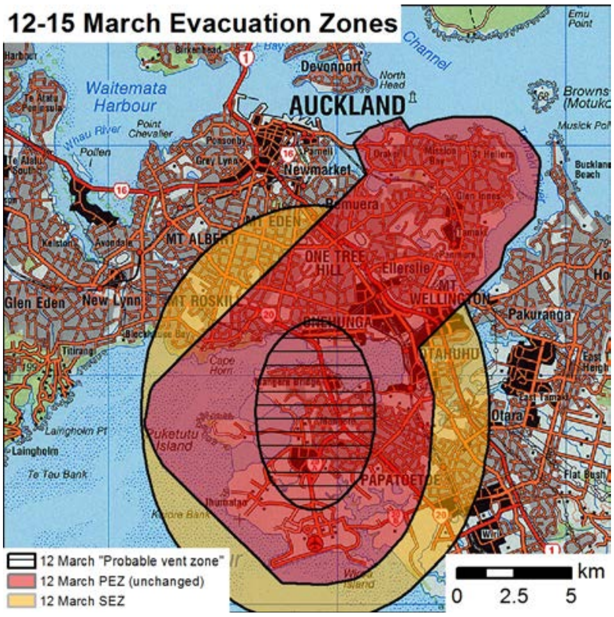


Figure 4.3 March 12 Primary (red; unchanged from 11 March) and Secondary (orange) Evacuation Zones. The latter is based on a distance 5 km from the edge of the probable vent location zone identified in Exercise Ruaumoko Science Alert Bulletin AK-2008/13 (2008) (hatched).

These evacuation zones remain in place until the start of the eruption. On 13 March the Exercise Ruaumoko Science Alert Bulletin AK-2008/15 (2008) has an updated smaller probable vent location zone, but at this stage we do not anticipate any changes in the evacuation zones.

4.4 EVACUATION ZONES DURING THE ERUPTION

Once the eruption begins there is much more clarity on the vent location from which to draw evacuation zones. We propose that evacuation zones remain in place until VAL is dropped from 3 to 2 on 16 March (Table 2.2), at which point they are revisited. We assume that during the eruption, the PEZ is effectively an exclusion zone, whilst the SEZ is a managed cordoned area which infrastructure providers can temporarily enter.

4.4.1 16 March–4 April evacuation zones

On 16 March the VAL is reduced from 3 to 2 (it increases back to VAL 3 on 18 March). We anticipate this would result in revisiting evacuation zones (Figure 4.4), particularly now that there is a definite vent location (and it is not a fissure) and appreciation for the extent of hazards. We suggest that the PEZ be based on a 3 km buffer from the outer edge of the Mt Ruaumoko initial edifice, and include Puketutu Island in the PEZ as otherwise it would be isolated. The SEZ consists of a 1 km buffer around the extent of the pyroclastic surge on the morning of 14 March (which extends 6 km from the vent) and includes all of Ihumatao and the Otahuhu areas (covering a typical total night-time resident population of 275,900 people). The rationale behind this is that a 5 km buffer as prescribed in the AVF Contingency Plan wouldn't encompass the entire area impacted by the surge, so there would be some allowance made for possibly worse to come.

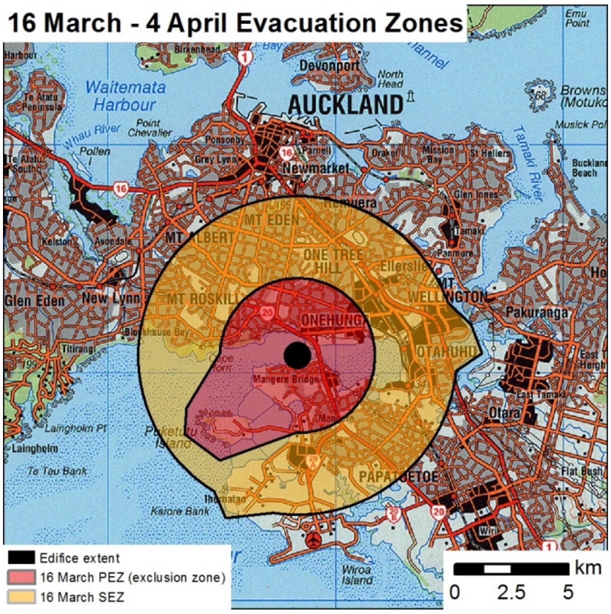


Figure 4.4 Primary (red) and Secondary (orange) Evacuation Zones revised on 16 March following the 14 March eruptions.

4.4.2 5–30 April evacuations

We propose that for ERI purposes, 16 March evacuation zones are maintained until 5 April, the third day of effusive activity by when volcanic gas levels have stabilised. The PEZ remains as it is, but we have removed the SEZ (Figure 4.5). The PEZ at this stage directly affects 57,300 people.

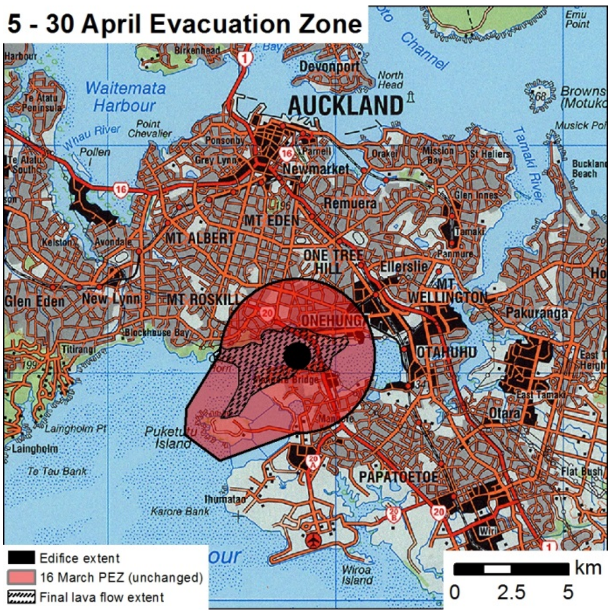


Figure 4.5 Primary Evacuation Zone (red) on 5 April and the final extent of the lava flow (emplacement finishes on 13 April) (hatched).

4.5 POST-ERUPTION STATUS

It is unclear what would constitute ‘crisis over’ given the prolonged nature of volcanic activity at times. In Table 2.2 we have designated 1 May as when the VAL goes from 2 to 1 and 1 June as when the VAL goes from 1 to 0, indicating that the eruption is officially over.

In this scenario, we have removed the PEZ on 1 May, roughly two weeks after the VAL was dropped to VAL 2. At this stage, we put an exclusion zone within 100 m of either (1) the lava flow extent or (2) deposit thickness over 0.5 m (Figure 4.6). This reflects a possible land-use choice (e.g., commemorative park and/or nature reserve) that may be undertaken. We stress that this is not the authors’ or affiliated institutions’ recommendation for recovery measures. Indeed, as this eruption effectively widens the isthmus, there may be a desire to eventually use the land for infrastructure or housing rather than leave it relatively untouched.

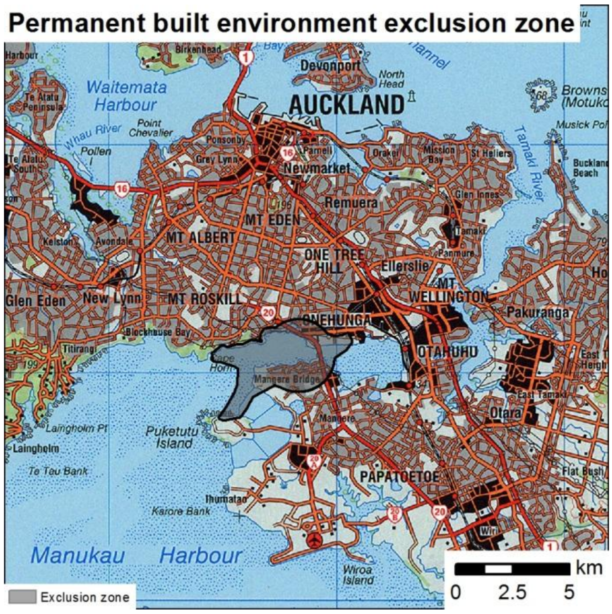


Figure 4.6 Permanent built environment exclusion zone following the Mt Ruaumoko scenario.

An estimated 8,700 people will be permanently displaced by the eruption, i.e., their home is within the permanent built environment exclusion zone.

5.0 ERUPTION DEPOSIT CLEAN-UP

The clean-up of volcanic deposits and damaged infrastructure is one of the most costly and time-consuming operations following a volcanic eruption in an urban environment (Hayes, 2014). In an AVF eruption, clean-up of the roading network is required for roads to return to full functionality, and also for key site access for other lifeline sectors. In instances where infrastructure service outage is due to damage to a (or several) given site and no service re-routing is possible, the service will only be restored once sufficient clean-up has been undertaken. Consequently, applying a clean-up model to the scenario is critical for evaluating restoration times in numerous sectors. In this section we present the clean-up model which underpins the service outage time series maps for a number of lifeline sectors. The Mt Ruaumoko clean-up model (Figure 5.1) follows a volcanic ash clean-up methodology presented in Hayes (2014).

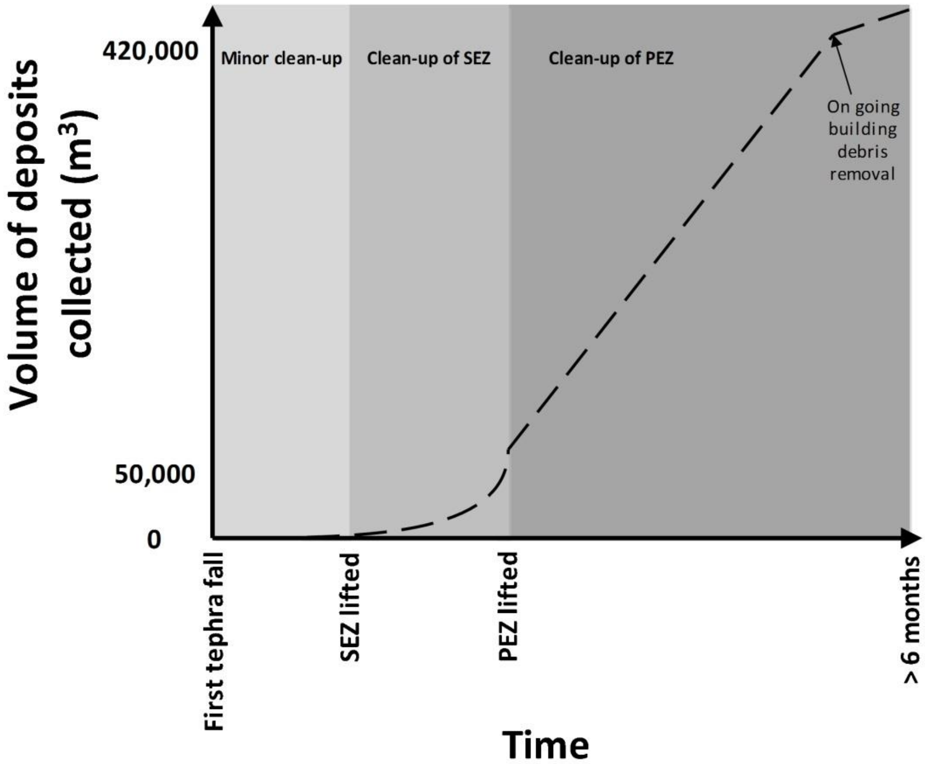


Figure 5.1 Volume of volcanic deposits cleaned-up as a function of time for Mt Ruaumoko scenario.

5.1 14 MARCH CLEAN-UP

After the two eruptions on 14 March, there is minor clean-up of roads and self-organised property clean-up (Figure 5.2) in areas covered by surge deposits and/or tephra fall (Figure 3.3b and Figure 3.4b) outside both the PEZ and SEZ (Figure 4.2; Figure 5.3). Starting late in the afternoon or early evening, roads are cleaned up using street sweepers in the 1–5 mm ash accumulation zone outside of the SEZ. Households self-organise clean-up and dispose of tephra into gardens. Clean-up activities last for about a day. No municipal clean-up occurs in the ≤1 mm ash accumulation area outside the SEZ due to the relatively low population density and low priority of assets. Within the SEZ, clean-up occurs on a limited number of critical transportation routes to maintain north-south links through Auckland.

Figure 5.2 Examples of (A) minor road clean-up and (B) self-organising property clean-up, both concerning ~1 mm of volcanic ash produced by the 6 August 2012 eruption of Te Maari, Mt Tongariro, New Zealand (photo credit: G. Wilson).

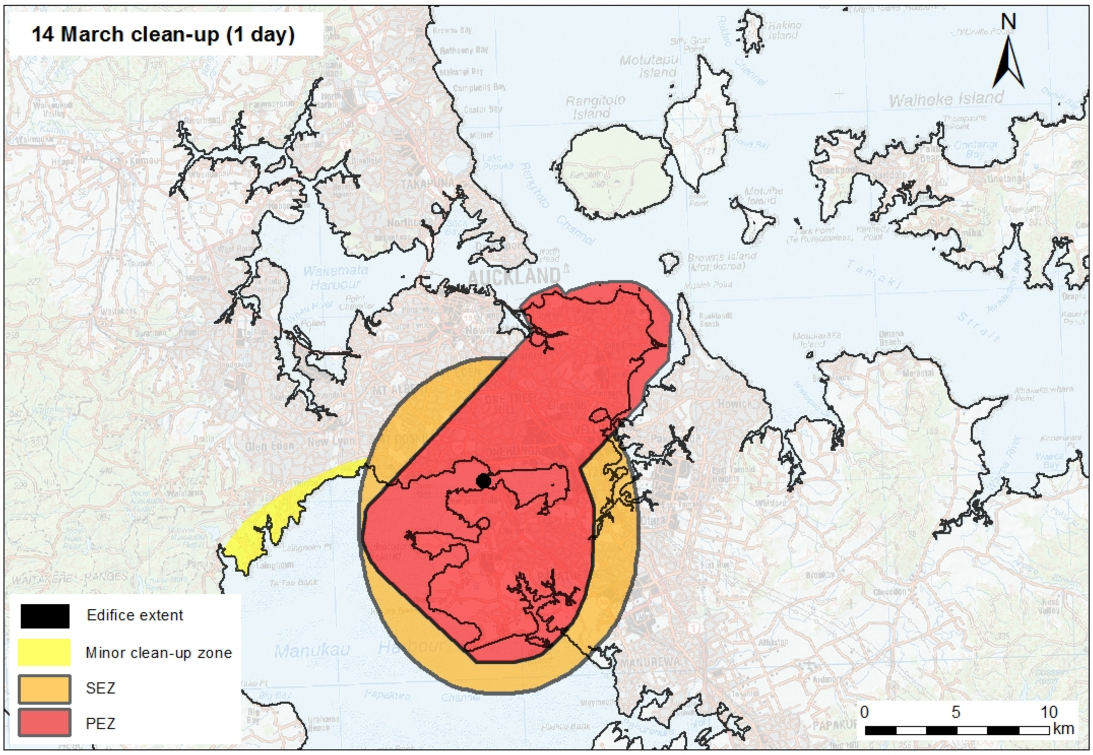


Figure 5.3 Clean-up operation undertaken following 14 March eruptions (yellow). Operations are expected to last 1 day with approximately 600 m^3 of tephra removed from roads. The PEZ (red) and SEZ (orange) are shown; no cleaning occurs within evacuated zones.

5.2 22 March Clean-Up

Following the eruptions on 21–22 March, there is minor clean-up of roads and self-organised property clean-up in areas covered by surge deposits and/or tephra fall (Figure 3.5b and Figure 3.6) outside both the PEZ and SEZ (Figure 4.2). Roads are cleaned up using street sweepers in the zone highlighted in Figure 5.4. Avondale Racecourse is opened as a temporary disposal site for tephra. Households self-organise clean-up and dispose of tephra into gardens. Clean-up activities last for about one week, with around 3,000 m^3 of tephra removed from roads. Only limited clean-up occurs within the PEZ-SEZ area, focussed on critical transportation routes, which are reopened with restrictions. Occasional ‘spot cleaning’ of roads close to the SEZ occurs due to remobilisation of deposits within the SEZ.

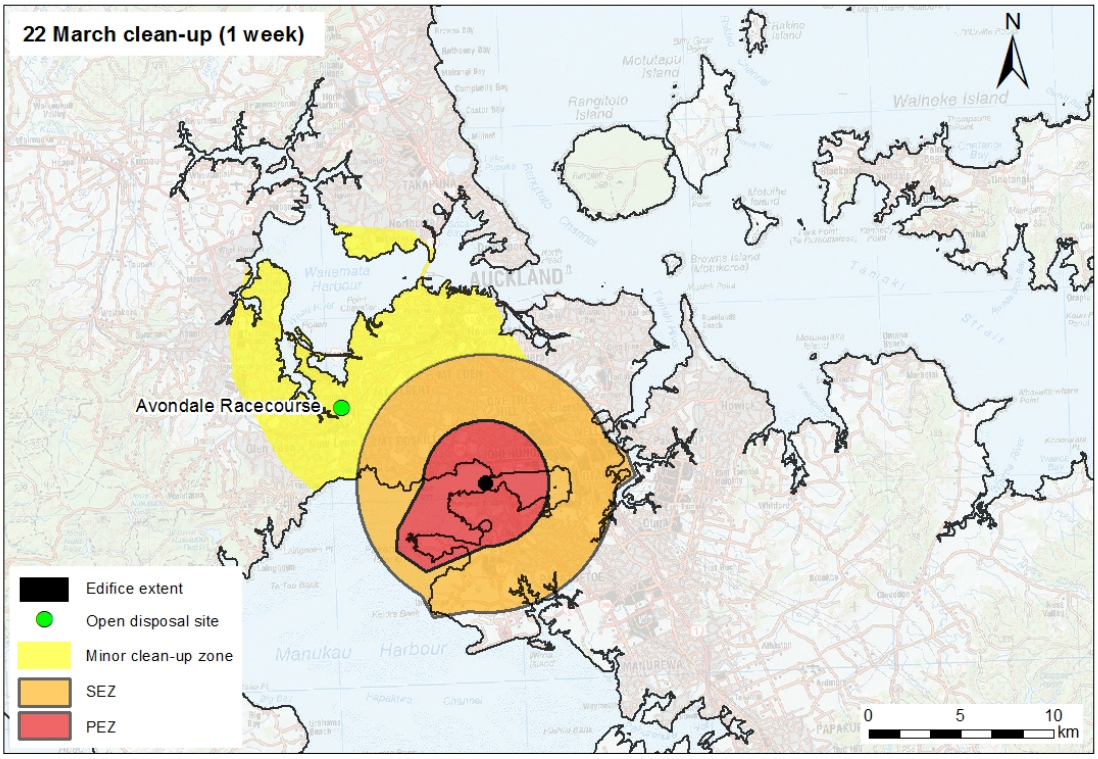


Figure 5.4 Clean-up operation undertaken on 22 March (yellow). Operations are expected to last around 1 week, with approximately 3,000 m^3 of tephra removed from roads. Open disposal sites is shown in green. The PEZ (red) and SEZ (orange) are shown; no cleaning occurs within evacuated zones.

5.3 5 April Clean-up

The lifting of the SEZ (Figure 4.3) allows gradual access to previously evacuated areas which, as they are closer to the volcano than areas already cleaned up, have more surge and tephra deposit area to remove. Thus, on 5 April, a major clean-up operation (Figure 5.5) within the lifted SEZ begins Figure 5.6). Property owners, volunteers and contractors begin clean-up of the SEZ by piling tephra at the roadside where heavy machinery loads it into trucks for transport to disposal sites. In addition to Avondale Racecourse, it becomes necessary to open Keith Hay Park and Aorere Park as disposal sites. Clean-up activity within the SEZ lasts for about one month, with over 40,000 m^3 of tephra removed from properties and roads. Occasional street sweeping operations in areas near the PEZ occurs due to remobilisation of deposits within the PEZ.

Figure 5.5 Example of a major ash clean-up operation, similar to modelled clean up starting on 5 April within the March SEZ. Here ~50 mm of volcanic ash was deposited on Jacobbacci, Argentina from the Cordon-Caulle eruption in 2011 (photo credit: A. Rodriguez).

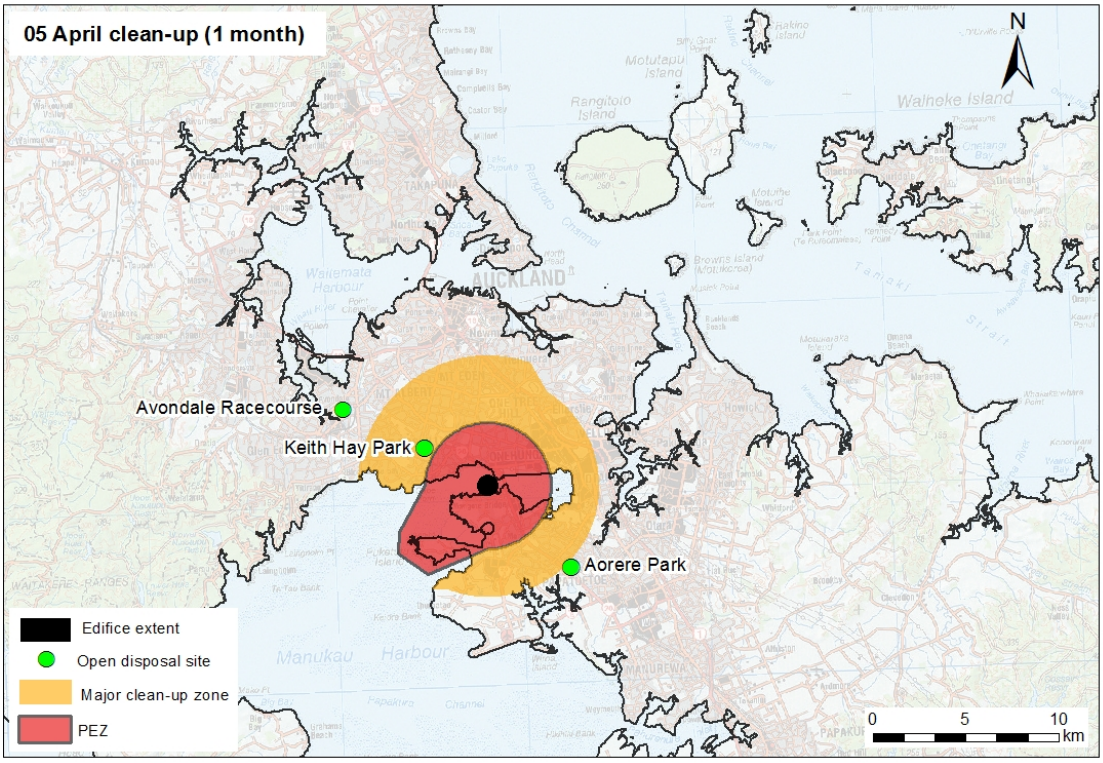


Figure 5.6 Clean-up operation beginning 5 April (orange). Operations are expected to last 1 month with approximately 40,000 m^3 of tephra removed from roads, paved surfaces, and properties. Open disposal sites are shown in green. The PEZ (red) is shown; no cleaning occurs in this zone.

5.4 1 May Clean-up

The lifting of the PEZ (Figure 4.5) allows access to previously evacuated areas which, as they are closer to the volcano than areas already cleaned up, have more surge and tephra deposit area to remove – a location may have up to 0.5 m of surge/tephra deposit to remove. Additionally, this area was impacted by pyroclastic density surges and so clean-up includes removing building debris and irreparably damaged buildings (Figure 5.7). Thus, on 1 May a major clean-up operation within the lifted PEZ begins (Figure 5.8). Due to building damage and potential for hazardous waste (e.g., asbestos) a controlled clean-up operation utilising contractors begins within the PEZ. Some roads are damaged beyond repair or, close to the

vent, are permanently buried by thick deposits. However, some roads are cleared using heavy machinery and trucks which take tephra to disposal sites. This part of the operation takes close to one month. As roads are cleared, property clean-up can begin. Due to the variety of different types of debris, it will be necessary to set up a waste sorting area to separate waste streams. As a consequence, property clean-up is extremely time-consuming with some areas still being cleaned up in October. In total over 420,000 m^3 of deposits are assumed to be removed, excluding building debris.

Figure 5.7 Example of a major ash and building debris clean-up operation, similar to modelled clean-up within eruption PEZ starting on 1 May. Here ~500 mm of volcanic ash required clean-up following the Mt Kelud, Indonesia, eruption in 2014 (photo credit: A. Rochman/AFP/Getty Images).

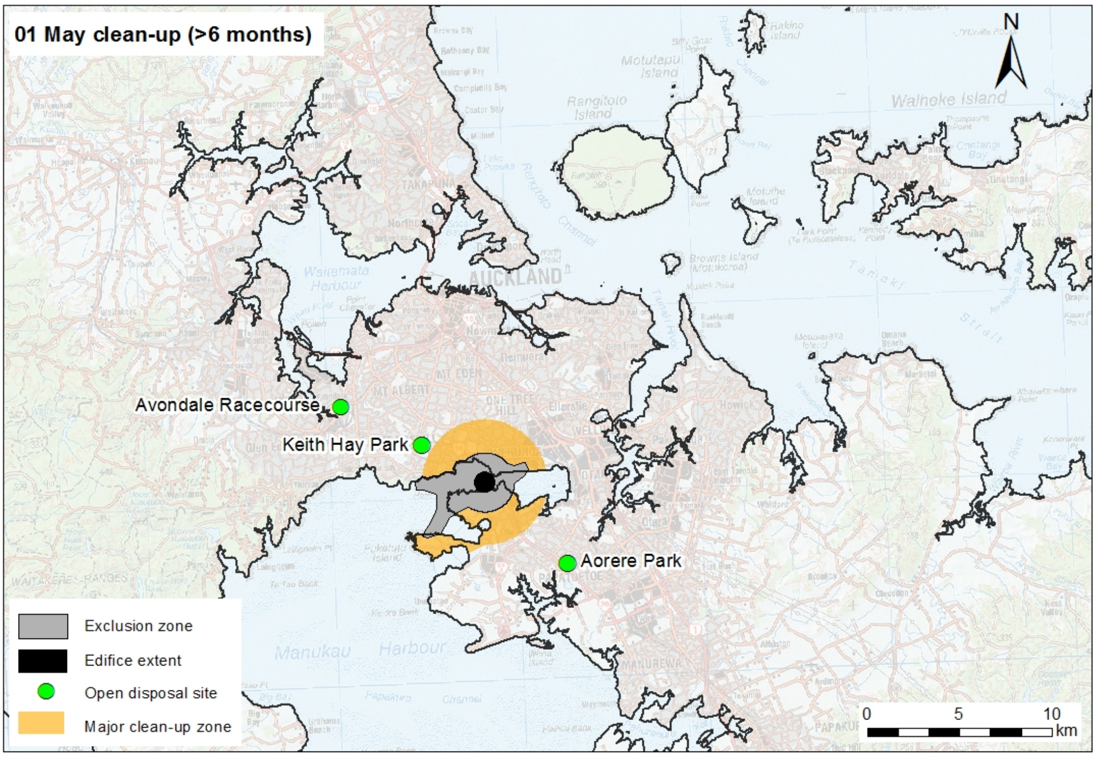


Figure 5.8 Clean-up operation beginning 1 May (orange). Open disposal sites are shown in green. Operations are expected to last over 6 months with approximately 420,000 m^3 of pyroclastic deposits removed.

5.5 LIKELY INTERDEPENDENCIES

Clean-up operations rely on mobilising adequate resources (e.g., trucks, bulldozers, and street sweepers) to the appropriate areas. It will be necessary to utilise mutual support agreements with contractors to assist with clean-up activities due to the spatial scale of the event and the volume of deposited material to be removed. In order to support these activities fuel supply will be required.

Water is often used during clean-up activities to dampen deposits and reduce the potential for remobilisation. As a result, water supplies often experience increased demand due to clean-up activities.

Once deposits are removed, they must be disposed of at an appropriate site. The clean-up operation scenario presented here assumes that disposal sites from the Auckland Volcanic Field Contingency Plan will be used. In recent discussions with AC CDEM, concern was raised that many of these sites could be better utilised as community gathering points. There was also concern that Keith Hay Park is prone to flooding, which would make it inappropriate for use as a disposal site. Alternative options include: utilising existing waste fill sites (unlikely due to large volume), marine disposal (requires further investigation of related issues), and other sites outside of the metropolitan area (no sites currently identified). A detailed analysis of options for disposal of volcanic deposits in Auckland will be the focus of future work.

6.0 ELECTRICITY: GENERATION, TRANSMISSION, AND DISTRIBUTION

6.1 VOLCANIC IMPACTS TO ELECTRICITY SECTOR

Electricity sector infrastructure is vulnerable to high-energy volcanic flow hazards (e.g., pyroclastic density currents (PDCs), lava flows; Wilson et al., 2014). In such cases, the damage is typically complete – the infrastructure is destroyed. The electricity sector is vulnerable to volcanic ash and gas aerosol contamination leading to flashovers (unintended electrical discharges on live systems), which typically render the circuit out of service until cleaned, and in some cases, damage repaired (Figure 6.1). Volcanic ash fall can also lead to accelerated wear to turbines and blockage of air handling systems leading to disruption of generation facilities. We refer the reader to Wardman et al. (2012a), Wardman et al. (2012b), and Wilson et al. (2012) for further details on impacts of volcanic ash to the electricity sector.

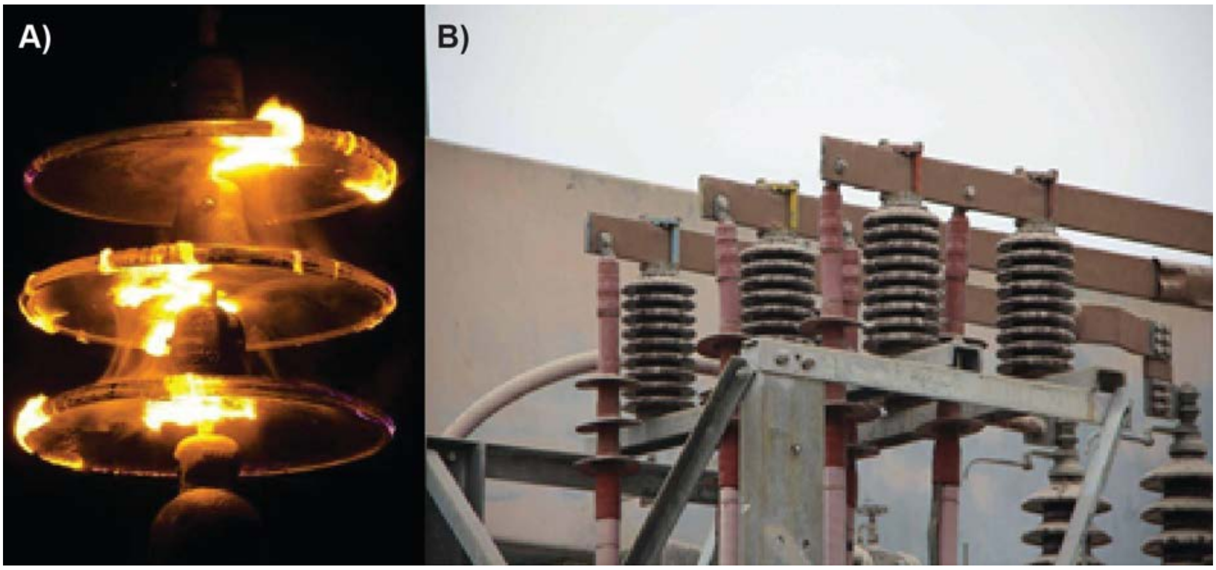


Figure 6.1 A) Electrical insulator flashover; here the insulator is exposed to 3 mm of fresh ash in a wet environment. This causes a short circuit on an electrical transmission line (photo credit: G. Wilson). B) Substation insulators covered in ash following the 2014 Kelud eruption, Indonesia (photo credit: Sumarsono).

6.2 ELECTRICITY SECTOR LEVEL OF SERVICE METRICS

Buxton et al. (2014) developed an electricity outage scenario for Auckland and presents Level of Service maps. These Level of Service maps, produced by Vector, showed two metrics – areas subject to three-hour rolling power outages and those with full power. The AVF scenario is more complex and will have three Level of Service metrics: power at normal reliability, rolling power outages, and no power. Following consultation with Transpower and Vector, it is not possible to specify the duration of the rolling outages. A greater level of analysis than was possible for this scenario is required to be able to specify the duration of the outages.

6.3 AUCKLAND ELECTRICITY: NATIONAL AND LOCAL GENERATION AND TRANSMISSION, AND LOCAL DISTRIBUTION

6.3.1 Generation

Most of Auckland's power is generated outside of the Auckland region, requiring transmission of electrical power via the national transmission network, operated by Transpower. Two local power stations, Ohahuhu B and Southdown are being decommissioned in 2015 and so will not be considered in this report. There is no major power generation north of Auckland.

6.3.2 Transmission

The Transpower high voltage (HV) electricity transmission network (national grid) transmits power from generation to population and industrial centres outages (Figure 6.2a). Power in the majority is transferred south to north via four main power lines. Distribution providers then deliver power to individual consumers.

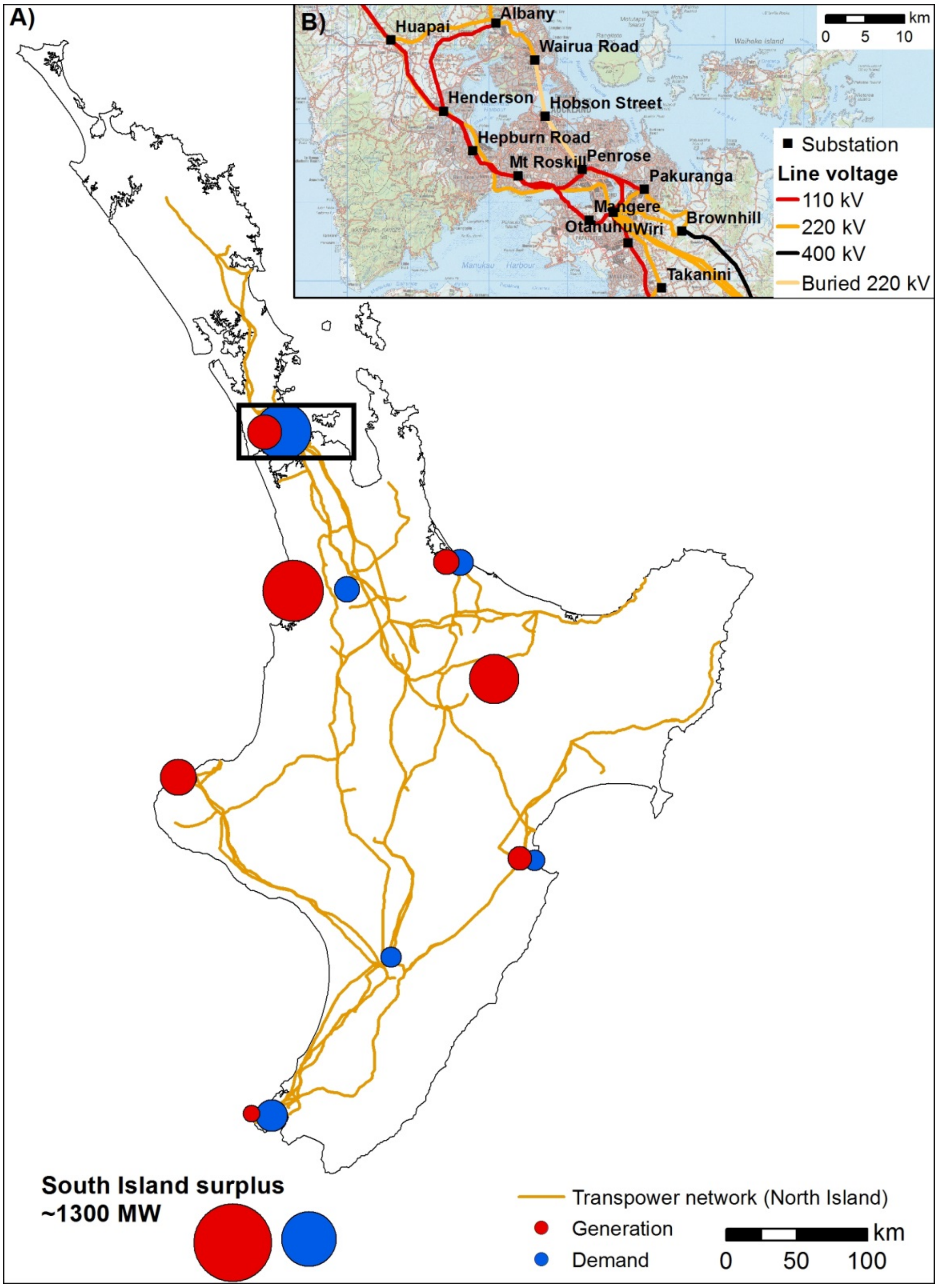


Figure 6.2 A) New Zealand North Island transmission grid, with red dots showing power generation sites, orange lines showing transmission lines, and blue dots showing demand. The diameter of the generation (red) and demand (blue) dots correspond to magnitude. The black box shows the extent of B). Auckland grid, colour-coded according to line voltage. Substations are shown with black squares and labelled.

The geography of the Auckland isthmus requires the three high voltage circuits (lines) supplying the city to be confined to a small geographic area, which greatly increases network vulnerability for Auckland and Northland (Figure 6.2b). The Otahuhu substation is a critical junction between Auckland/Northland and the national grid. From Otahuhu there are three main lines to Auckland/Northland, one with a substation in Mangere, one through Southdown, and one through Penrose. From Penrose there is an underground cable connecting to Hobson Street and then the North Shore (the tunnel is maintained by Vector).

Both the Penrose and Mangere substation connect to Mt Roskill, and from there lines go northward. A power disruption to Auckland would also disrupt the entire Northland region, as it is dependent on power transmission through Auckland.

All Auckland transmission circuits have detectors to isolate faults. Subaerial towers and lines would be vulnerable to most subaerial volcanic hazards and is relatively well defined and described above. There is less knowledge as to what impact volcanic hazards would have on buried assets. Expert judgement by Transpower and Vector engineers identified an increase of 10°C within the Vector tunnel, which houses the underground cable connecting Penrose to North Shore, would be worrisome and at the very least cause a capacity reduction.

During a prolonged Transpower outage, Transpower and the distribution companies would allocate power, resulting in rolling outages across the region. Temporary lines can be put in relatively quickly (two to three days per tower, with two to three towers per km in high density areas).

6.3.3 Distribution

Vector (Auckland from Papakura to Wellsford) and Counties Power (South Auckland and northern Waikato) are the two main power distribution companies in the Auckland Region. Given the geographic scope of the Mt Ruaumoko scenario, we focus on the Vector distribution network.

Vector receives high voltage electrical power from Transpower at substations within the Auckland region (Figure 6.2b). Vector distributes this power through their own network, which includes substations, and overhead and buried power lines.

The Mangere substation provides an electrical power feed to Auckland Airport, Mangere wastewater treatment plant, Middlemore Hospital and the surrounding region. Most of the powerlines in this area are buried. The Penrose substation is crucial to the overall network. It delivers power to the Eastern Bays region, is critical for transferring power to other parts of the network and, in conjunction with the substation at Southdown, provides power to the entire suburban electric rail network in Auckland. The Mt Roskill substation powers much of the CBD and region east of New Lynn.

6.4 MT RUAUMOKO SCENARIO

6.4.1 Generation and transmission network impacts

One power station (Southdown) will be impacted by the Mt Ruaumoko eruption, but as it is being decommissioned later this year, we won’t consider it for this scenario. We note the Otahuhu B power station (Contact Energy) is also being closed soon.

The transmission network will be directly impacted by the Mt Ruaumoko eruption. Transpower have indicated they will not pre-emptively shut down a portion of the network prior to the event.

6.4.1.1 14 March

We are unsure what impacts the surge might have on substation infrastructure – there is no documented equivalent situation anywhere in the world. Three substations (Mangere, Penrose, and Mt Roskill) between 5 and 6 km from the vent and are exposed to < 5 kPa in the first surge on 14 March. It is unclear what sorts of temperatures might accompany the

surge at this distance (Brand, personal communication 2015), a parameter of importance for sensitive electronics and electrical network components. At Maungutaketake, charred wood > 1 km from the vent suggests temperatures ⩾ 200°C (Brand et al., 2014). However, in the dilute portions of the flow, temperatures are likely to be considerably cooler.

In part to preclude catastrophic collapse of Auckland, we will assume that the three exposed substations (Mangere, Penrose, and Mt Roskill) will survive the surge – it wouldn't be consistent to keep one and destroy the others as they are all roughly the same distance from the vent. We assume that pyroclastic surges destroy the power lines traversing the near vent region, but that the buried cable from Penrose to Hobson Street is undamaged (Figure 6.3). The result is a highly vulnerable network in which Penrose substation is the linchpin, power to western Auckland must first be transmitted north via the underground Vector tunnel and then go counterclockwise around the Waitemata Harbour. There is insufficient capacity to transmit power to the entire region.

The second surge in the afternoon of 14 March and the accompanying tephra fall do not cause additional damage to the system, nor is the tephra thick enough in undamaged areas to cause flashovers.

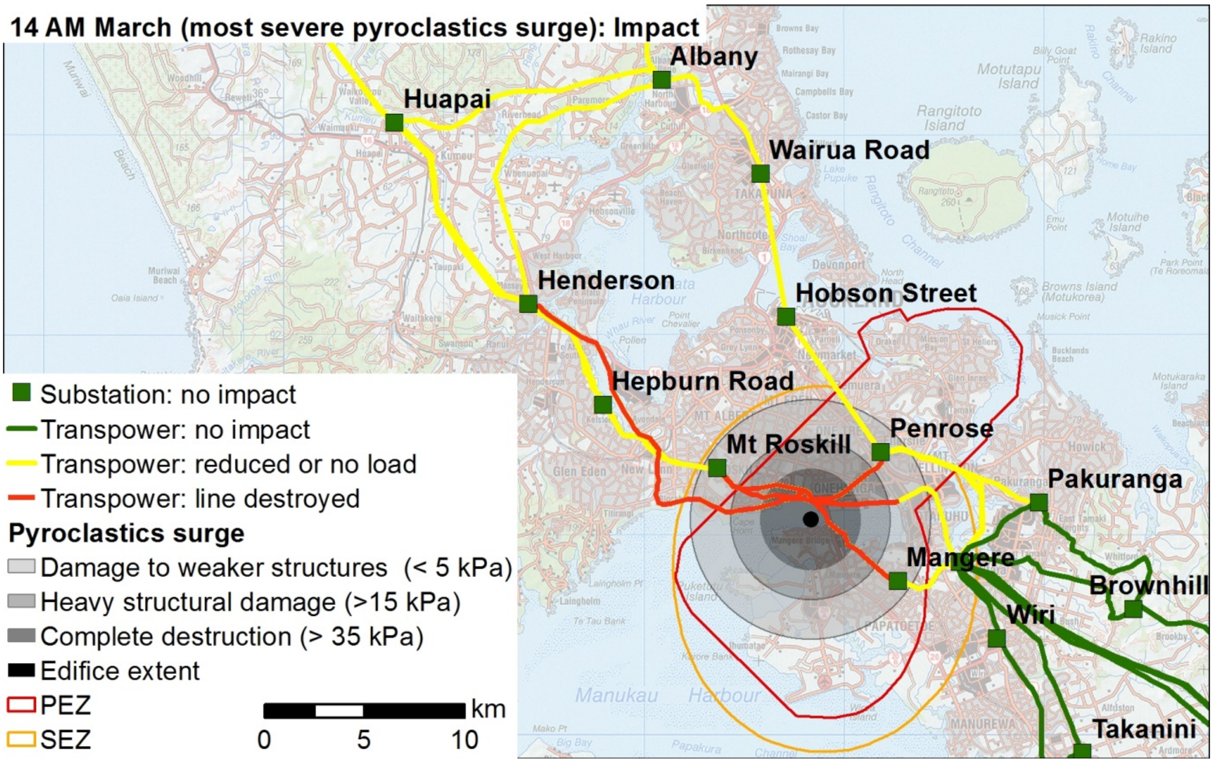


Figure 6.3 Impact of 14 March AM pyroclastic surge to Transpower network. Functioning substations (squares) and transmission lines are shown in green, lines that are physically impacted or with a reduced load are shown in yellow, and destroyed lines are shown in red. The extent of the pyroclastic surge is shown in grey, with darker grey areas suffering more damage. The PEZ (red) and SEZ (orange) are indicated. The Mt Ruaumoko edifice is black.

6.4.1.2 25 March

Following the devastation on 14 March, plans will be put in place to build a new transmission line (once the situation permits) between Penrose and Mt Roskill substations. On 21 March tephra fall covers a considerable portion of Auckland (Figure 6.4), but not much is covered by > 3 mm. Mt Roskill substation receives ~ 3 mm. More tephra falls on 22 March (not shown), but it doesn't extend past the evacuation zone. The tephra fall makes the system vulnerable

to flashovers at Mt Roskill substation, which happens at the next rainfall on 25 March. Mt Roskill substation is inoperable until proper cleaning can occur. Vector estimated it would take a day to clean, but given access and possible personnel complications we assume Mt Roskill substation won't be restored until the SEZ is lifted.

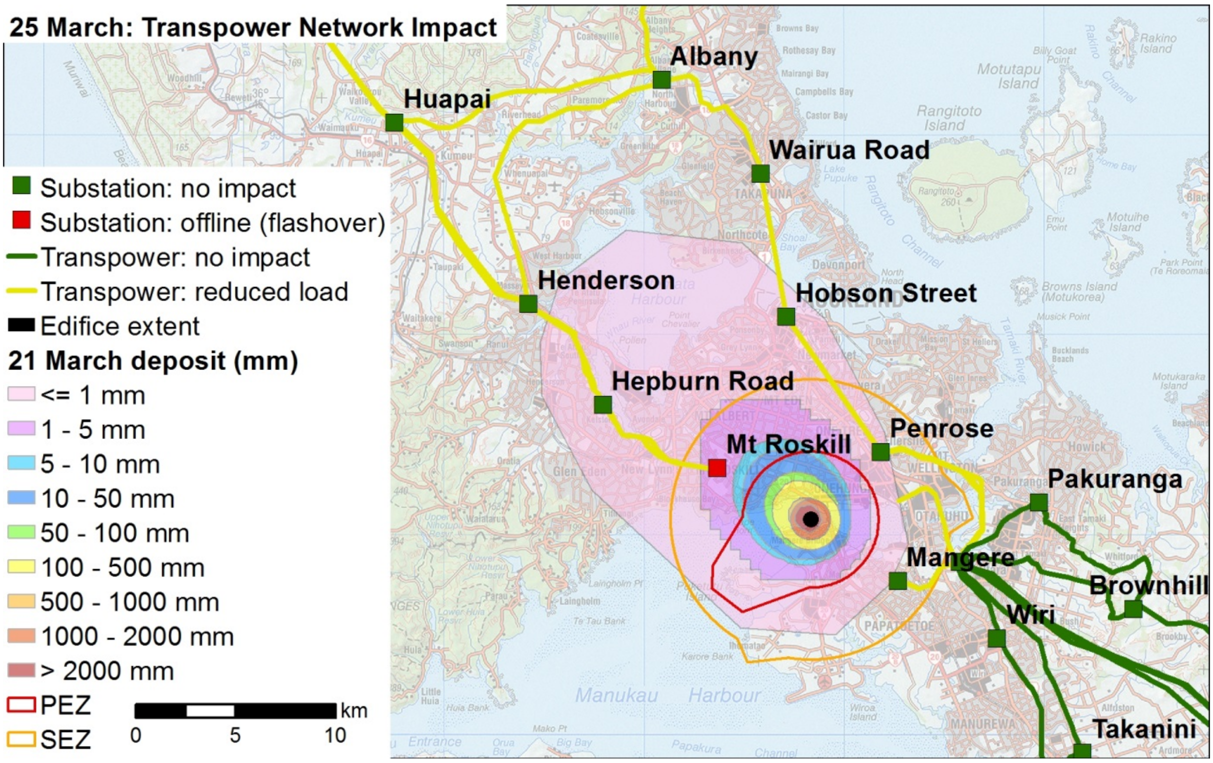


Figure 6.4 Status of Transpower network on 25 March following rainfall on 21–22 March tephra fall deposits. Functioning substations (squares) and transmission lines are shown in green, lines with a reduced load are shown in yellow, and substations offline due to flashover are in red. Previously destroyed lines are not. The combined tephra fall and pyroclastic surge deposit is indicated with colours corresponding to deposit thickness (see legend). The PEZ (red) and SEZ (orange) are indicated. The Mt Ruaumoko edifice is black.

6.4.1.3 5 April

On 5 April the SEZ is lifted and work can commence on building a temporary transmission line between Penrose and Mt Roskill substations. 8.5 km is the direct distance between the two so we will assume that the new line is 10 km long. Assuming a total of 30 new towers with 2–3 days per tower and delays associated with clean-up and equipment delivery, we suggest that the new line will be in place by 15 July. There will likely be rolling blackouts all the way through Northland until this is completed, unless distribution companies could achieve considerable electrical power conservation.

In the long term a permanent transmission line between Penrose and Mt Roskill would be built and additional redundancy would be added so that Penrose is not the sole substation transferring power from south to north of Auckland. Transpower indicated that new lines would likely be built away from the new volcanic area.

6.4.2 Distribution network impacts

As with Transpower, Vector will not pre-emptively take anything offline prior to the eruption. Vector infrastructure will be heavily impacted, particularly all the overhead power lines. Vector is highly dependent on the load coming from Transpower, but can reroute available

power fairly quickly. Vector is able to monitor usage, and so transfer power from areas with low demand to areas with high demand. Likewise, areas with no demand (e.g., evacuated zones) will receive no power.

The major impact is the 14 March morning pyroclastic surge destroying infrastructure. Vector engineers indicated that the Vector power poles are designed to cope with 900 Pa wind, and suggested that a 2 kPa threshold would be a good starting point for assuming power pole failure. Figure 6.5, provided by Vector, shows all the power poles (low and high voltage) within a portion of surge zone. This represents a major loss of infrastructure and would take a long time to secure replacement material and rebuild. Vector substations within the > 15 kPa surge exposure zone may sustain permanent damage.

Figure 6.5 Modelling by Vector showing power poles exposed to the 14 March AM surge. Red dots are low voltage power poles and blue dots are high voltage power poles. Surge strength indicated with shading, with magenta being the > 35 kPa zone, green being the > 15 kPa zone, and peach being the zone of < 5 kPa .

Although we have assumed that the Transpower lines in and out of the three substations in the surge zone remain operational, the distribution networks out of Penrose and Mt Roskill will be down due to the power pole situation. The area near Penrose is within the PEZ until 16 March and so there will be no demand there. The distribution network out of Mangere substation is mostly buried and so is more resilient.

In their modelling (Section 6.4.3), Vector assumed that from 14 to 21 March,

- All above ground equipment exposed to > 15 kPa surge is permanently out of service;
- Overhead lines exposed to < 15 kPa surge (peach area in Figure 6.5) is inoperable;
- No personnel can enter PEZ or SEZ for repairs.

Vector would be able to shift power westward from Penrose to Mt Roskill via Liverpool substation (not shown). However, manual switching would likely be required, so would necessitate access to the PEZ (11–15 March) or SEZ (16 March–4 April) depending on the date of restored access.

According to Vector, the major limitation will be how much power Transpower can provide through their network. Vector expect rolling outages but very few blackouts to inhabited areas – as blackouts would occur where the overhead power lines are destroyed and in localised areas due to flashovers when > 3 mm ash is rained upon. They estimate it would take a few days to clean properly following a flashover.

Service restoration priorities would be evacuation centres, hospitals, and emergency services. Power would not be restored to evacuated areas until directed to by CDEM (power is one of the criteria required for return).

Within the surge impact zone, replacing all the downed power poles will require considerable resource and material. We suggest it will take a year following the PEZ being lifted for the power distribution system to be restored, with restoration first in accessible areas with few deposits.

6.4.3 Electricity level of service maps

Vector did in-house modelling of level of service following our meeting with them (Appendix 1). We transferred this to the community board level of service maps, a scale considerably coarser than what Vector used internally and was used in Buxton et al. (2014). We assume that Waiheke community board is unaffected as it is not connected to the main transmission and distribution network. Whilst our maps do not show it, rolling power outages in Auckland extend all the way through Northland.

6.4.3.1 14–24 March

The 14 March surge causes power outages north of the isthmus. Much of the evacuation zone is without power due to damage and lack of demand. Figure 6.6a shows Vector's estimate of power outages, and we have added rolling outages for everything north of there (including Northland). Figure 6.6b shows our transplantation of Vector's map to community board level.

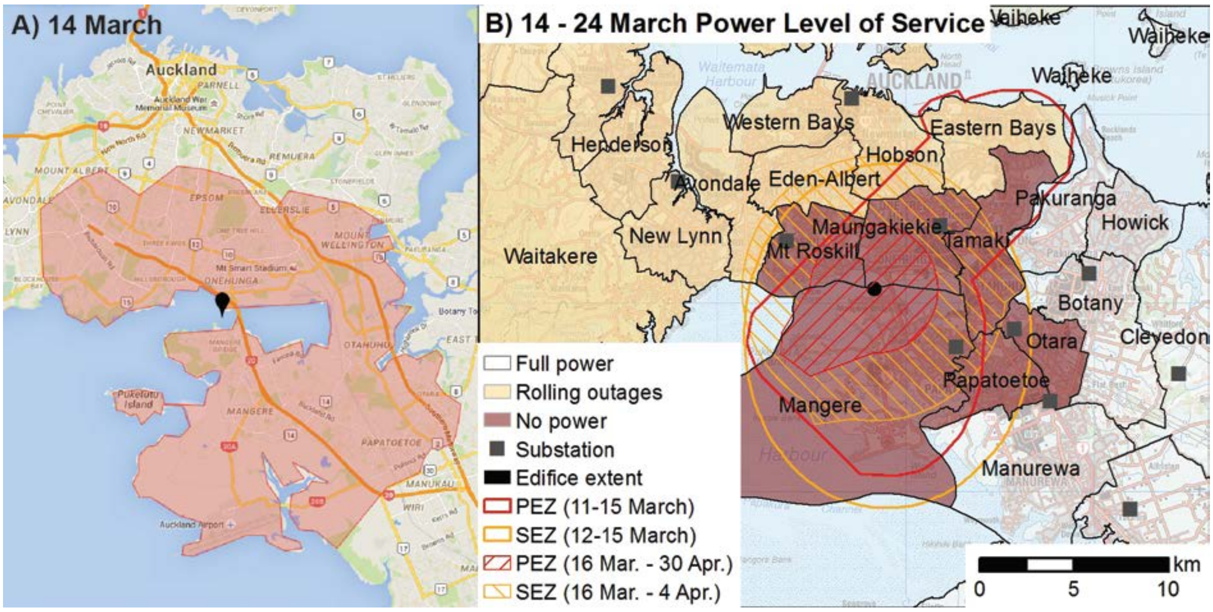


Figure 6.6 Electricity level of service maps for 14–24 March. (A) Results of modelling by Vector with areas with no power indicated in red. (B) Level of service maps by community board. In yellow are areas with rolling outages, and in red are areas with no power. The PEZ (red) and SEZ (orange) are indicated, outlined for initial evacuation zones and hatched for evacuation zones starting on 16 March. Substations are shown as grey squares for reference. The Mt Ruaumoko edifice is shown in black in both.

There is tephra fall on 21 March impacting a large previously un-impacted area, but there are no further outages until rainfall on 25 March.

6.4.3.2 25 March–4 April

Flashovers following rainfall at Mt Roskill take Mt Roskill substation and some distribution lines offline, causing further impact (Figure 6.7).

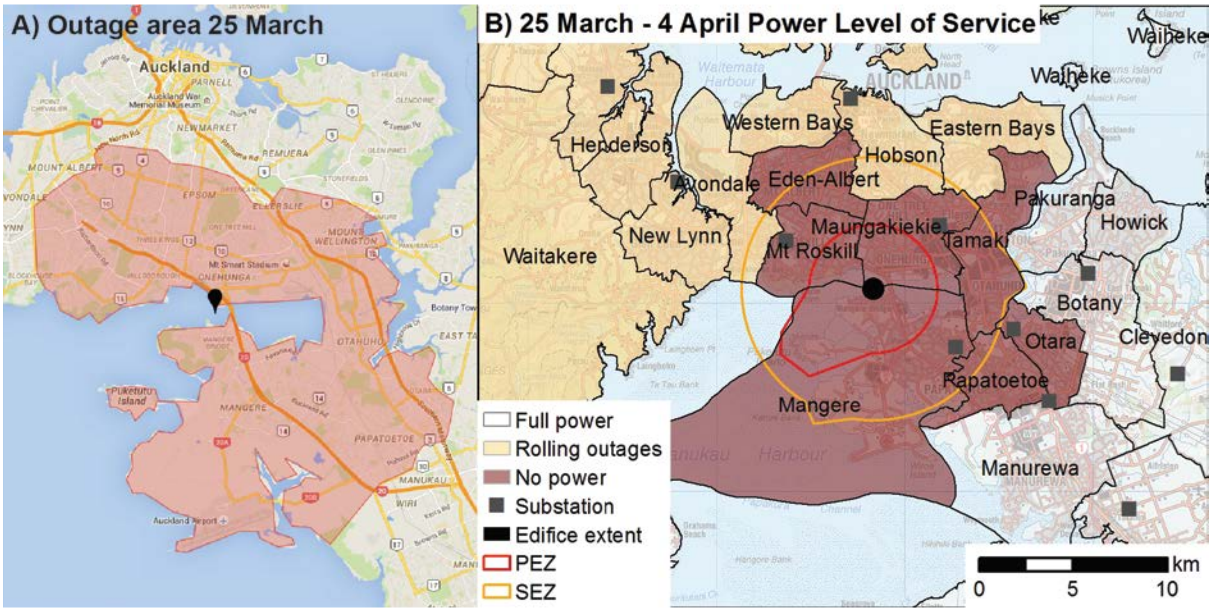


Figure 6.7 Electricity level of service map for 25 March–4 April. (A) Results of modelling by Vector with areas with no power indicated in red. (B) Level of service map by community board. In yellow are areas with rolling outages, and in red are areas with no power. The PEZ (red) and SEZ (orange) are outlined. Substations are shown as grey squares for reference. The Mt Ruaumoko edifice is shown in black in both.

6.4.3.3 5–30 April

Once the SEZ is lifted, Mt Roskill substation cleaning is completed, and work begins to construct a new transmission line (completion 15 July). Work begins on restoring the distribution network in the surge zone. We assume that all areas south of Otahuhu and east of Mangere have full power (Figure 6.8).

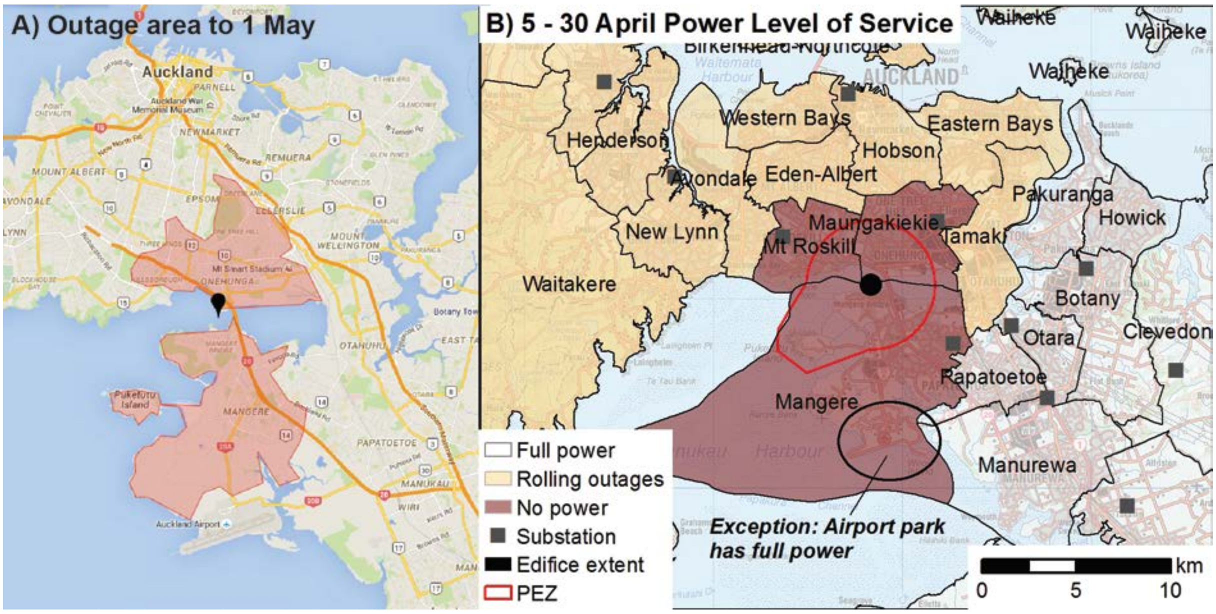


Figure 6.8 Electricity level of service map for 5–30 April. (A) Results of modelling by Vector with areas with no power indicated in red. (B) Level of service map by community board. In yellow are areas with rolling outages and in red are areas with no power. The airport area within the Mangere community board has full power unlike displayed on the map. The PEZ (red) is outlined. Substations are shown as grey squares for reference. The Mt Ruaumoko edifice is shown in black in both.

6.4.3.4 1 May–14 July

Power is restored to Mangere by 1 May, although areas north of Otahuhu (all the way through Northland) continue to have rolling outages while the transmission line is built (Figure 6.9).

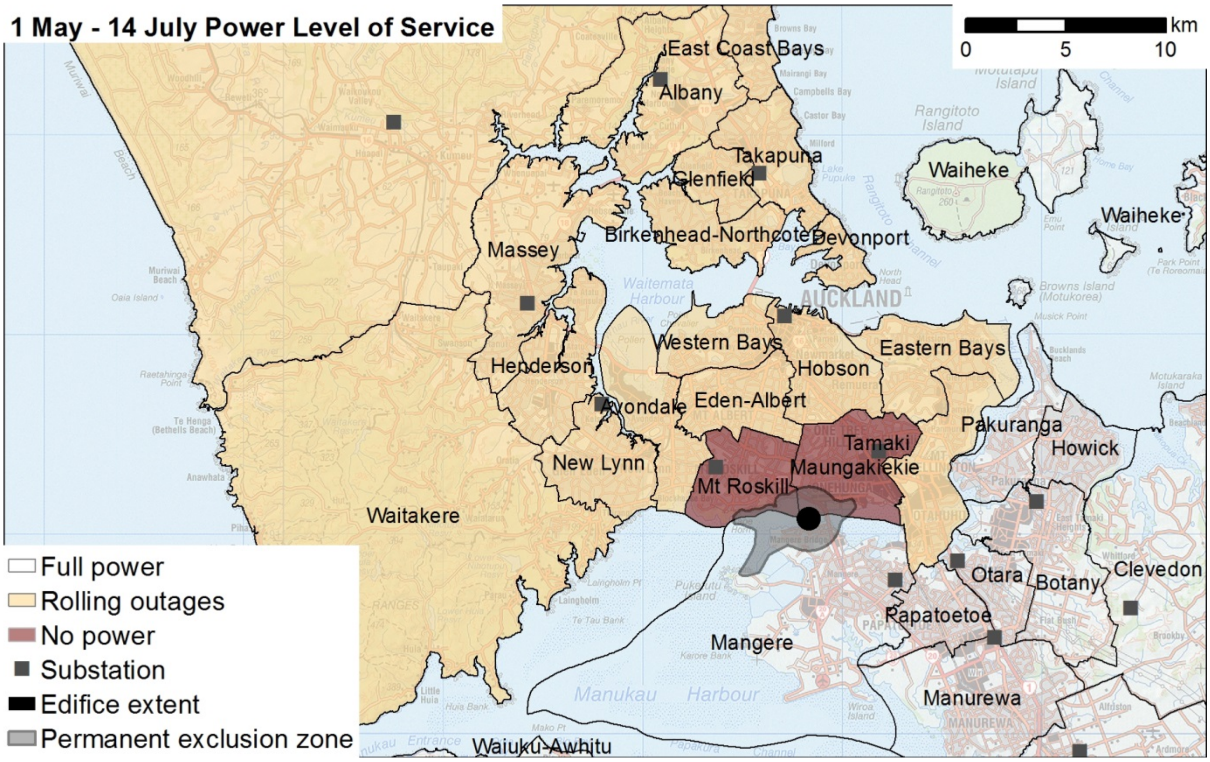


Figure 6.9 Electricity level of map for 1 May–15 July by community board. In yellow are areas with rolling outages and in red are areas with no power. The permanent exclusion zone is indicated, and substations are shown as grey squares for reference. The Mt Ruaumoko edifice is shown in black.

6.4.3.5 15 July (Year 1)–31 May (Year 2)

Once the transmission line is in place, there are no more power shortages apart from the area impacted by the surge (Figure 6.10). However, restoration of the distribution network in surge impacted areas is ongoing and will depend on demand.

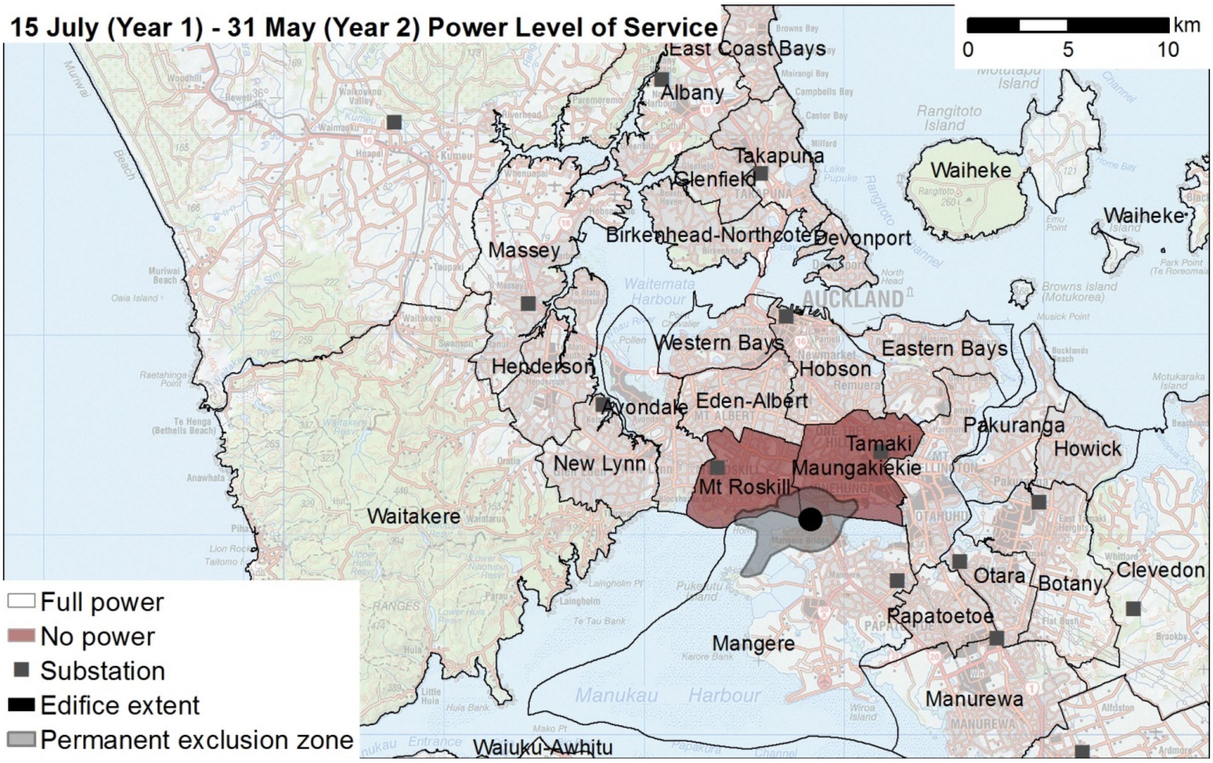


Figure 6.10 Electricity level of map for 15 July (Year 1) to 31 May (Year 2) by community board. In red are areas with no power. The permanent exclusion zone is indicated, and substations are shown as grey squares for reference. The Mt Ruaumoko edifice is shown in black.

6.5 LIKELY INTERDEPENDENCIES

The power sector depends on functional road and freight services (rail and marine) for access to sites damaged or in need of maintenance and material delivery. In particular, transmission towers will need to be installed when the new transmission line is put in place. In the same vein, the power sector will need site access, which at times may necessitate entry into cordoned areas.

The power sector also requires trained engineers with site-specific knowledge. Engineers from elsewhere in the country could be brought in, but would need supervision.

7.0 FUEL

7.1 VOLCANIC IMPACTS TO THE FUEL SECTOR

In one of the few documented instances of volcanic eruptions directly impacting the fuel sector, pyroclastic surges from the Soufrière Hills Volcano led to a fuel terminal at Plymouth Port being abandoned (Kokelaar, 2002). Fuel supply was re-routed to a small jetty in the north of the island, and ultimately there were no fuel shortages (Sword-Daniels et al., 2014). Previous work aimed at anticipating volcanic impacts to the fuel sector has suggested (AELP-2, 2014):

- Tephra fall accumulating on floating storage tank roofs may require their use to be restricted, which could reduce the storage capacity;
- Impacts to road transportation could slow or prohibit the distribution of fuel from storage terminals;
- Damage to pumping stations could slow or prohibit the flow of fuel through pipelines;
- Seismicity and land deformation could rupture buried pipelines in areas proximal to an eruption;
- Closure of pipelines due to potential risk of rupture and contamination of the natural environment;
- Electricity supply problems could limit the ability of pumping stations or refineries to operate.

There is no knowledge of what would happen if a buried fuel pipeline would be covered by a lava flow, although pipeline engineers have noted the pipe would be abandoned at the very least due to safety concerns.

7.2 FUEL SECTOR OUTAGE METRICS

We adopt the following metrics for the fuel outage in the Auckland region: no fuel, fuel restrictions, and full supply. We distinguish between petrol/diesel and jet fuel. We do not consider national implications, such as potential changes to how fuel arrives/is delivered to other New Zealand regions.

7.3 AUCKLAND FUEL SUPPLY

The Refinery Auckland Pipeline (RAP) starts at the Marsden Point Oil Refinery in Whangarei and extends 170 km south to the Wiri fuel storage facility in South Auckland (Figure 7.1). The 270 mm diameter pipe is buried entirely underground and can pump petrol, diesel, and jet fuel sequentially along the length of the pipeline. To increase the flow rate there are two pumping stations along the pipeline in Wellsford and Kumeu. Once the fuel reaches the Wiri terminal it undergoes sampling and testing, before distribution. Automotive products are distributed by road tankers, while jet fuel is supplied directly to Auckland International Airport via a small pipeline from Wiri. The RAP crosses Mangere Harbour in a buried section between Hillsborough west of White Bluff and Ambury Regional Park in Mangere.

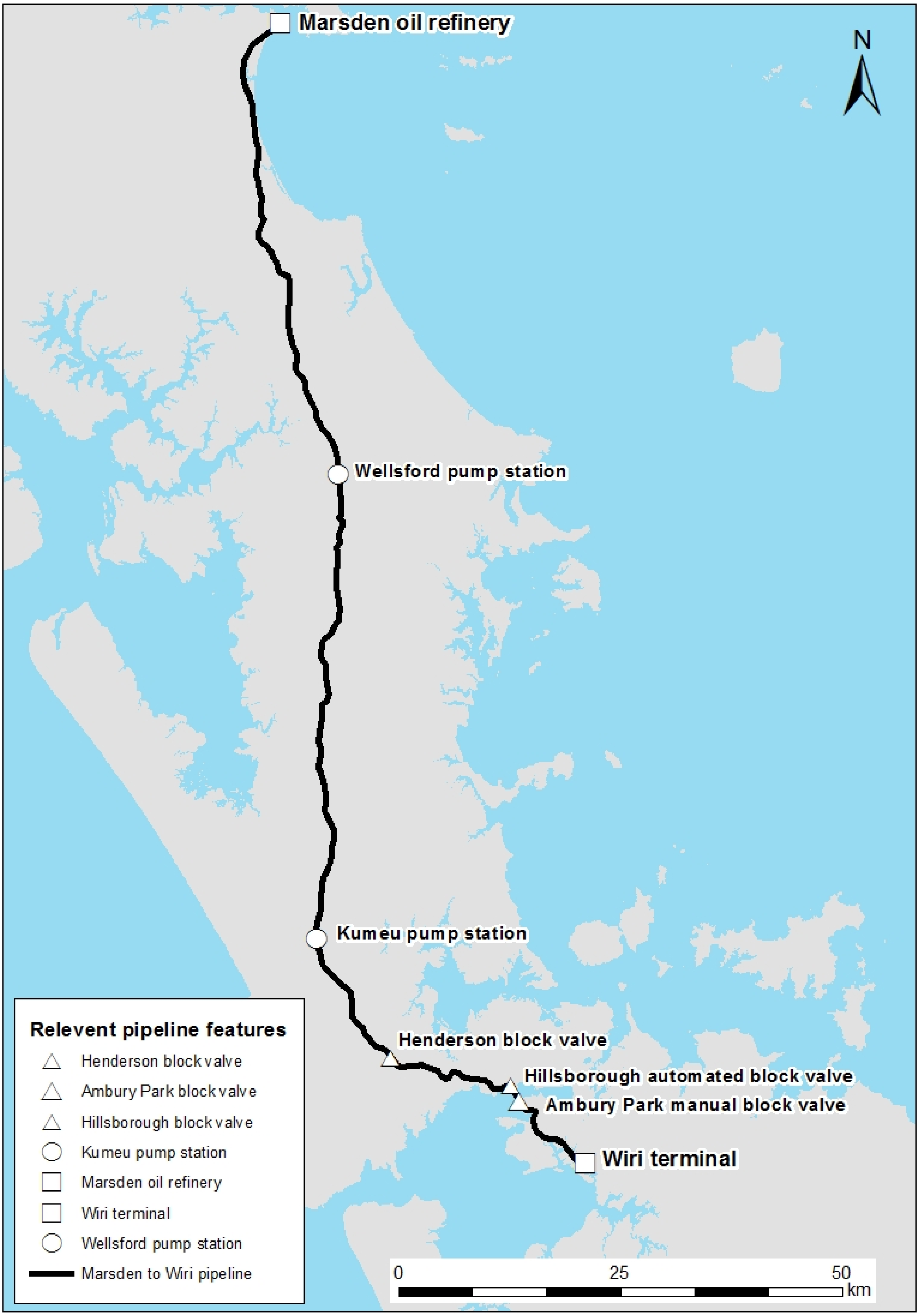


Figure 7.1 Overview of the Refinery Auckland Pipeline (RAP; black line). Block valves indicated with open triangles, pump stations with open circles, and the two endpoints (Marsden oil refinery and Wiri terminal) with open squares.

7.4 MT RUAUMOKO SCENARIO

Disclaimer: The authors emphasise that, as with the rest of this report, this section should not be taken as a prediction of events, impacts, and/or actions, nor is it a recommendation or endorsement of any existing or future policy. Additionally, we focus just on Auckland – we do not consider national-level ramifications which would likely occur were there to be a disruption to the pipeline. We note that that the MERIT economic model will capture national implications.

7.4.1 Fuel supply network impacts

7.4.1.1 Pre-eruption pipeline closure

The Marsden to Wiri pipeline will remain operational until seismicity and land deformation begins to cause concern about the risk of a rupture of the pipeline on 8 March.

On 9 March, once the initial main evacuations have been completed, automated block valves at Hillsborough and Henderson, and manual valves at Ambury Park and Links Road will be closed to isolate the section of the pipeline which transverses the high seismicity zone and Mangere Harbour, as was done during Exercise Ruaumoko (AELG & NELC, 2008). This prevents all petrol, diesel, and jet fuel from reaching Wiri storage Terminal.

On 12 March the SEZ is implemented, which forces the evacuation of the Wiri Terminal. The Links Road valve is located just outside the SEZ and remains closed.

7.4.1.2 Eruption pipeline damage

The Mt Ruaumoko eruption begins on 14 March. Although land deformation is not specifically modelled within this report, it is anticipated that complete destruction to the pipeline crossing Mangere Inlet occurs at the beginning of the eruption due to the proximity to the vent and sensitivity to ground deformation. Base surges on 14 March morning damage the automated block valve at Hillsborough.

Subsequent surges do not cause additional damage to fuel infrastructure, nor to tephra deposits or ballistics.

The lava flow from 3–14 April inundated the Mangere Inlet, covering the buried pipeline and destroying the Ambury Park valve. This forces permanent abandonment of the pipeline between Hillsborough and the Mangere Wastewater Treatment Plant area. However, as the nearest valve south of the destroyed Ambury Park valve is at the Wiri terminal, a new valve site will have to be constructed north of Wiri.

7.4.1.3 Post-eruption restoration

Due to the importance of fuel supply to Auckland's functionality, it was suggested a floating storage of petrol and diesel at Auckland container wharf could be built after the eruption commences. This would require ministerial grants, consents, and very high security (military level). Additional trucks and drivers may be required from Australia. Jet fuel would be sent to Wellington and Christchurch via ship. We note that once jet fuel supplies at Wiri storage facility are completely depleted, Auckland International Airport will not have access to additional jet fuel (see Section 10).

Repair work on the pipeline and at the WOSL terminal cannot begin until 1 May when the PEZ is lifted. We anticipate a one week delay at this stage whilst health and safety assessments are undertaken (not only volcanic but potentially hygienic due to raw sewage discharge) and a plan is finalised. It is estimated it would take two to four weeks for a temporary line to be built provided all necessary waivers, consents and pipeline route for temporary line are granted. It is feasible that by 1 June a temporary line could be built and fuel supply would resume. A permanent line would be built in the coming months and years, although for the purposes of the ERI scenario the temporary line signals full fuel service. Due to over 10 m of lava overlying the damaged pipeline making access difficult, rerouting of the pipeline would be undertaken.

7.4.2 Fuel level of service

Table 7.1 describes fuel level of service for the Auckland region for the duration of the scenario.

Table 7.1 Fuel level of service table.

Date	Petrol/diesel	Jet A-1
8 March	Full service	Full service
9 March	Fuel restrictions	No fuel
1 June	Full service	Full service

7.5 LIKELY INTERDEPENDENCIES

The supply of fuel to Auckland and beyond is critical for many aspects of the economy and emergency response. There are a number of likely interdependencies:

- Road access: Supplying fuel to various service stations is done by truck, which will require roads with minimal damage
- Electricity/power supply: Pumping at service stations and supply terminals relies on power supply. Some service stations are likely to experience power outages which will limit their ability to supply fuel and so resupply of fuel will likely prioritise to those with backup generators. Wiri storage facility has backup generators which will allow the pumping of fuel to continue.
- Auckland International Airport: Jet fuel is supplied to the airport through a pipeline from Wiri storage facility. If this connection is lost, or jet fuel supplies are depleted, aircraft will not be able to refuel at the airport.
- Emergency operations: Fuel consumption by ambulance, fire, and police is likely to increase during the scenario. A long term fuel supply shortage could limit their capacity to respond to emergencies.
- Clean-up operations: Clean-up of eruption deposits will require the mobilisation of a large number of trucks, sweepers, bulldozers, and graders. Fuel supply limitations could increase the time it takes to clean-up. This would then have further flow on effects on health, infrastructure, and economic activities.
- Wastewater: due to the discharge of large volumes of raw sewage into the Mangere Harbour, there will likely be health and safety concerns for repairing the pipeline.

8.0 ROADS

8.1 VOLCANIC IMPACTS TO ROAD TRANSPORT

During a volcanic eruption, functional road transport networks are critical for evacuations, as well as for immediate and long-term recovery once direct threats have subsided. Roads are the most important transport sector in relation to other ‘lifelines’ and in terms of public use (Daly & Johnston, 2015). Proximal hazards associated with an eruption often lead to severe impacts such as the blockage of roads by lava flow and surges (or entrained debris), and extensive vehicle and road surface damage by ballistics.

Observations from previous eruptions demonstrate that widespread impacts to road transport from volcanic ash are often substantial, resulting in significant societal impacts. Common impacts from volcanic ash that have been observed and recorded in the past include:

- Skid resistance reduction on ash-covered roads, leading to braking difficulties, increased stopping distances and a rise in accident rates.
- Visual range reduction during both initial ashfall and ash remobilised by wind, vehicles or other human activities, again increasing road accident rates, particularly with an increased chance of multiple vehicle collisions.
- Engine air intake filter contamination, resulting in poor engine performance or engine failure and vehicle breakdowns.

8.2 ROAD NETWORK LEVEL OF SERVICE METRICS

A user-focused metric for road outages that can provide useful information for the economic model has proved difficult to develop. Put simply, from an end-user point of view, the purpose of the roading network is to convey goods and people (services, consumers, and workforce). The ability of the network to do this at 100% is reduced when direct impacts from volcanic hazards mean that routes become unavailable, alternative routes need to be taken, or speeds need to be reduced. Additionally, the ability to convey goods and people may reduce due to congestion on the network, causing a reduction in speed or the use of alternative routes.

When considering the economic impacts of road outages, additional costs are incurred to transport goods and provide services when there is no available route, additional distance is travelled, and/or additional time is required for a journey. Reduced road capacity may also lead to a reduction in the available workforce and potentially the number of consumers.

The RA 3 researchers are currently building a road network model that is able to make basic assumptions about alternative routes. This will allow for additional costs due to greater distances and/or additional time to be modelled. In terms of road outage inputs for this model, the level of service for a section of road, as a proportion of full capacity, has been determined based on the evacuation zones implemented and volcanic hazards affecting the network at the relevant time steps. The level of service metrics and factors considered to assign the values are shown in Table 8.1.

Table 8.1 Road network level of service metrics.

Value	Road level of service
1	Full service – road fully open
0.9	Minor reduction in service possible – earthquake damage/inspections
0.7	Reduced traction and visibility – accumulation of tephra or base surge deposits <25 mm
0.5	Access restricted – evacuation only
0.2	Very limited access – damage and blockage
0.1	No access allowed except critical staff
0	No service – road closed to all

The effects of congestion, accidents and vehicle breakdowns on traffic flow are not considered for the levels of service provided. Although the authors recognise that such impacts are likely to be substantial at times, further work is required to understand the number of residents who will likely remain in different neighbourhoods in order to make estimations of demand and flow. However, it is anticipated that, following closure of the South Western Motorway (SH20), increases in traffic on other motorways and arterial routes will occur. During evacuations, on-ramp signals to motorways will likely operate on peak weekday evening settings, causing additional congestion along arterial routes that lead to motorways but aiding traffic flow along the motorways themselves.

8.3 AUCKLAND ROAD NETWORK

A smoothly operating transport network in Auckland is important for the regional and national economy (AELP-1, 1999). The road network in Auckland is extensive, with multiple State Highways, and many arterial (Figure 8.1) and local routes across the region. Auckland's geography however, poses some interesting constraints on road transport. The Waitemata and Manukau Harbours act as major obstacles, constricting routes through narrow stretches of land on the isthmus and one of four motorway bridges (Figure 8.1) must be crossed in order to enter or leave the city area by motorway. The majority of roads are of the metalled pavement surface type. Auckland's roads service highly populated areas and consequences of any disruption may be widespread.

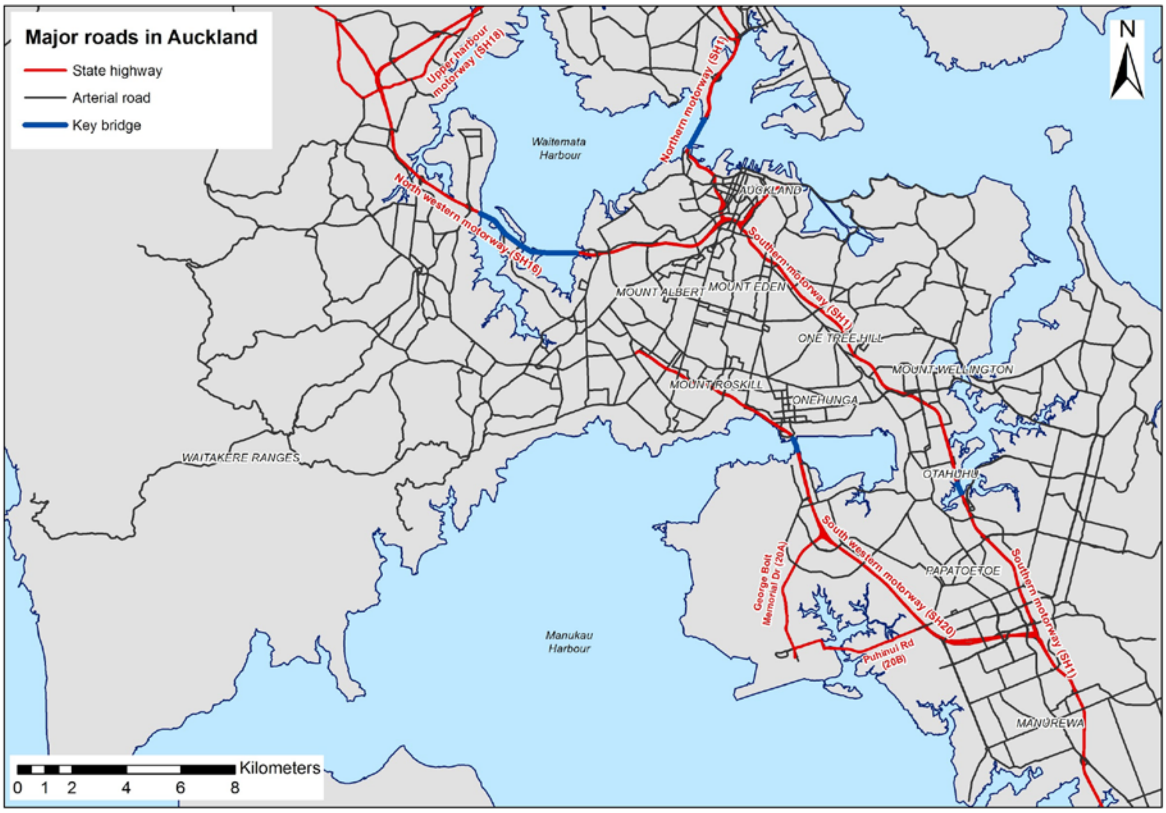


Figure 8.1 State highways (red), arterial routes (dark grey), and key bridges (blue) in the central Auckland area; minor roads are not displayed for clarity.

Currently, 85% of trips in Auckland are made by private car, and around 15,000 extra cars join Auckland's roads every year (Auckland Council, 2013a). The bus network provides the bulk of public transport in Auckland and is geographically the most comprehensive of the transportation assets. It is also by far the most frequently utilised component of the public transportation sector, with 42.8 million bus journeys recorded in 2007 (ARTA, 2009, Tomsen, 2010). Walking mostly takes place within a transport system that must work for a range of road users. However, pedestrians also use routes outside road corridors as part of a continuous network (NZTA, 2009). Due to the complexities involving different routes, walking and cycling are not considered in our modelling at present, although the authors recognise them as important modes of transport.

8.4 Mt Ruaumoko Scenario

8.4.1 Auckland road network impacts

Table 8.2 details physical impacts to the road network resulting from the Mt Ruaumoko scenario, and is followed by maps (Figure 8.2 to Figure 8.9) showing these impacts.

Table 8.2 Auckland road network physical impacts over the course of the Mt Ruaumoko scenario.

Date	Relevant event details	Impact summary	Figure
22 February	VAL increases from 0 to 1	No physical impact	
08 March	08 March PEZ implemented	No physical impact	
11 March	11 March PEZ implemented	No physical impact	
12 March	12 March SEZ implemented	No physical impact	
13 March	Volcanic gases detected. Shallow earthquakes (up to M4.5).	Potential minor damage to some bridges and roadside equipment in areas proximal to earthquake epicentres (inspections may be required). • Potential for minor blockage by landslides from steep slopes onto roads. *Length of road in impacted area ~2,900 km*	8.2
14 March AM	Base surge causes complete destruction 0–4 km from vent and some damage 4–6 km from vent. Shallow earthquakes (up to M4.5).	Road infrastructure destroyed or severely damaged 0–4 km from vent including: South western Motorway (SH20) from New Windsor to Kirkbride Road, including Mangere Harbour Bridge George Bolt Memorial Drive (SH20A) from South western motorway to Kirkbride Road Onehunga Roads Roads in the south of Epsom Roads in Mangere Bridge Roads to north of Mangere. *115 km road destroyed.* *202 km road severely damaged with complete blockage.* Some road infrastructure damaged with major blockages 4–6 km from vent including: • Southern motorway (SH1) from Newmarket to Mt Wellington • Ellerslie-Panmure Highway and South eastern Highway to east of SH1 • Great South Road north of Otahuhu • Greenlane West • Manukau Road and Dominion Road north of Epson *457 km road with some damage and major blockages* Further potential minor damage to some bridges and roadside equipment in areas proximal to earthquake epicentres (inspections may be required). • Potential for minor blockage by landslides from steep slopes onto roads.	8.3

Date	Relevant event details	Impact summary	Figure
14 March PM	Tephra fallout to west. Shallow earthquakes (up to M4.8).	Tephra deposition on some roads including: • Roads in Titirangi and south Waitakere Ranges • Roads in Green Bay area. *163 km road outside of the initial surge area experiences direct tephra deposition.* *Note. Remobilised ash may extend to roads beyond the area mentioned but no substantial impacts are anticipated.* Further potential minor damage to some bridges and roadside equipment in areas proximal to earthquake epicentres (inspections may be required). • Potential for minor blockage by landslides from steep slopes onto roads.	8.4
16 March	11 March PEZ and 12 March SEZ lifted. 16 March PEZ and 16 March SEZ implemented	Following clean-up and any necessary repair or removal of blockages, only minor accumulation of deposits remains on: • Southern motorway (SH1) between Newmarket and Mt Wellington • Ellerslie-Panmure Highway east of SH1. All other roads within initial surge area remain destroyed, damaged or blocked to some degree. Tephra deposition is cleaned up or removed by rainfall beyond the SEZ extent – no further impact. *Note. Any minor damage from previous earthquakes has been repaired with no further impact to the road network at this stage.*	8.5
21 March	Tephra fallout to north west. Base surge.	Physical impact to the roads within 0–6 km from the vent remains similar to 16 March (with some further accumulation of surge and tephra deposits). Tephra deposition also occurs on roads to north west of SEZ including: • Southern Motorway (SH1) from Ellerslie northwards, extending onto the Northern Motorway (SH1) over the Auckland Harbour Bridge • Northern section of South western Motorway (SH20) • North western Motorway (SH16) from Auckland City to Lincoln Road • Roads in central Auckland, Te Atatu Peninsula and Te Atatu South and the south Birkenhead area on the North Shore. *984 km road beyond the initial base surge area experiences tephra accumulation. Thus, a total of 1,758 km of road is impacted at this stage (the largest extent throughout the scenario).*	8.6

Date	Relevant event details	Impact summary	Figure
30 March	Tephra fallout to south east.	Following clean-up, there is no further impact from the previous tephra accumulation beyond the SEZ. Continued clean-up of remobilised tephra, means only minor accumulation of deposits remains on: • Southern motorway (SH1) between Newmarket and Mt Wellington • Ellerslie-Panmure Highway east of SH1 New clean-up activity and any necessary repair or removal of blockages, means only minor accumulation of deposits remains on: • South eastern Highway east of SH1 • Route covering Greenlane East – Greenlane West – Balmoral Road – St Lukes Road. All other roads within initial surge area remain destroyed, damaged or blocked to some degree.	8.7
05 April	Lava flows. 16 March SEZ lifted.	Continued clean-up of remobilised tephra, means only minor accumulation of deposits remains on: • Southern motorway (SH1) between Newmarket and Mt Wellington • Ellerslie-Panmure Highway east of SH1 • South eastern Highway east of SH1 • Route covering Greenlane East – Greenlane West – Balmoral Road – St Lukes Road. New clean-up activity and any necessary repair or removal of blockages, means only minor accumulation of deposits remains on: • Manukau Road extending north from Greenlane West • South western Motorway (SH20) south of Massey Road • Route extending circularly around the east through the initial 4–6 km base surge area from the airport to Newmarket (covering George Bolt Memorial Drive – Kirkbride Road – Massey Road – Mangere Road – Walmsley Road – Saleyards Road – Great South Road) All other roads within initial surge area remain destroyed, damaged or blocked to some degree, although are accessible from this date for clean-up following the lifting of the SEZ.	8.8
01 May	16 March PEZ lifted. Permanent exclusion zone implemented.	Following clean-up, repair of damage and removal of blockages, roads are restored beyond the extent of the severe damage/complete blockage zone caused by the initial surge (0–4 km from the vent). *The previous total road length in this area was 305 km.*	8.9

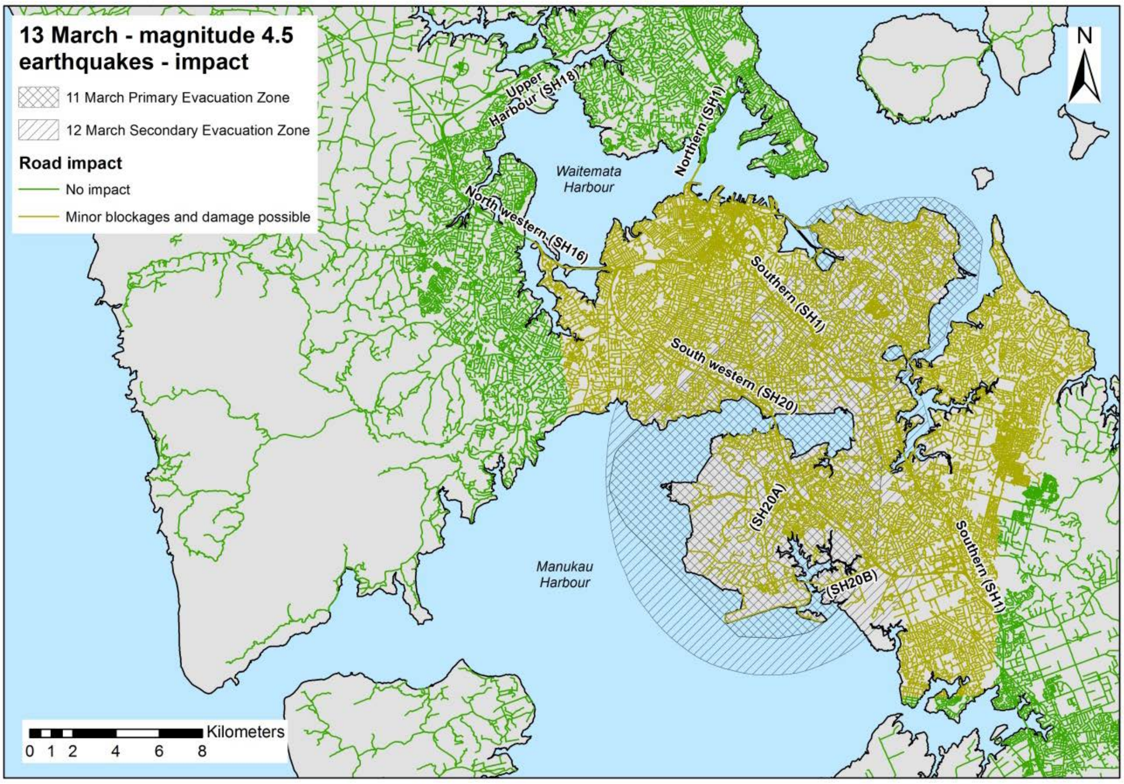


Figure 8.2 Physical impacts for road network on 13 March following M4.5 earthquakes. In light green are roads with no impact, and in mustard green are roads which may have minor blockages or roading damage from earthquakes. The PEZ (cross-hatched) and SEZ (hatched) are indicated.

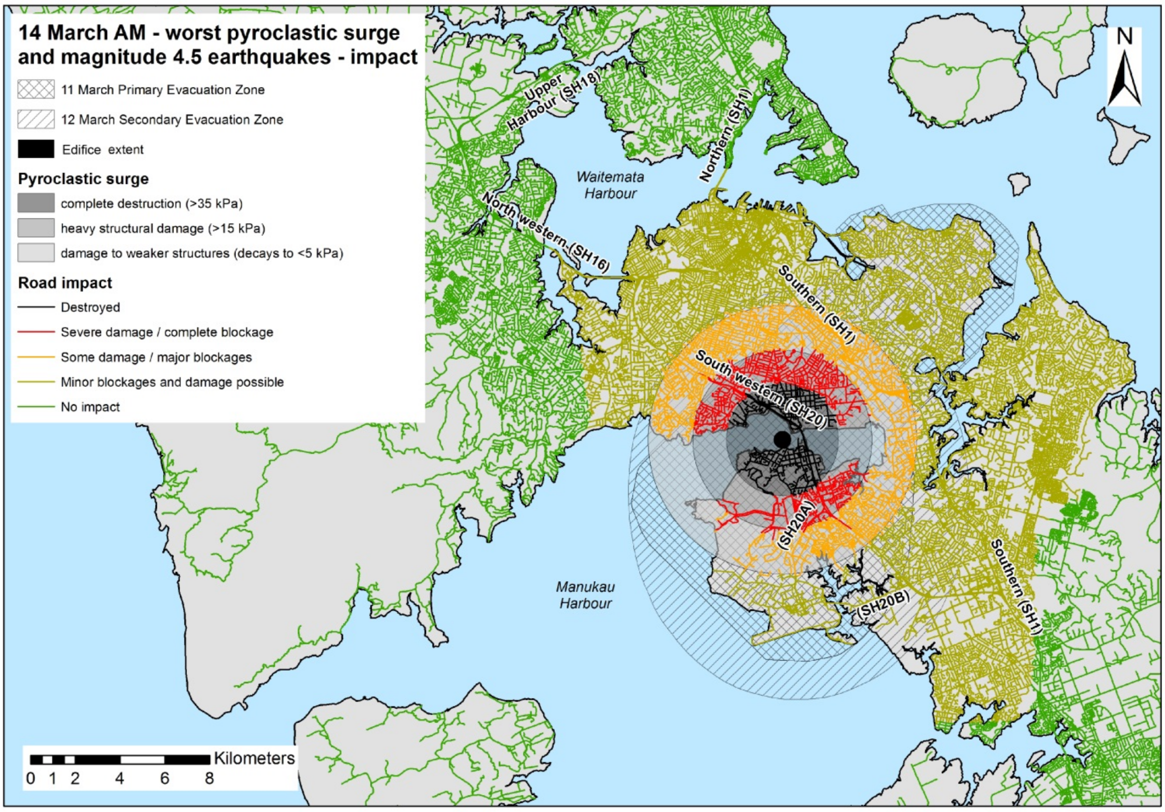


Figure 8.3 Physical impacts for road network on 14 March AM following worst case pyroclastic surge (grey) and M4.5 earthquakes. Destroyed roads are black, severely damaged roads are red, and roads with some damage are orange. In light green are roads with no impact, and in mustard green are roads which may have minor blockages or roading damage from earthquakes. The PEZ (cross-hatched) and SEZ (hatched) are indicated. The edifice is shown in black.

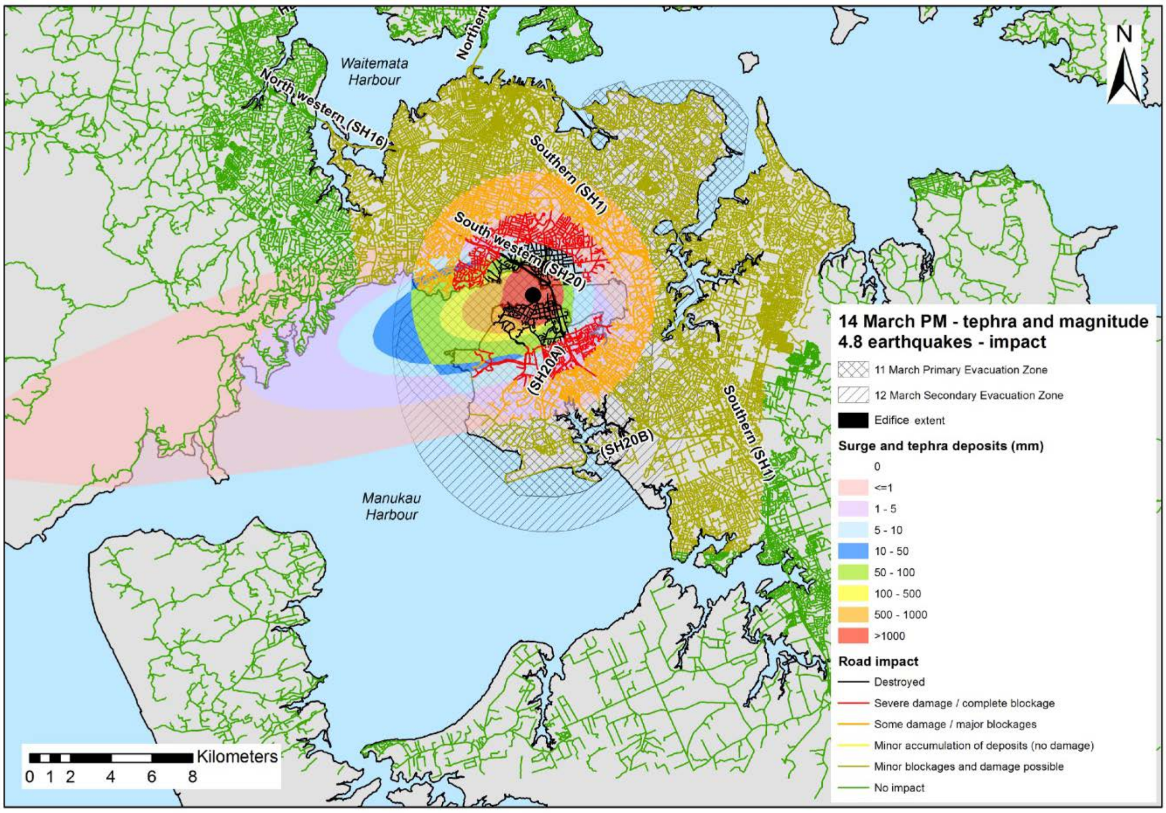


Figure 8.4 Physical impacts for road network on 14 March PM following tephra fall and M4.8 earthquakes with impacts coloured according to severity as in Figure 8.3. The cumulative surge and tephra fall deposit according to thickness shown for reference – see legend. The PEZ (cross-hatched) and SEZ (hatched) are indicated. The edifice is shown in black.

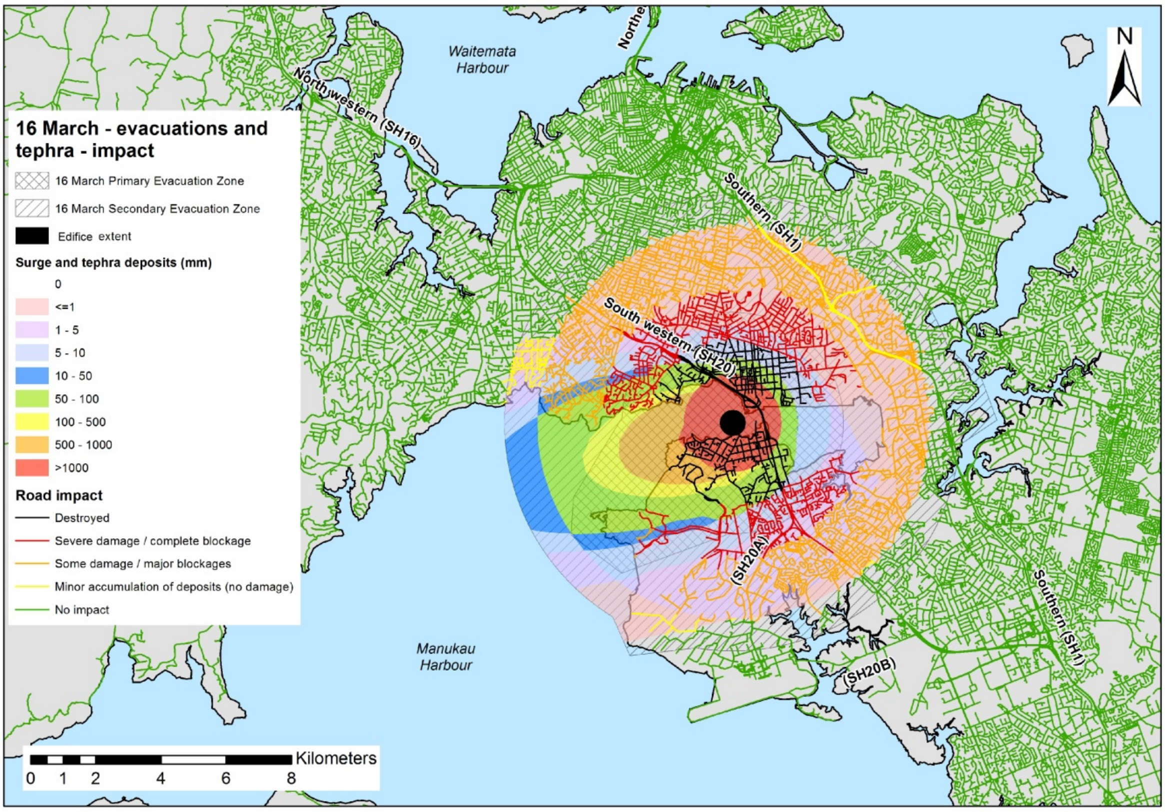


Figure 8.5 Physical impacts for road network on 16 March following clean-up, rainfall and the implementation of new evacuation zones and additional tephra fall. Hazards and impacts are coloured according to severity as in Figure 8.4. The PEZ (cross-hatched) and SEZ (hatched) are indicated.

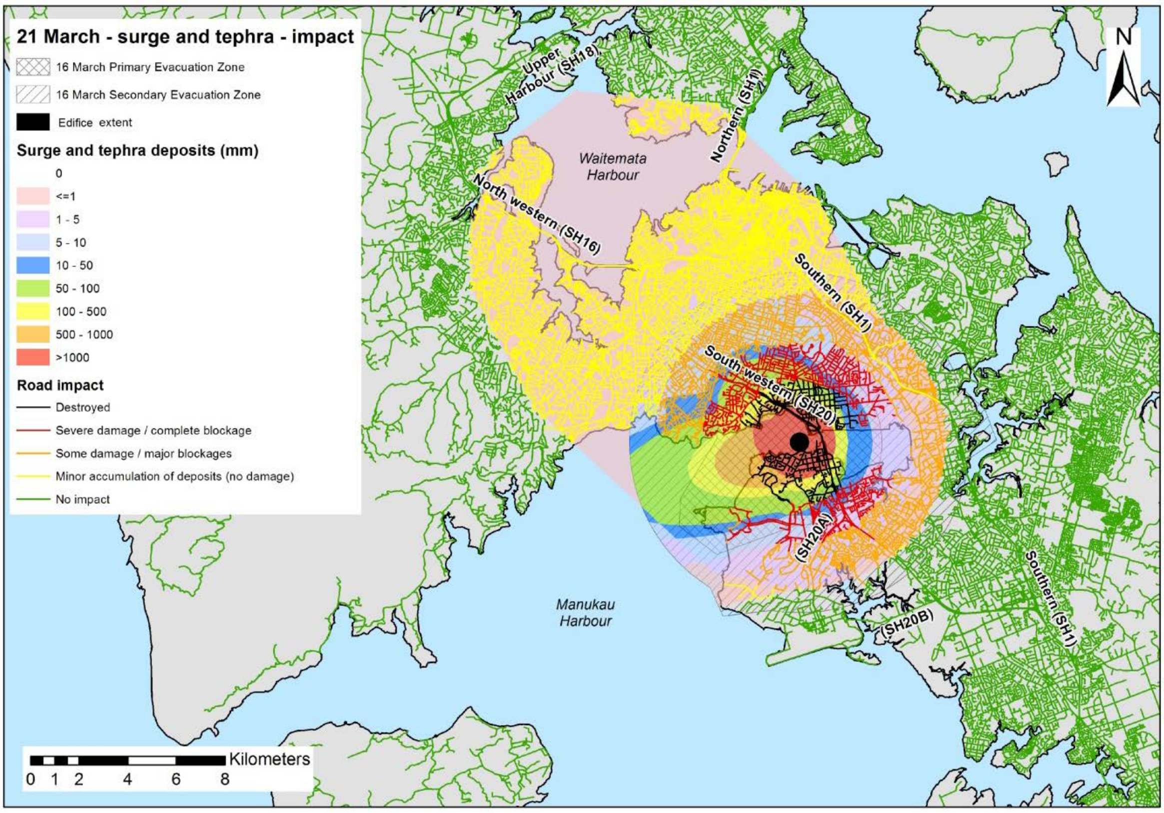


Figure 8.6 Physical impacts for road network on 21 March following average case pyroclastic surge and new tephra fall. Hazards and impacts are coloured according to severity as in Figure 8.4. The PEZ (cross-hatched) and SEZ (hatched) are indicated.

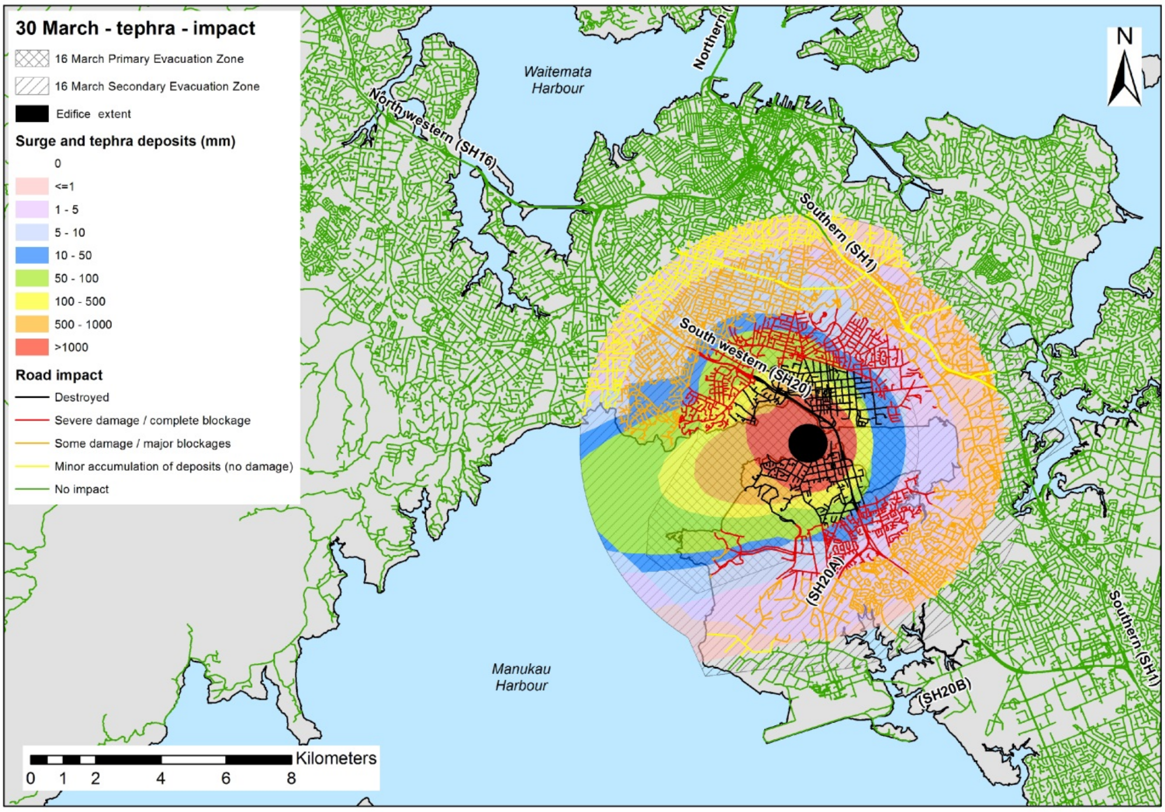


Figure 8.7 Physical impacts for road network on 30 March following clean-up and new tephra fall. Hazards and impacts are coloured according to severity as in Figure 8.4. The PEZ (cross-hatched) and SEZ (hatched) are indicated.

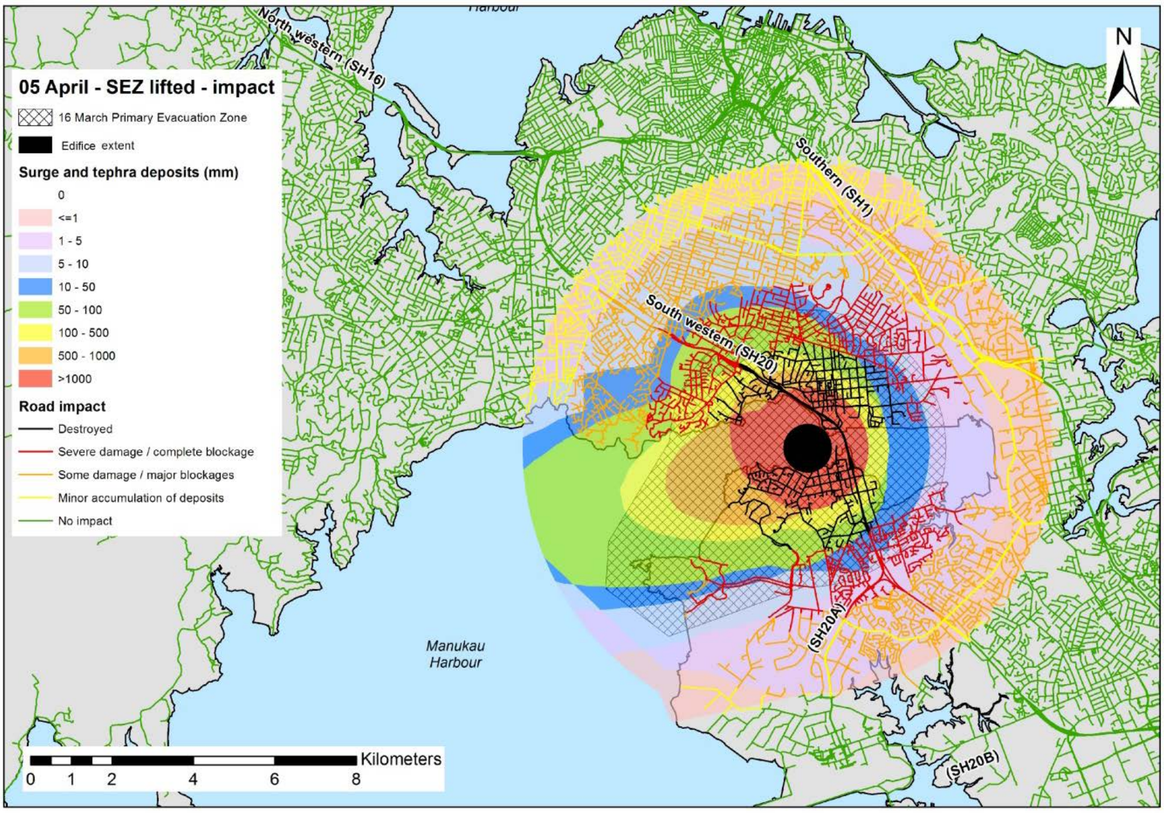


Figure 8.8 Physical impacts for road network on 5 April following further clean-up and the lifting of the SEZ. Hazards and impacts are coloured according to severity as in Figure 8.4. The PEZ (cross-hatched) is indicated.

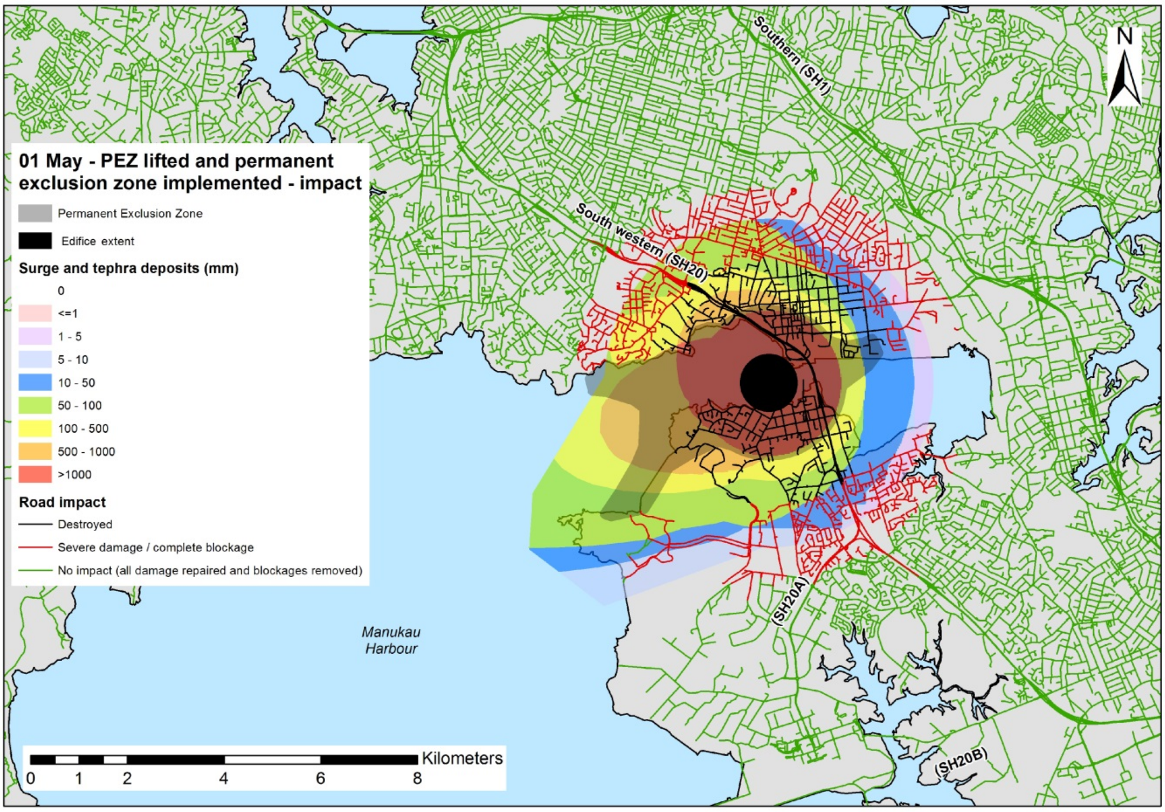


Figure 8.9 Physical impacts for road network on 1 May following further clean-up, lifting of the PEZ and implementation of the permanent exclusion zone (dark grey). Hazards and impacts are coloured according to severity as in Figure 8.4.

8.4.2 Auckland road level of service

Table 8.3 details the level of service of the road network over the course of the Mt Ruaumoko scenario, and is followed by maps (Figure 8.10 to Figure 8.20) showing these level of services.

Table 8.3 Level of service for Auckland's road network over the course of the Mt Ruaumoko scenario.

Date	Relevant event details	Level of service summary	Figure
22 February	VAL increases from 0 to 1	Full service. *Note. Some self-evacuation and preparation for evacuation may lead to increase in traffic congestion (due to increased vehicle journeys) but the implications are considered minor on overall service.*	N/A
08 March	08 March PEZ implemented	Evacuations occur from the PEZ. Access becomes restricted for most entering the zone. However, some people such as those assisting with evacuation, critical lifeline infrastructure staff, hospital staff, emergency workers, and those assisting with distribution of critical resources, can still enter the area. All road transport between north and south Auckland is disrupted including: • South western Motorway (SH20) between New Windsor and Mangere including Manukau Harbour Crossing • Great South Road north of Otahuhu • Southern Motorway (SH1) between Mt Wellington and Ellerslie • Ellerslie-Panmure Highway including Panmure Bridge • South eastern Highway including Waipuna Bridge • Tamaki Drive east of Hobson Bay. *784 km road affected by 08 March PEZ.* *Notes. As the eruption has not started and no volcanic hazards are occurring, all other infrastructure remains fully operational. Traffic signals, Variable Message Signs (VMS) and Police are used to optimise evacuation flow.* *Re-configuration of some motorway lanes may occur to increase capacity out of the PEZ, particularly on the Southern Motorway travelling south from the PEZ.*	8.10
11 March	11 March PEZ implemented	No access to roads affected by the initial PEZ on 08 March except emergency workers and lifeline staff maintaining critical infrastructure services. Evacuations occur from a new PEZ section in the Mangere area. Access becomes restricted for most entering this zone. However, some people such as those assisting with evacuation, critical lifeline	8.11

Date	Relevant event details	Level of service summary	Figure
		infrastructure staff, hospital staff, emergency workers, and those assisting with distribution of critical resources, can still enter the area. Roads affected include: • South western Motorway (SH20) south to Puhinui Road (SH20B) • George Bolt Memorial Drive (SH20A) and Auckland Airport • Puhinui Road (SH20B). *1019 km road is now affected by the new wider (11 March) PEZ.* *Traffic signals, VMS, Police, and lane re-configuration are used to optimise evacuation flow where necessary.*	
12 March	12 March SEZ implemented	No service (roads closed) in area covered by 11 March PEZ. Evacuations occur from a SEZ, based on the probable vent location and extending up to 2 km from the 11 March PEZ in places. Access becomes restricted for most entering this zone. However, some people such as those assisting with evacuation, critical lifeline infrastructure staff, hospital staff, emergency workers, and those assisting with distribution of critical resources, can still enter the area. Roads affected include: • Southern Motorway (SH1) through Otahuhu • South western Motorway (SH20) through New Windsor and west of Manukau *1415 km road is now affected by evacuation zones (11 March PEZ and 12 March SEZ)* *Although no critical lifelines staff are allowed in the PEZ, it is expected that other infrastructure remains operational. VMS and traffic signals remain functional to optimise evacuation flow from the SEZ.*	8.12
13 March	Volcanic gases detected. Shallow earthquakes (up to M4.5).	No service (roads closed) in area covered by 11 March PEZ and 12 March SEZ. Minor reduction in service is possible on roads impacted by earthquakes. This may include roads in: • Auckland City • Northern Motorway (SH1) between city and Auckland Harbour Bridge • North western Motorway (SH16) between city and Te Atatu Peninsula • South Auckland ~5 km from PEZ and SEZ.	8.13
14 March AM	Base surge causes complete destruction 0–4 km from vent and some damage 4–6 km	Level of service in morning remains the same as 13 March due to the same evacuation zones and continuing earthquakes.	N/A

Date	Relevant event details	Level of service summary	Figure
	from vent. Shallow earthquakes (up to M4.8).	*Damage to parts of the network occurs due to base surge but closures are already in effect.* *Note. Impact on electricity transmission and distribution may affect road level of service for the entire Auckland region, particularly due to potential traffic signal and VMS failure, and fuel station pump failure. However, this is not depicted on the maps.*	
14 March PM	Tephra fallout to west.	Tephra in afternoon causes reduced service (due to reduced traction and visibility affecting driving) on some roads including: • Roads in Titirangi and south Waitakere Ranges • Roads in Green Bay area.	8.14
16 March	11 March PEZ and 12 March SEZ lifted. 16 March PEZ and 16 March SEZ implemented	Road service restored on roads beyond new 16 March PEZ and SEZ extents including: • Roads in Auckland City • Northern Motorway (SH1) between city and Auckland Harbour Bridge • Roads in East Auckland including Panmure and Waipuna Bridges • Southern Motorway (SH1) north to Otahuhu • Puhinui Road (SH20B) to Auckland Airport • Roads to west affected by previous tephra fall. Southern (SH1) Motorway and Ellerslie-Panmure Highway to east are reopened through PEZ and SEZ during daytime to restore road links between north and south (with hazard thresholds established for immediate reclosure): • 50 km/h advisory speed limit is implemented • Regular road sweeping occurs on this road to keep tephra deposits to a minimum. However, reduced traction and visibility is expected from remobilised ash • Exit ramps from SH1 within evacuation zone are blocked (other than Ellerslie-Panmure Highway). No service on all other roads within PEZ and SEZ.	8.15
21 March	Tephra fallout to north west. Base surge.	No service (roads closed) through PEZ and SEZ including SH1 and Ellerslie-Panmure Highway due to threat from surge and tephra fall. Tephra deposition causes reduced service (due to reduced traction and visibility) on roads to north west of SEZ including: • Southern Motorway (SH1) from Ellerslie northwards, extending onto the Northern Motorway (SH1) over the Auckland Harbour Bridge	8.16

Date	Relevant event details	Level of service summary	Figure
		• Northern section of South western Motorway (SH20) • North western Motorway (SH16) from Auckland City to Lincoln Road • Roads in central Auckland, Te Atatu Peninsula and Te Atatu South and the south Birkenhead area on the North Shore.	
22 March	Tephra	Level of service remains the same on roads to north west affected by 21 March tephra fall (ash remobilisation). Road sweeping recommences on SH1 and Ellerslie-Panmure Highway to re-established north-south road services (with same restrictions as 16 March). Critical lifeline staff only are permitted access within the SEZ (up to the extent of the outer initial surge deposit) to attempt infrastructure repairs. No service elsewhere within the PEZ and SEZ.	8.17
30 March	Tephra fallout to south east.	Full service is restored to roads beyond SEZ that were affected by 21 March tephra fall. Service within PEZ and SEZ remains the same as 22 March except on two additional critical links which are reopened through the zones during daytime (with hazard thresholds established for immediate reclosure). In addition to SH1 and the Ellerslie-Panmure Highway, these roads are: • South eastern Highway from SH1 to Waipuna Bridge • An east-west route covering Greenlane East-Greenlane West – Balmoral Road – St Lukes Road • The following restrictions remain in place on all roads through the PEZ and SEZ: • 50 km/h advisory speed limit is implemented • Regular road sweeping occurs on roads to keep tephra deposits to a minimum. However, reduced traction and visibility is expected from remobilised ash • Exit ramps and intersections within evacuation zone are blocked.	8.18
05 April	Lava flows. 16 March SEZ lifted.	In addition to the critical routes re-established on 30 March, others have been restored (with same restrictions and reduced service due to traction and visibility issues): • Manukau Road extending north from Greenlane West • South western Motorway (SH20) south of Massey Road	8.19

Date	Relevant event details	Level of service summary	Figure
		• Route extending circularly around the east through the initial 4–6 km base surge area from the airport to Newmarket (covering George Bolt Memorial Drive – Kirkbride Road – Massey Road – Mangere Road – Walmsley Road – Saleyards Road – Great South Road). Only reduced service due to traction and visibility issues remains on some roads beyond the outer initial surge deposit. Very limited access occurs on roads affected by the initial surge deposit up to the extent of the PEZ. No service (roads closed) within PEZ.	
01 May	16 March PEZ lifted. Permanent exclusion zone implemented.	Full service is restored to all roads beyond 4 km from the vent. Very limited access occurs 2–4 km from the vent. No service (roads closed indefinitely) 0–2 km from the vent including the South western Motorway (SH20) section and Manukau Harbour Crossing which are permanently destroyed/buried.	8.20

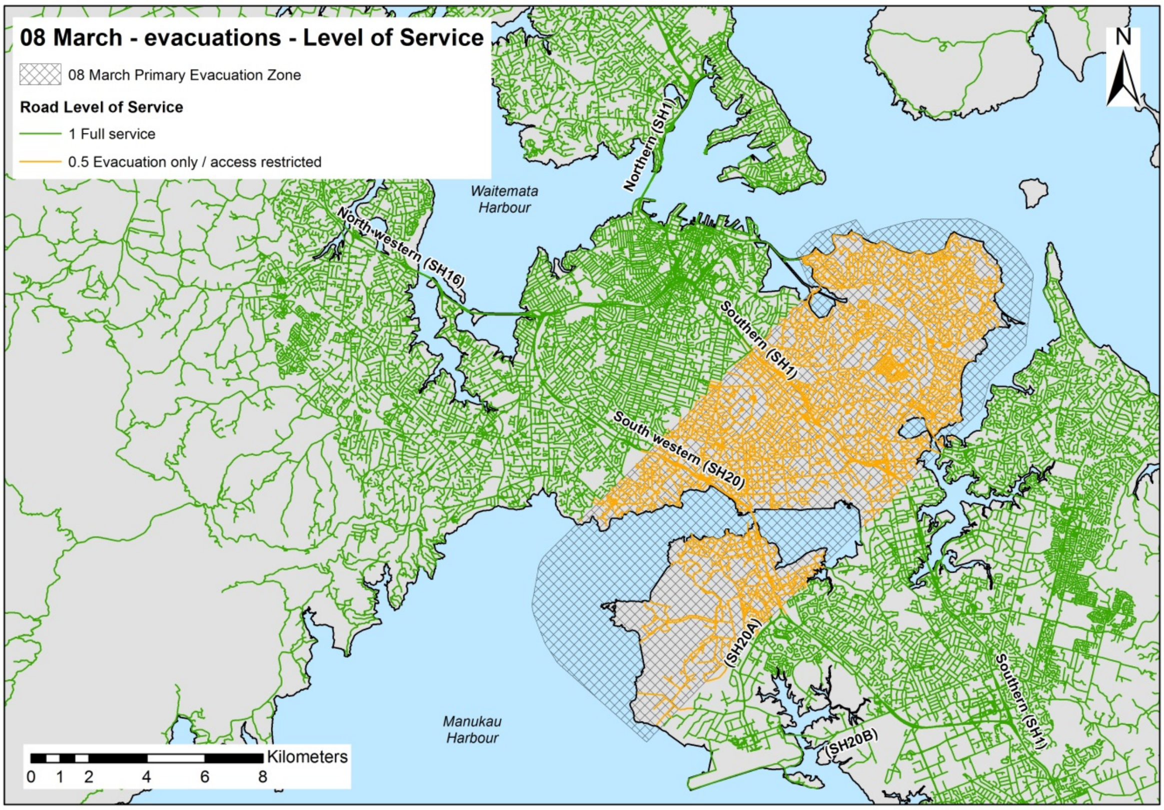


Figure 8.10 Road network level of service on 8 March following implementation of the PEZ (cross-hatched). Full service roads are in green and roads which can only be used for evacuation purposes are in orange.

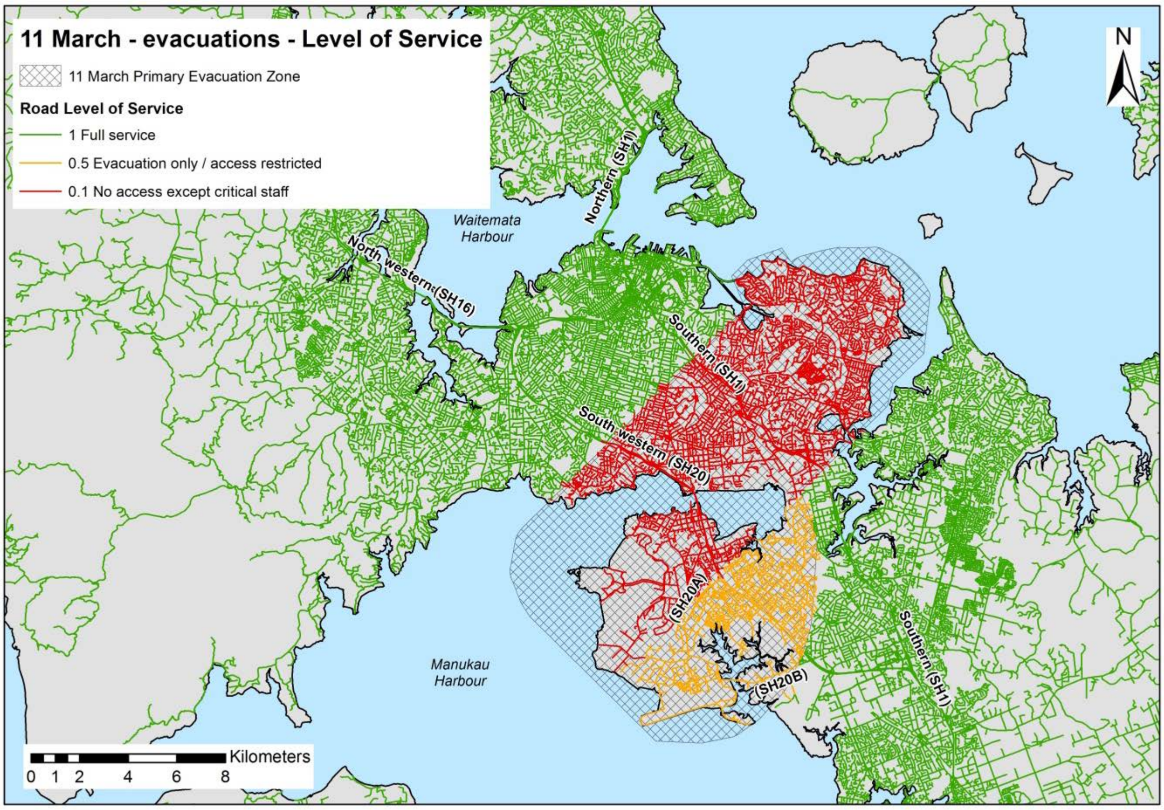


Figure 8.11 Road network level of service on 11 March following implementation of a new PEZ (cross-hatched). Full service roads are in green, roads which can only be used for evacuation purposes are in orange, and roads which can only be used by critical staff are in red.

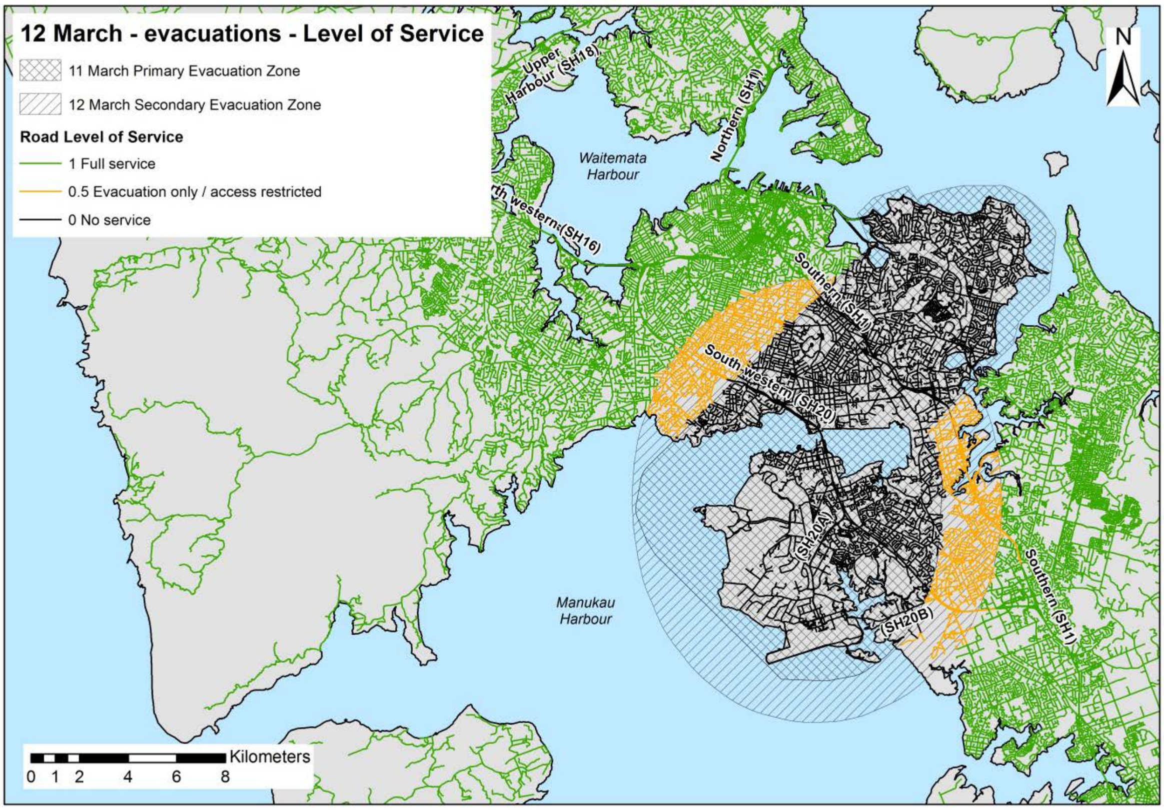


Figure 8.12 Road network level of service on 12 March following implementation of the SEZ (hatched); the PEZ is also indicated (cross-hatched). Full service roads are in green, roads which can only be used for evacuation purposes are in orange, and roads with no service are in black.

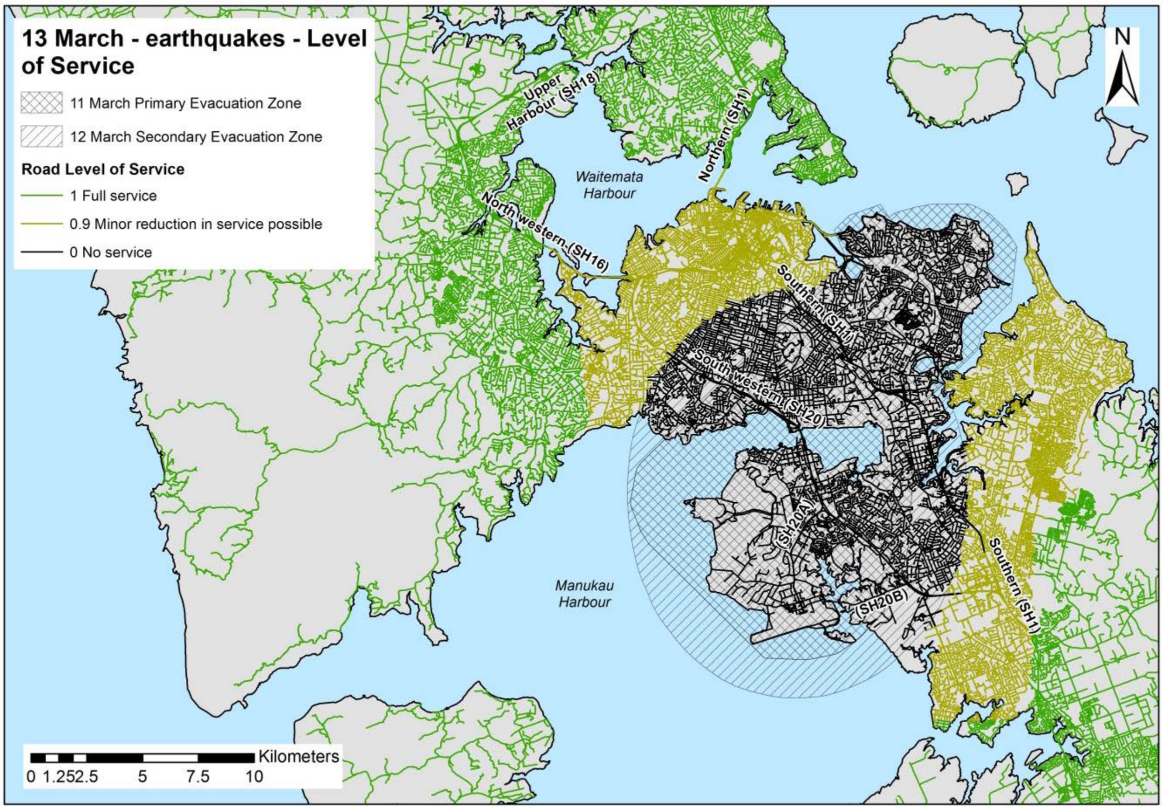


Figure 8.13 Road network level of service on 13 March following M4.5 earthquakes with the PEZ (cross-hatched) and SEZ (hatched) indicated. Full service roads are in green, roads with a minor service disruption are in mustard green, and roads with no service are in black.

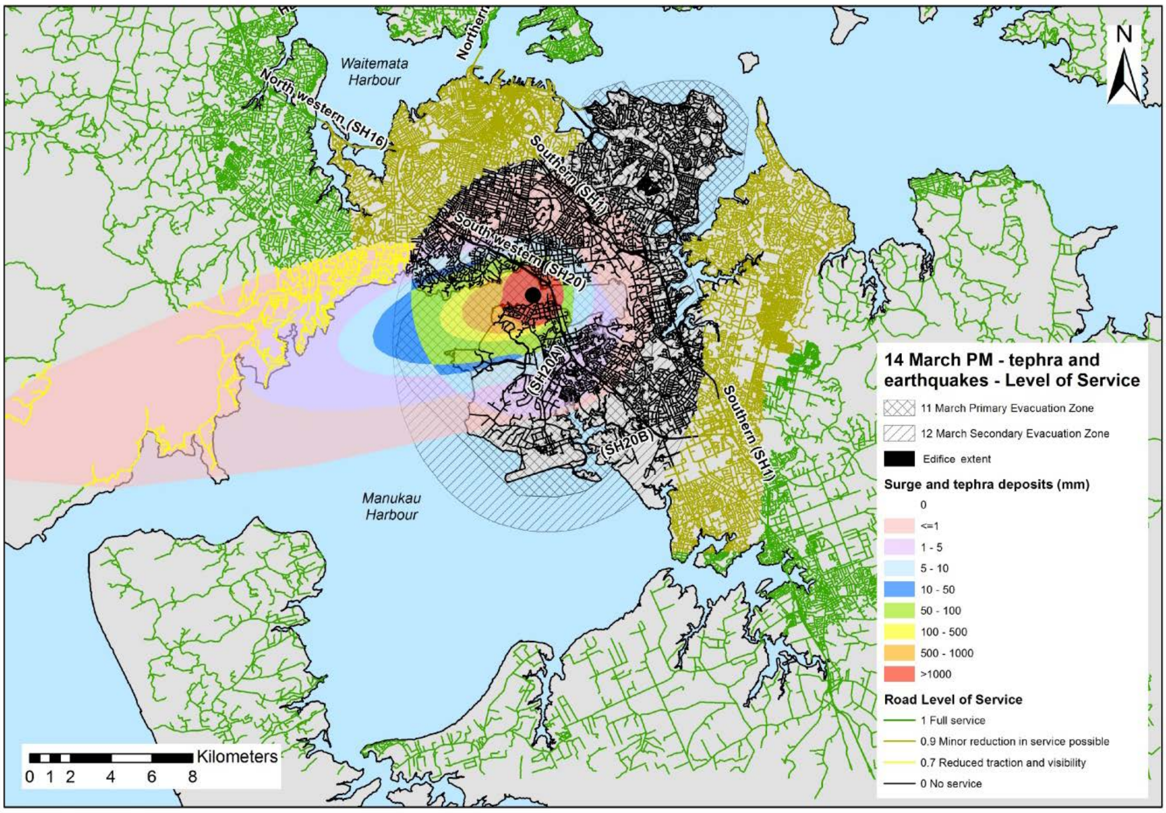


Figure 8.14 Road network level of service on 14 March PM following M4.8 earthquakes and tephra fall (see legend for deposit thickness). The PEZ (cross-hatched) and SEZ (hatched) are indicated. Full service roads are in green, roads with a minor service disruption are in mustard green, roads with reduced traction and visibility are in yellow, and roads with no service are in black. The edifice is shown in black.

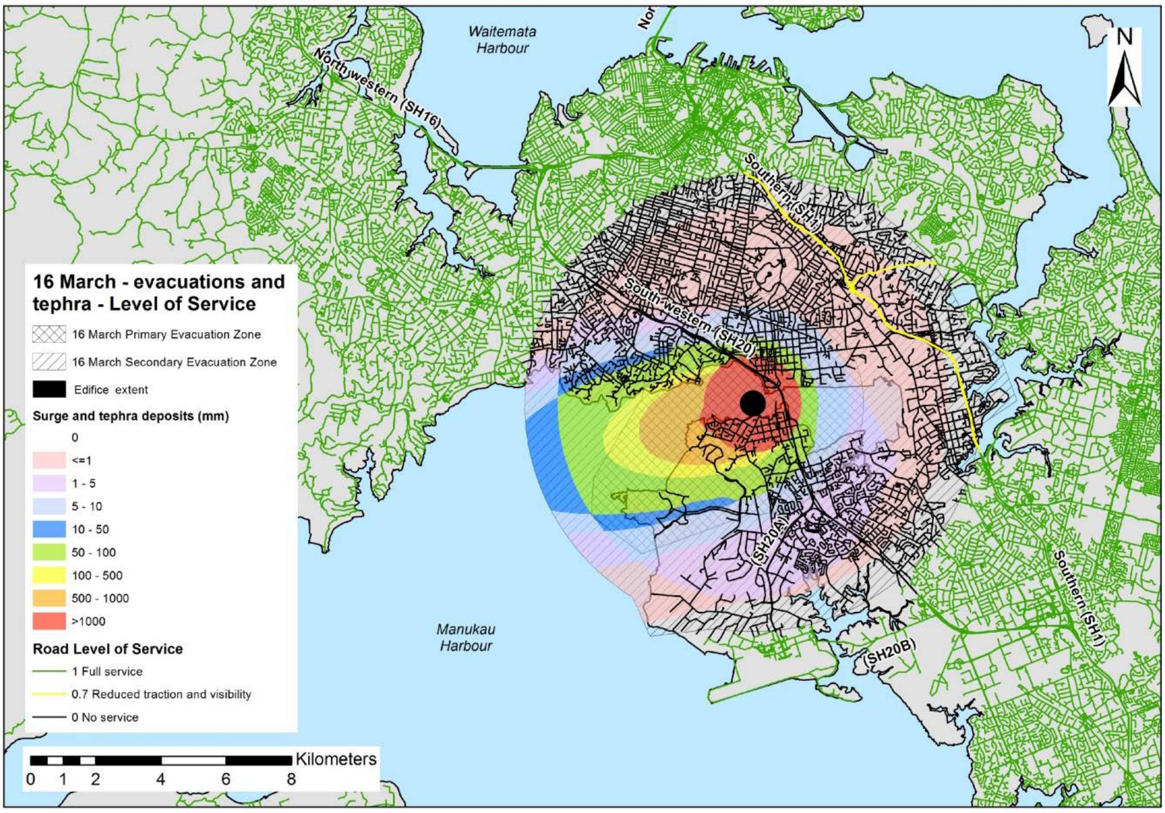


Figure 8.15 Road network level of service on 16 March following clean-up and implementation of new evacuation zones; the PEZ (cross-hatched) and SEZ (hatched) are indicated. Hazards and level of service are coloured according to severity as in Figure 8.14.

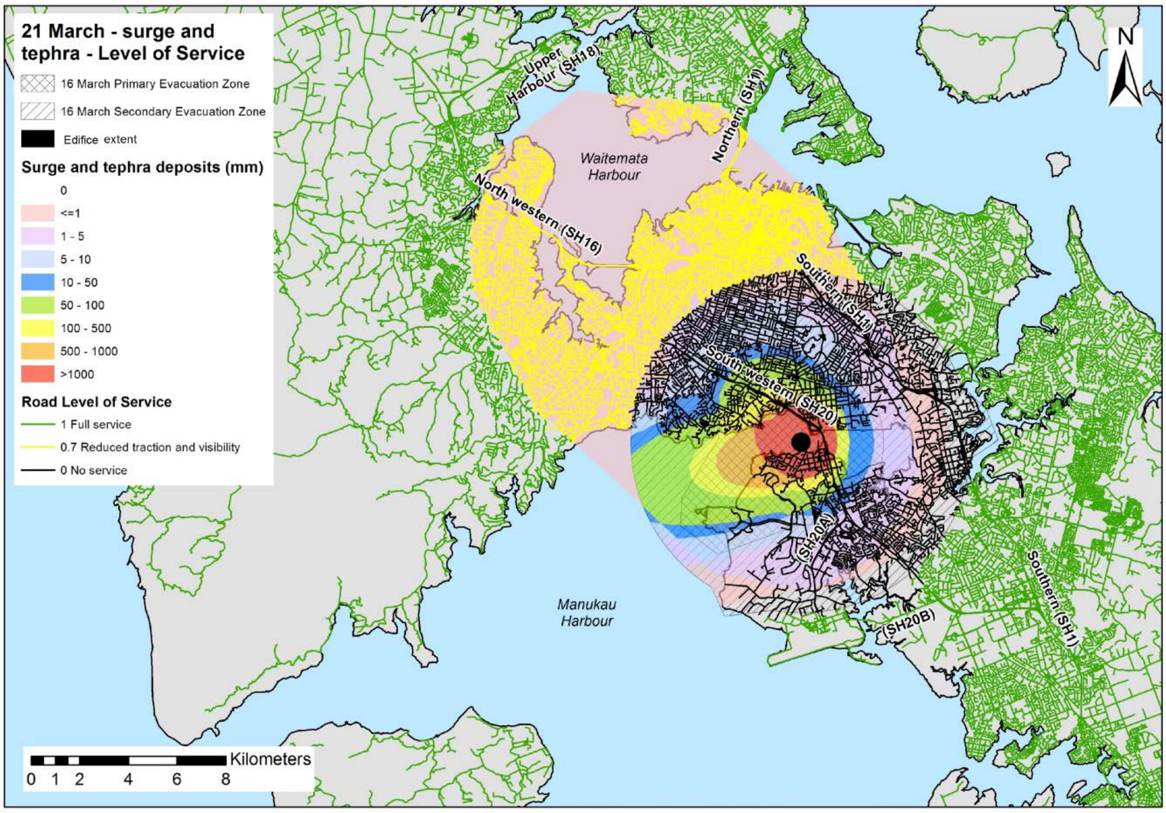


Figure 8.16 Road network level of service on 21 March following average-case surge and new tephra fall; the PEZ (cross-hatched) and SEZ (hatched) are indicated. Hazards and level of service are coloured according to severity as in Figure 8.14.

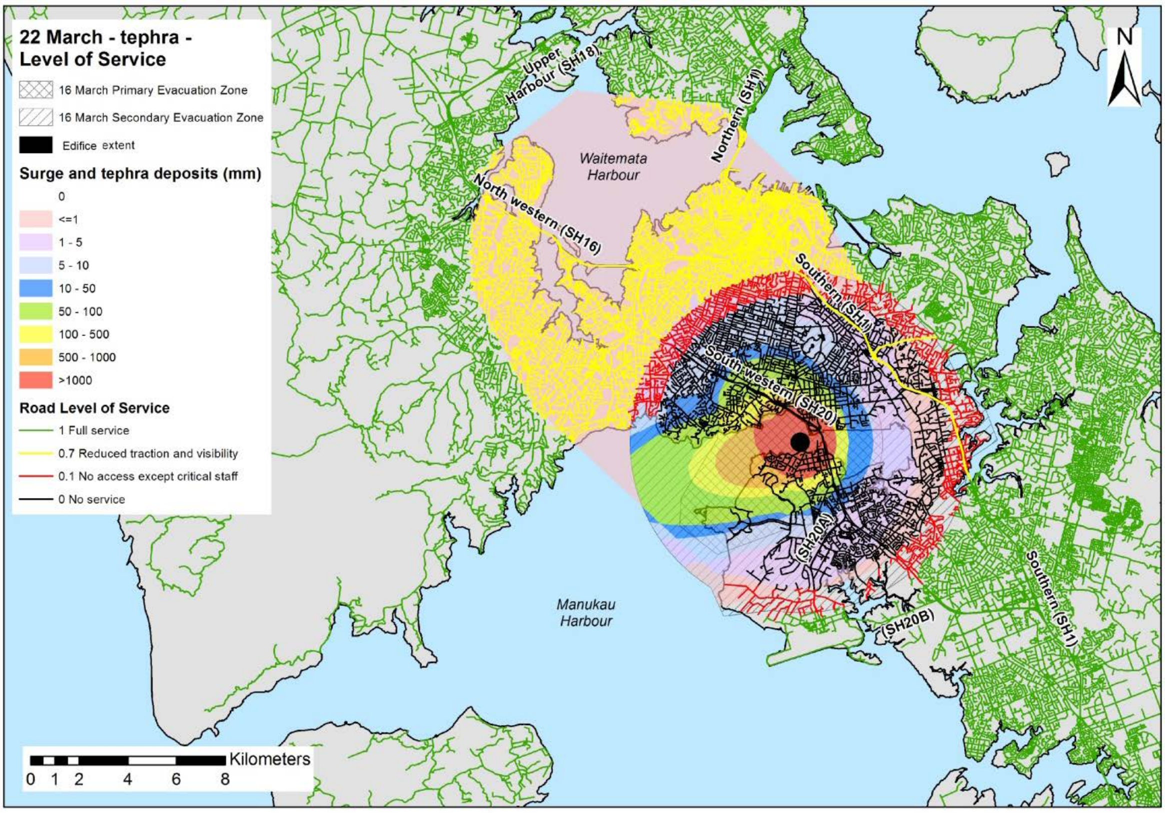


Figure 8.17 Road network level of service on 22 March following clean-up. The PEZ (cross-hatched) and SEZ (hatched) are indicated. Full service roads are in green, roads with reduced traction and visibility are in yellow, roads which can only be used by critical staff are in red and roads with no service are in black. The uncleaned deposit thickness is shown (see legend) and the edifice is in black.

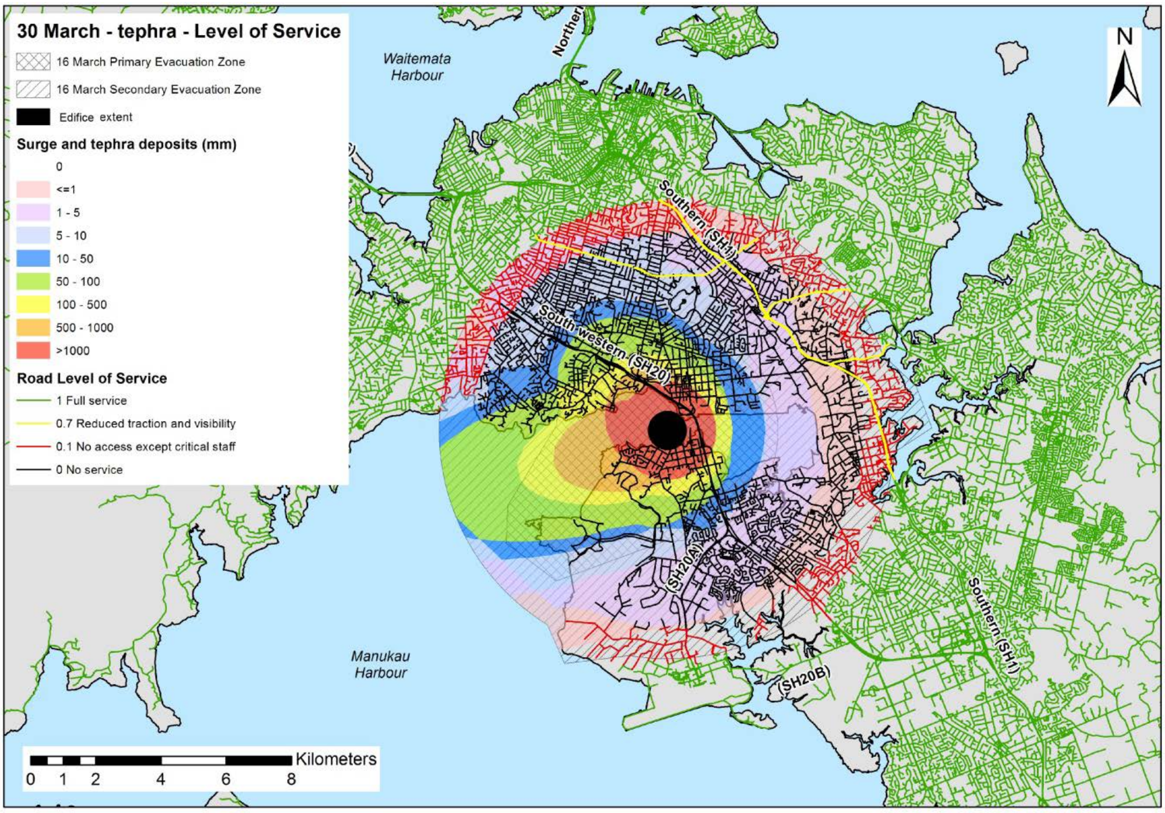


Figure 8.18 Road network level of service on 30 March following further clean-up; the PEZ (cross-hatched) and SEZ (hatched) are indicated. Hazards and level of service are coloured according to severity as in Figure 8.17.

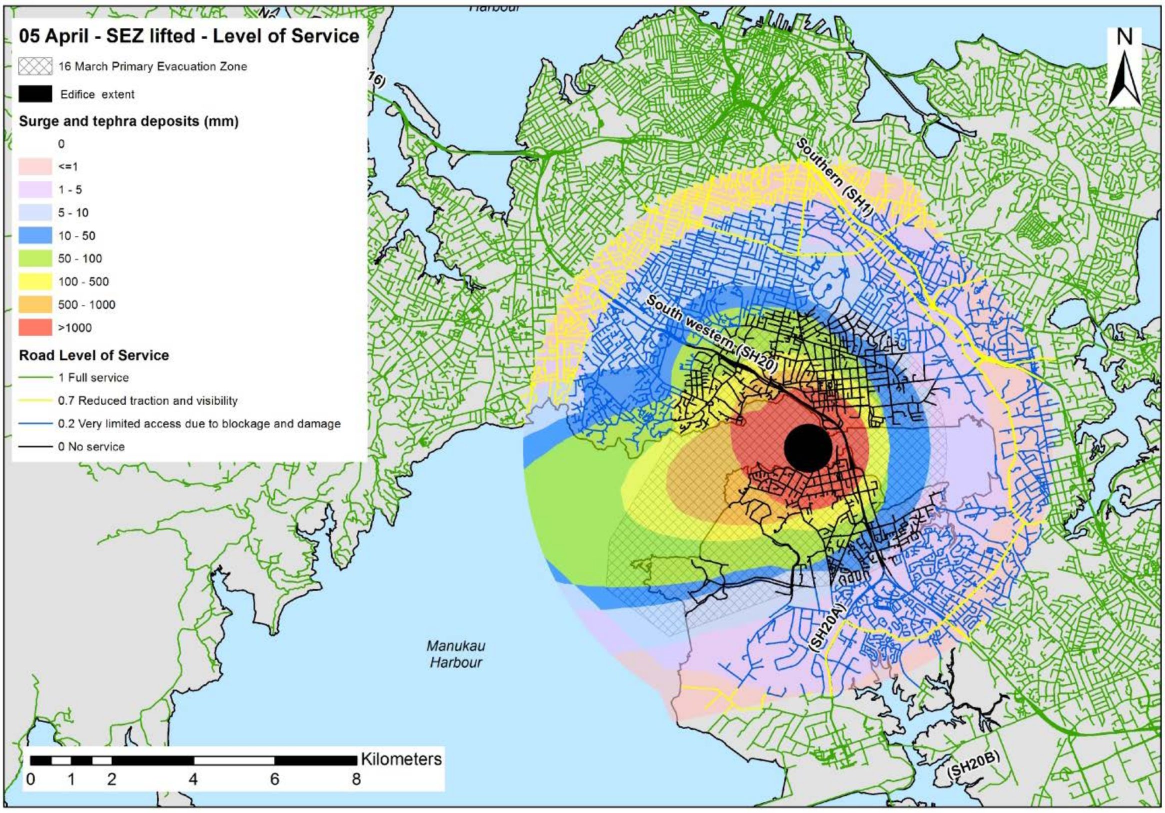


Figure 8.19 Road network level of service on 5 April following further clean-up and lifting of the SEZ; the PEZ (cross-hatched) is indicated. Full service roads are in green, roads with reduced traction and visibility are in yellow, roads with very limited access due to blockage and damage are in blue and roads with no service are in black. The uncleaned deposit thickness is shown (see legend) and the edifice is in black.

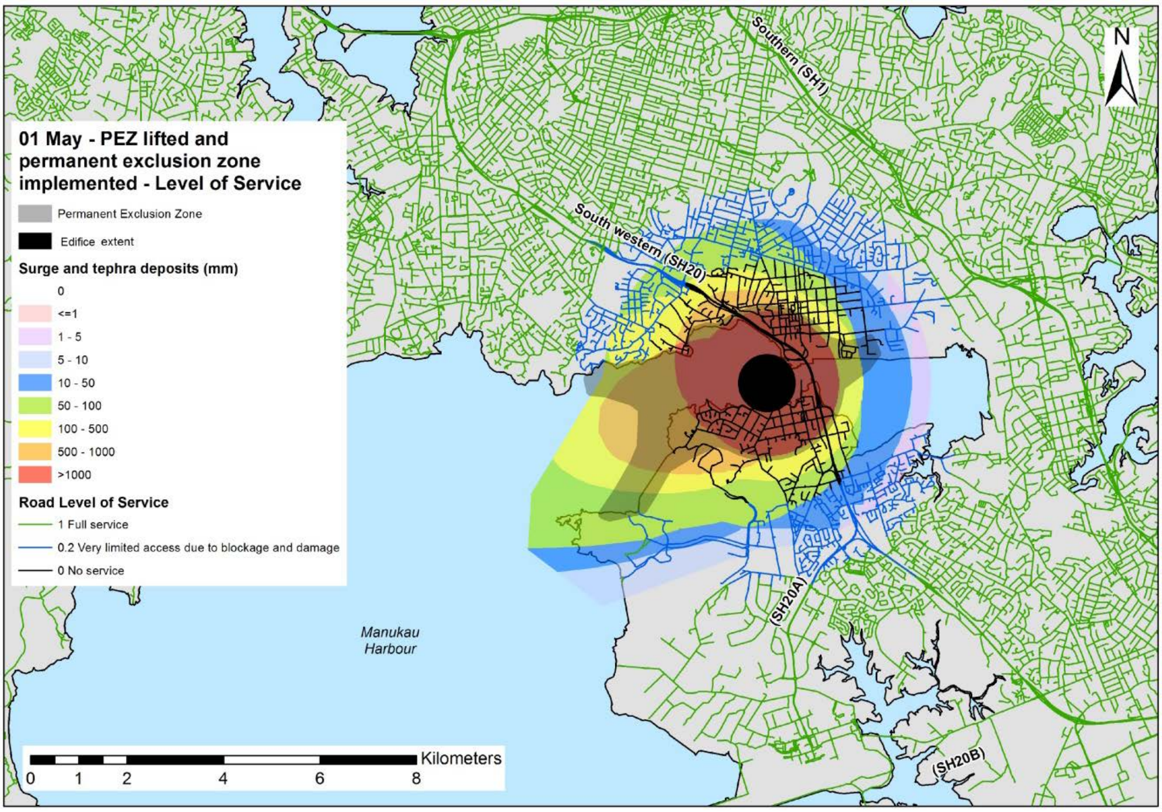


Figure 8.20 Road network level of service on 1 May following further clean-up, lifting of the PEZ and implementation of the permanent exclusion zone (dark grey). Hazards and level of service are coloured according to severity as in Figure 8.19.

8.5 LIKELY INTERDEPENDENCIES

Changes in road demand may result from impacts on other transportation infrastructure. For example, when rail services cease to operate, some passengers may revert to road transport and the diversion of flights from Auckland Airport elsewhere will likely increase demand on roads surrounding these alternative airports, perhaps also on routes leading to the central Auckland region.

Failure or disruption of electricity supply is arguably the most important infrastructure interdependency for road transport. Traffic signal and Variable Message Sign (VMS) failure can occur, with Police support required at major intersections and traffic congestion expected as a result. David Murphy from the Auckland Transport Operations Centre noted that there were difficulties finding enough generators for the traffic signals at ~150 intersections that were impacted during the 2014 Penrose electricity substation failure. Far more intersections are impacted during the ERI AVF scenario so potential knock-on effects on overall traffic flow are substantial.

Fuel supply is recognised as a particularly important interdependency for road transportation. The disruption of north-south road connections will disrupt supply to fuel stations by tanker. Large changes in demand are also anticipated in different areas, whether it be due to evacuations or relocation of residents from impacted areas. Additionally, electricity failure will cause disruption of pumping from some fuel stations.

Increased demand for water for road cleaning and water restrictions within the same time frame (due to eruption impacts on water supply infrastructure) during the scenario may affect the ability to clean roads, particularly following the tephra falls on 14 March and 21 March. Therefore, physical impacts on roads and the reduced level of service that they provide could be extended beyond the times shown.

9.0 RAIL

9.1 VOLCANIC IMPACTS TO RAIL NETWORKS

There have been few recorded volcanic impacts to rail during historic eruptions, likely in part due to the less extensive (or absence of) rail networks compared to roads in volcanically active areas. Many impacts have resulted from proximal hazards, particularly lahars and lava flows, such as the Tangiwai 1953 Disaster (Ruapehu, 1945) and blockage of the Circumvesuvian Railway (Vesuvius 1906 and 1944) (Blong, 1984). Other impacts include track displacement by ground deformation, visibility reduction due to airborne ash and engine damage.

Given the types of hazards present in the AVF scenario, the impacts of ash on signalling and potential train-to-track communication disruption for electric rail is of particular interest. Following the 2011 Kirishima volcanic eruption in Japan, trace quantities of both wet and dry ash led to the mechanical failure of switches due to loss of electrical contact between trains and track, stopping services on the network (Magill et al., 2013).

9.2 RAIL LEVEL OF SERVICE METRICS

There are two key pieces of infrastructure that form the majority of the rail network: stations and lines. Note that for the purpose of this study, lines cover both rail tracks and overhead lines of the rail network. Stations and lines may be impacted by volcanic hazards in different ways and the restoration of services for each also varies. Therefore, separate outage metrics for each have been developed (although are displayed together on the same maps).

A separate metric has also been used for freight transportation. This is because the freight network uses different aspects of the rail infrastructure to people/commuter transportation. For example, freight transportation uses diesel engines rather than the electric traction infrastructure, and freight transportation does not use all stations.

From an end-user point of view, the key purpose of the rail network is very similar to that of the roading network, that is, to convey goods (freight) and people (we have assumed largely workforce commuters). During this scenario, the ability of the rail infrastructure to convey people and freight is reduced by direct physical impacts to the rail line and stations, resulting in a reduction in speed (taken to mean fewer trains and therefore reduced capacity on the line). Evacuation zones may restrict the direction of transportation and the availability of stations or cause complete closure of both lines and stations. These factors have been taken into account when developing the level of service metrics.

The tables describing levels of service impacts note possible timetabling impacts on lines that are otherwise not physically affected by the scenario. Consideration was given to showing these lines as subject to a reduced level of service, due to the expectation that there would be fewer trains operating. However, the extent of this disruption is difficult to quantify and a specific level of service has not been used to depict this impact. Rather, reduced timetabling is noted in the tables where it is expected to apply.

The metrics for levels of service for stations and lines are shown in Table 9.1 and Table 9.2 respectively. For these metrics, the numbers are to be taken as the proportion of full service available. For example, a rail line value of 0.7 means that the section of line is operating at 70% typical capacity, that is, it will be able to convey 70% of the people that it would normally convey.

Table 9.1 Rail station level of service metrics.

Rail Station Metric	Level of Service
1	Full service – station open
0.5	Partial service – entry to station only/no exit from stopping trains
0	No service – station closed

Table 9.2 Rail line level of service metrics.

Rail Line Metric	Level of Service
1	Full service – line open
0.7	No stopping service due to evacuation zone
0.5	Evacuation service only. Airborne ash with 40 km/h limit
0.3	Rolling outages due to earthquakes/ash/inspections
0	No service – line closed

The metrics for level of service for freight transport are explained in Table 9.3. These are descriptive rather than numeric, as we have not been able to obtain sufficient information to set a value on reduction in service.

Table 9.3 Freight transportation level of service metrics.

Freight transportation metric	Level of service
Full service	Freight transportation via the rail line is operating at normal capacity
Reduced service	Freight transportation via rail can occur, but at lower overall volumes
No service	No freight transportation via rail is able to occur

9.3 AUCKLAND RAIL NETWORK

Auckland's rail network is managed as four lines (Figure 9.1). The Southern and Western Lines together make up part of the North Island Main Trunk line, a single north-south line traversing the North Island. The Eastern Line provides a connection around the east of the CBD. The Onehunga Line connects the CBD with Port of Onehunga. The Southdown branch and Westfield sidings (Figure 9.2) link to the Southern Line north of Westfield Station.

In many instances the line consists of two or three tracks, but their close proximity means that if one is damaged the others are likely to be too (AELP-2, 2014). Over the past five years, the use of Auckland's trains has more than doubled, rising to over 7.5 million passenger journeys per annum (AT, 2013). This number is forecast to continue to grow strongly and the recent completion of electrification of much of the network puts passenger rail at high dependence on the electricity network.

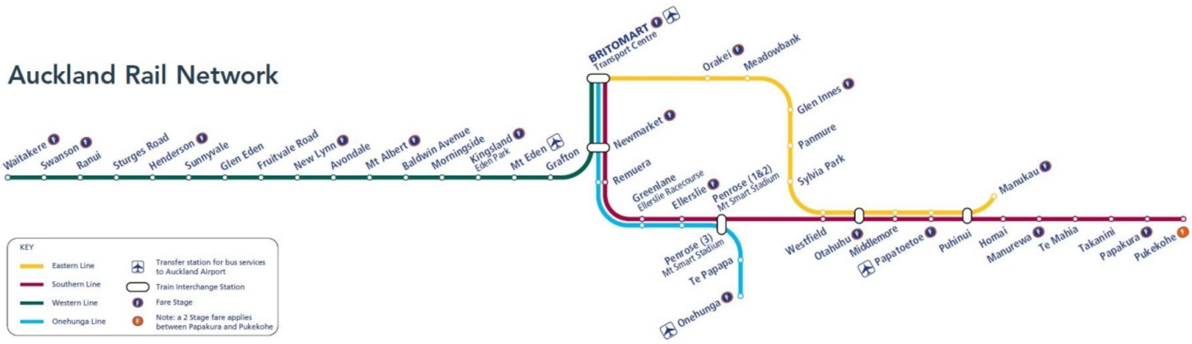


Figure 9.1 Auckland electrified suburban rail network with line and station names (AT 2015).

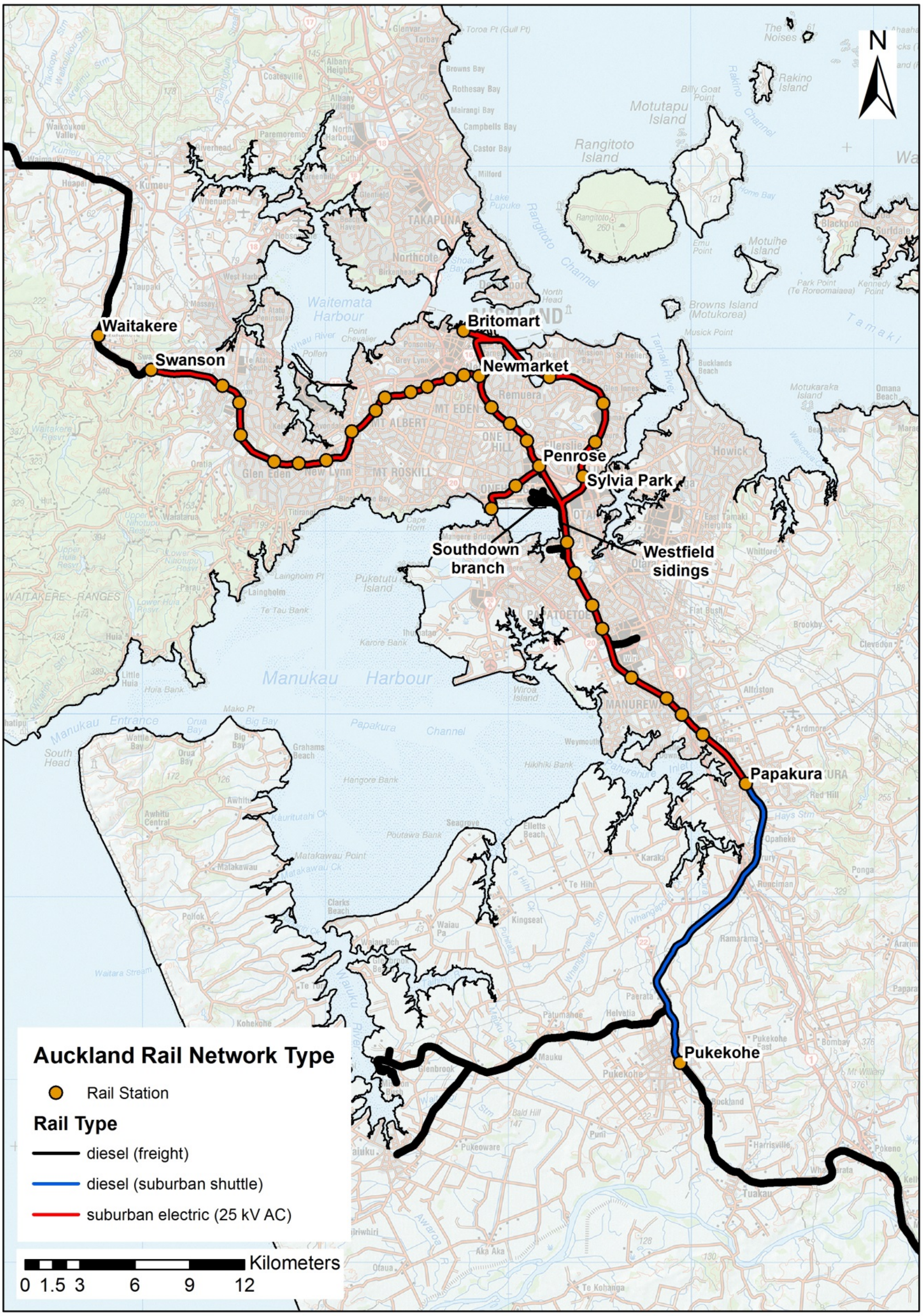


Figure 9.2 Auckland rail network showing stations and type of rail. Orange dots show rail stations, with key stations labelled. In black are freight lines, in blue are diesel lines, and in red are electrified lines.

All rail between Swanson in the west and Papakura in the south is electrified (Figure 9.2), with the electric system supplied by two connections to the *Transpower* national grid, at Southdown and Penrose substations. A diesel shuttle service runs between Papakura and Pukekohe on the Southern Line. The Western Line between Swanson and Waitakere is currently not operational and buses are used for this section. Diesel freight services also operate on the rail network through Auckland (Figure 9.2), particularly along the North Island Main Trunk line from Whangarei to Tauranga (via Westfield), and from Westfield to the *Ports of Auckland* Waitemata seaport and Wiri Intermodal Freight Hub. A local shunt service operates between the *Ports of Auckland* Waitemata seaport and Westfield.

9.4 MT RUAUMOKO SCENARIO

9.4.1 Auckland rail network impacts

Table 9.4 details physical impacts to the rail network resulting from the Mt Ruaumoko scenario, and is followed by maps (Figure 9.3 to Figure 9.10) showing these impacts.

Table 9.4 Auckland rail network physical impacts over the course of the Mt Ruaumoko scenario.

Date	Relevant event details	Impact summary	Figure
22 February	VAL increases from 0 to 1	No physical impact	N/A
08 March	08 March PEZ implemented	No physical impact	N/A
11 March	11 March PEZ implemented	No physical impact	N/A
12 March	12 March SEZ implemented	No physical impact	N/A
13 March	Volcanic gases detected. Shallow earthquakes (up to M4.5).	Rail stations: • No physical impact expected *Note. Although earthquakes may be felt across the entire electric suburban network, no damage to station infrastructure is anticipated* Rail lines: • Potential damage to rail and components across the suburban electric network from earthquakes and ground deformation (inspections required). *Note. Southern part of network is perhaps more susceptible due to geology (peat and ash).* • Potential for blockage by landslides from steep slopes onto tracks and tunnel entrances such as near Newmarket.	9.3
14 March AM	Base surge causes complete destruction 0–4 km from vent and some damage 4–6 km from vent. Shallow earthquakes (up to M4.5).	Rail stations: • Onehunga and Te Papapa stations destroyed or severely damaged beyond reasonable repair by base surge • Possible damage to stations on Southern Line between Greenlane and Otahuhu (inclusive) by outer surge (<5 KPa).	9.4

Date	Relevant event details	Impact summary	Figure
		Rail lines: • Onehunga Line between Penrose and Onehunga, and Southdown branch destroyed or severely damaged by base surge • Possible damage to Southern Line between Remuera and Middlemore, and sidings from Westfield by initial outer surge (<5 KPa). • Potential damage to rail and components across the suburban electric network from further earthquakes and ground deformation (inspections required).	
14 March PM	Tephra fallout to west. Shallow earthquakes (up to M4.8).	Rail stations: • Onehunga and Te Papapa stations remain destroyed or severely damaged • Possible damage remains to stations on Southern Line between Greenlane and Otahuhu (inclusive) by initial outer surge (<5 KPa). Rail lines: • Onehunga Line between Penrose and Onehunga, and Southdown branch remain destroyed or severely damaged by initial base surge • Possible damage remains to Southern Line between Remuera and Middlemore, and sidings from Westfield by initial outer surge (<5 KPa) and associated deposits. • Potential damage to rail and components across the suburban electric network from further earthquakes and ground deformation (inspections required). *Note. Tephra fall to west does not directly fall on the rail network. Remobilised ash may reach the Western Line between Glen Eden and New Lynn but no physical impacts are anticipated.*	9.5
16 March	11 March PEZ and 12 March SEZ lifted. 16 March PEZ and 16 March SEZ implemented	Rail stations: • Onehunga and Te Papapa stations remain destroyed or severely damaged • Possible damage remains to stations on Southern Line between Greenlane and Otahuhu (inclusive) by initial outer surge (<5 KPa). Rail lines: • Onehunga Line between Penrose and Onehunga, and Southdown branch remain destroyed or severely damaged by initial base surge	9.6

Date	Relevant event details	Impact summary	Figure
		• Possible damage remains to Southern Line between Remuera and Middlemore, Eastern Line from Westfield to Sylvia Park and Britomart to Orakei, and sidings from Westfield by initial outer surge (<5 KPa) and associated deposits. *Note. Any damage to components from previous earthquakes is repaired with no impact to the rail network beyond 6 km from the vent at this stage.*	
21 March	Tephra fallout to north west. Base surge.	Rail stations: • Onehunga and Te Papapa stations remain destroyed or severely damaged • Possible damage remains to stations on Southern Line between Greenlane and Otahuhu (inclusive) by initial outer surge (<5 KPa). Rail lines: • Onehunga Line between Penrose and Onehunga, and Southdown branch remain destroyed or severely damaged by initial base surge • Possible damage remains to Southern Line between Remuera and Middlemore, Eastern Line from Westfield to Sylvia Park and Britomart to Orakei, and sidings from Westfield by initial outer surge (<5 KPa), associated deposits. • Possible damage to rail components on Southern Line between Britomart and Otahuhu, and Western Line between Britomart and Sturges from ash deposition and infiltration. *Note. Initial component failures from ash accumulation beyond the SEZ are fixed by late on 22 March. However, some failures may continue due to resuspended and re-deposited ash on the network.*	9.7
30 March	Tephra fallout to south east.	Rail stations: • Onehunga and Te Papapa stations remain destroyed or severely damaged • Possible damage remains to stations on Southern Line between Greenlane and Otahuhu (inclusive) by initial outer surge (<5 KPa). Rail lines: Onehunga Line between Penrose and Onehunga, and Southdown branch remain destroyed or severely damaged by initial base surge	9.8

Date	Relevant event details	Impact summary	Figure
		Possible damage remains to Southern Line between Newmarket and Middlemore, Eastern Line from Westfield to Sylvia Park, and sidings from Westfield by initial outer surge (<5 KPa) and accumulating tephra deposits.	
05 April	Lava flows. 16 March SEZ lifted.	Rail stations: • Onehunga and Te Papapa stations remain destroyed or severely damaged *Note. Previous damage to stations on Southern Line between Greenlane and Otahuhu (inclusive) by initial outer surge (<5 KPa) has been repaired.* Rail lines: • Onehunga Line between Penrose and Onehunga, and Southdown branch remain destroyed or severely damaged by initial base surge • Possible damage from tephra continues to Southern Line between Newmarket and Middlemore, Eastern Line from Westfield to Sylvia Park, and sidings from Westfield until clean-up prevents further remobilisation and infiltration to components.	9.9
01 May	16 March PEZ lifted. Permanent exclusion zone implemented.	Rail stations: • Onehunga and Te Papapa stations remain destroyed or severely damaged. Rail lines: • Onehunga Line between Penrose and Onehunga remains destroyed or severely damaged by initial base surge *Notes. Demand to reconstruct the infrastructure required to reopen this section of the Onehunga line is expected to be low. The stations and line may be decommissioned or relocated based on rebuild activities.* *Although the Southdown branch is marked as being restored on the figure, demand may be too low for this to occur at this stage with the damage and possible closure of storage and distribution facilities in this area.*	9.10

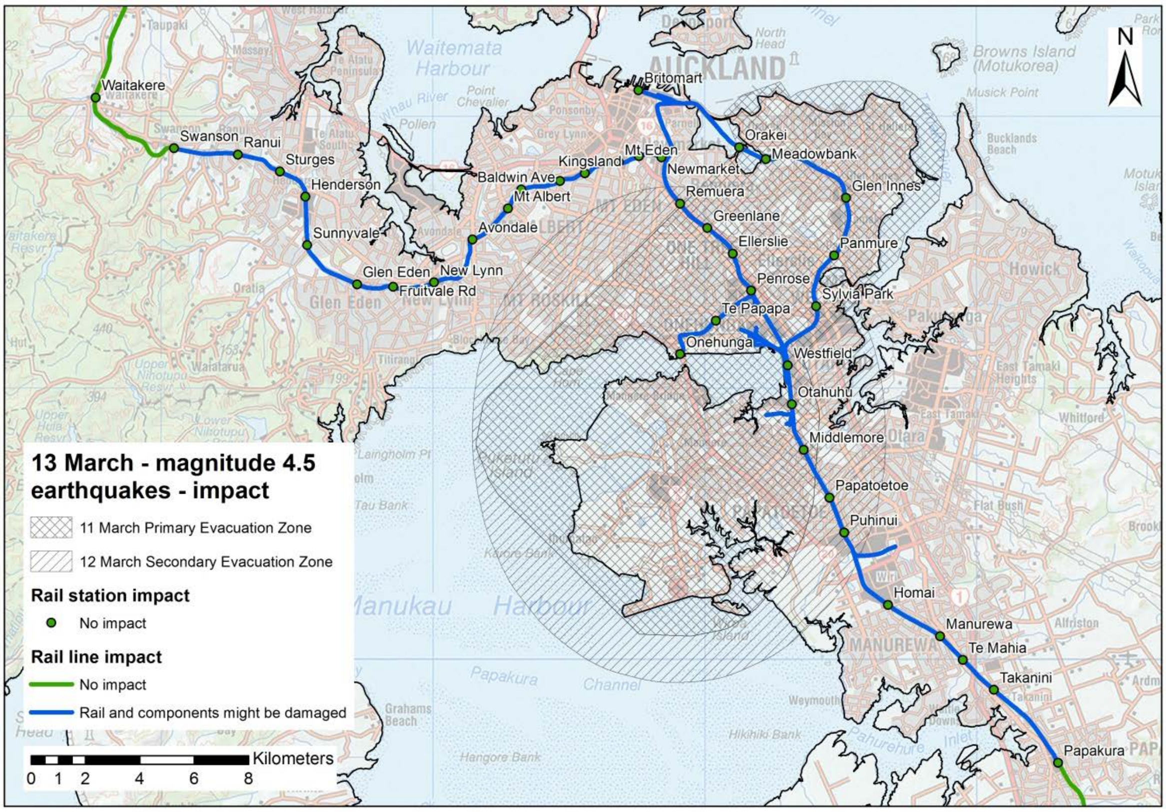


Figure 9.3 Physical impacts for rail network on 13 March following M4.5 earthquakes; the PEZ (cross-hatched) and SEZ (hatched) are indicated. Stations are shown with circles and labelled. In blue are possibly damaged assets, and in green are undamaged assets.

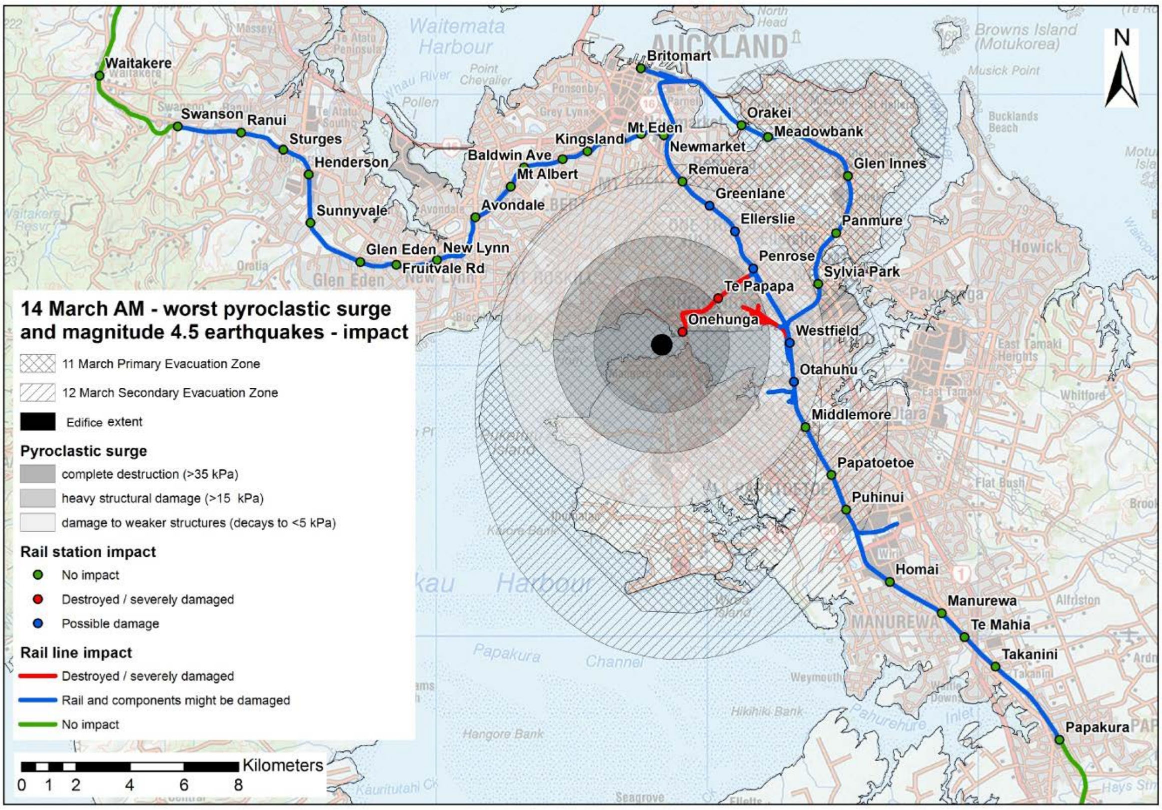


Figure 9.4 Physical impacts for rail network on 14 March AM following M4.5 earthquakes and worst-case pyroclastic surge (grey); the PEZ (cross-hatched) and SEZ (hatched) are indicated. Stations are shown with circles and labelled. In red are destroyed assets, in blue are possibly damaged assets, and in green are undamaged assets. The edifice is shown in black.

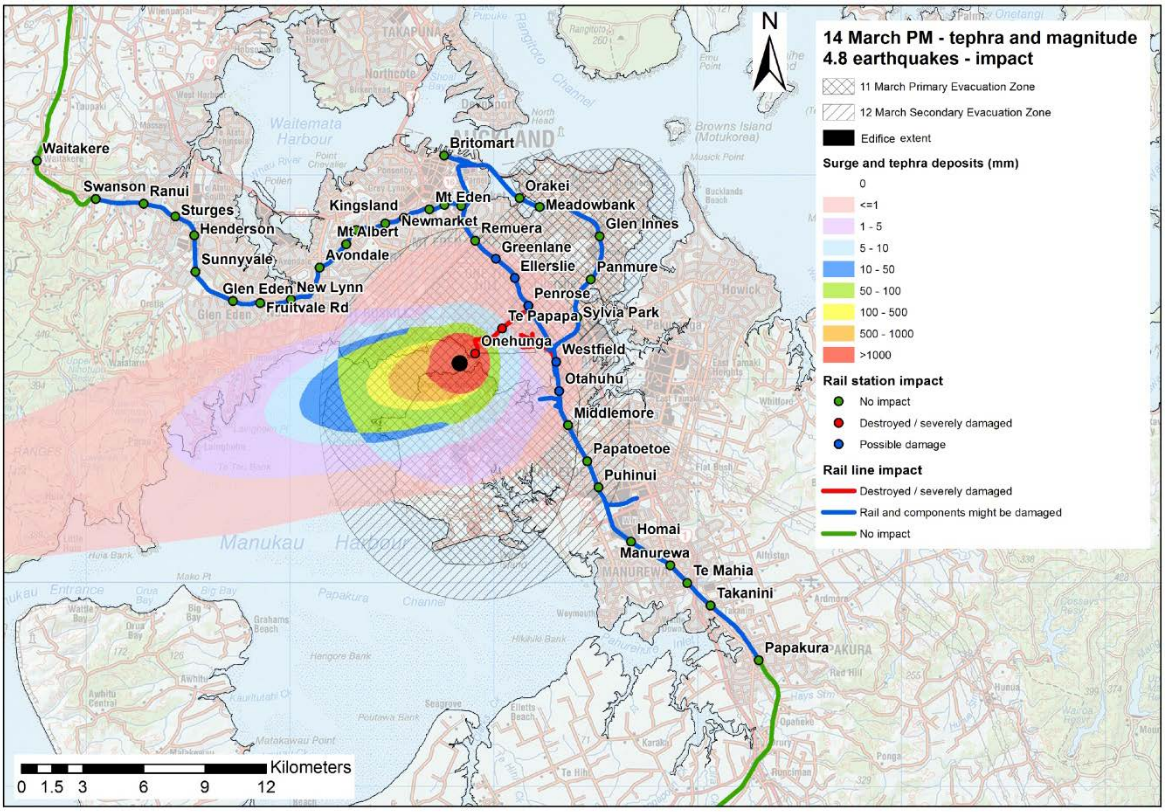


Figure 9.5 Physical impacts for rail network on 14 March PM following M4.8 earthquakes and tephra fall (see legend for deposit thickness). The PEZ (cross-hatched) and SEZ (hatched) are indicated. Stations are shown with circles and labelled. Damage state is coloured according to severity as in Figure 9.4.

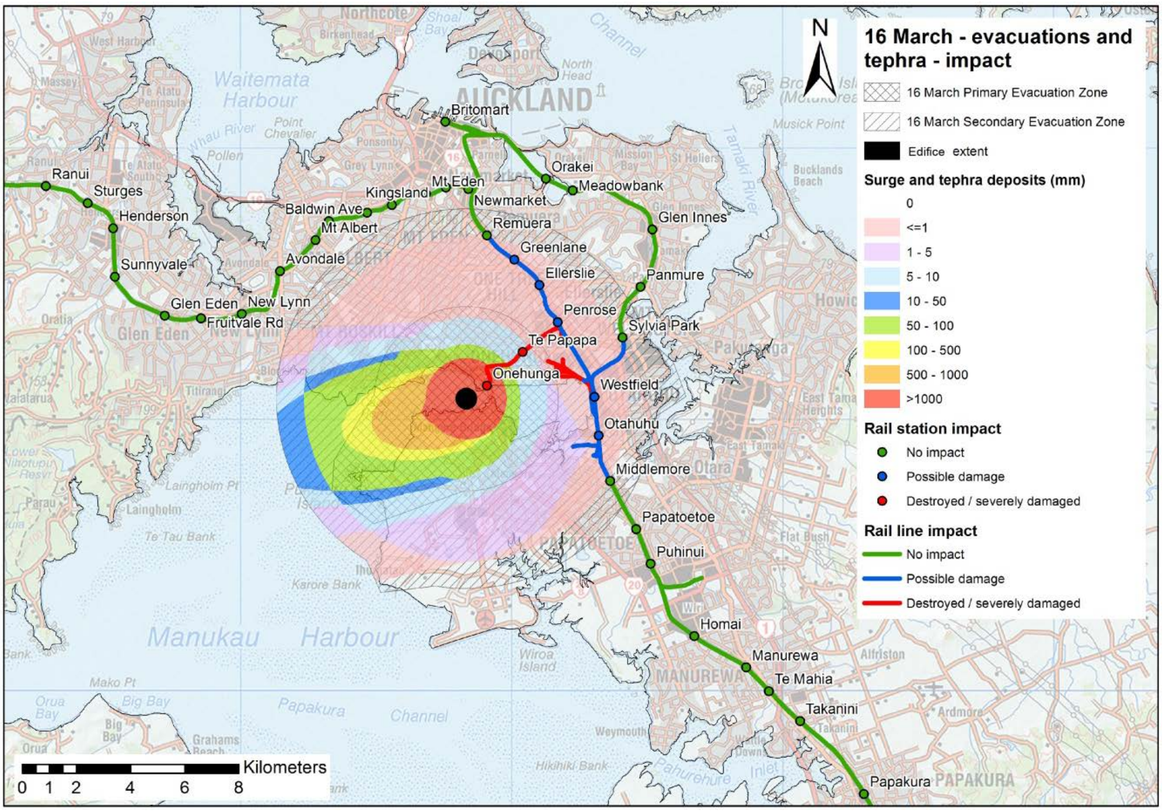


Figure 9.6 Physical impacts for rail network on 16 March following clean-up, new tephra fall and implementation of new evacuation zones; the PEZ (cross-hatched) and SEZ (hatched) are indicated. Stations are shown with circles and labelled. Hazard and damage state are coloured according to severity as in Figure 9.4.

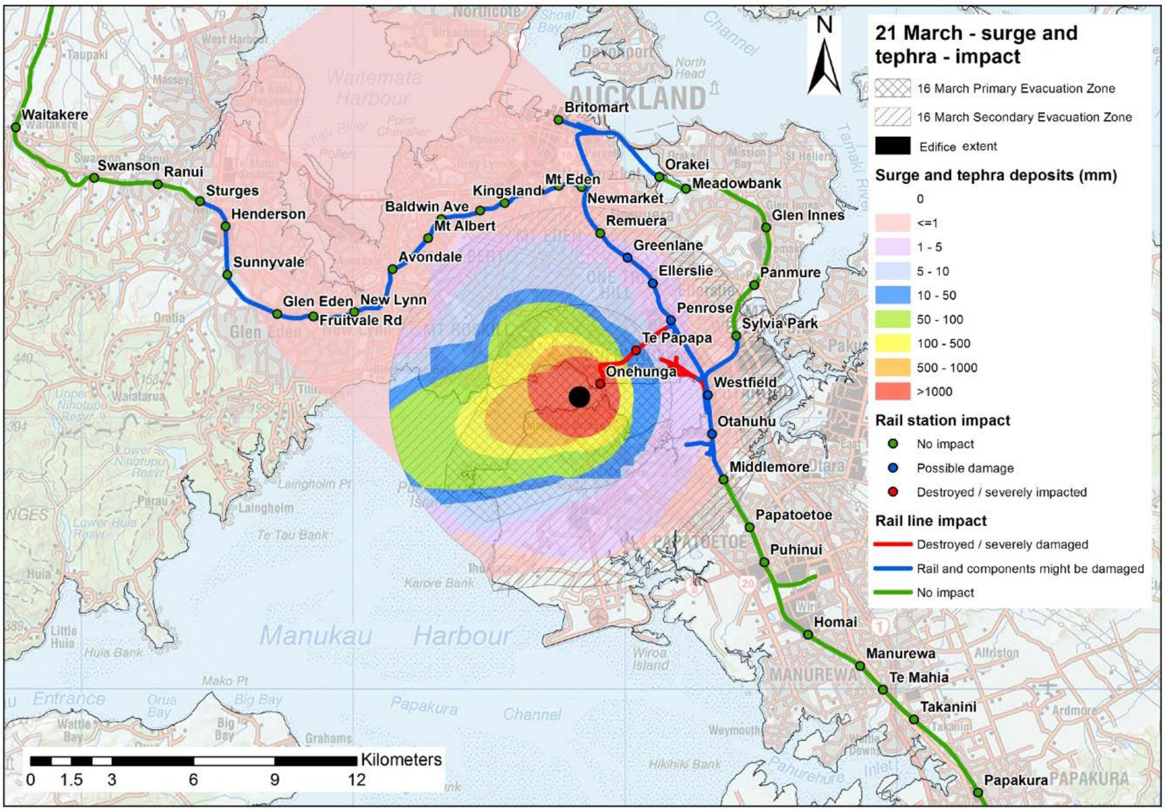


Figure 9.7 Physical impacts for rail network on 21 March following average-case pyroclastic surge and new tephra fall; the PEZ (cross-hatched) and SEZ (hatched) are indicated. Stations are shown with circles and labelled. Hazard and damage state are coloured according to severity as in Figure 9.4.

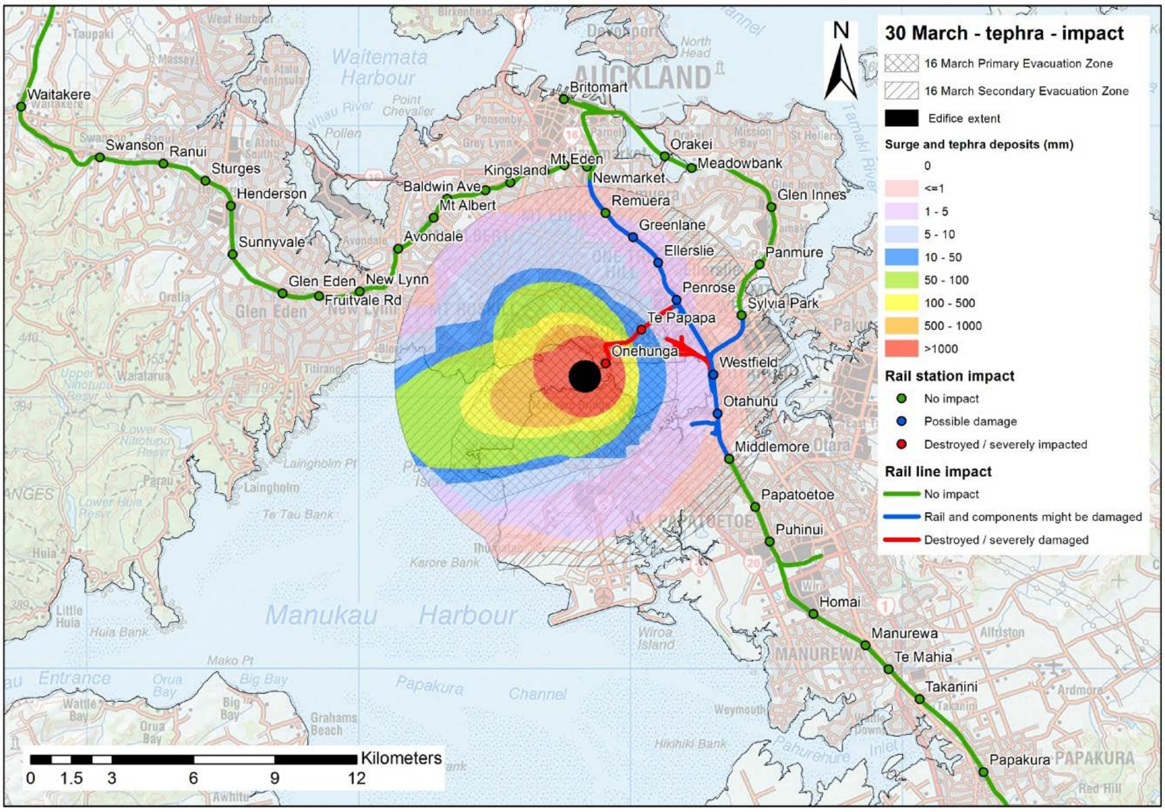


Figure 9.8 Physical impacts for rail network on 30 March following clean-up and tephra fall; the PEZ (cross-hatched) and SEZ (hatched) are indicated. Stations are shown with circles and labelled. Hazard and damage state are coloured according to severity as in Figure 9.4.

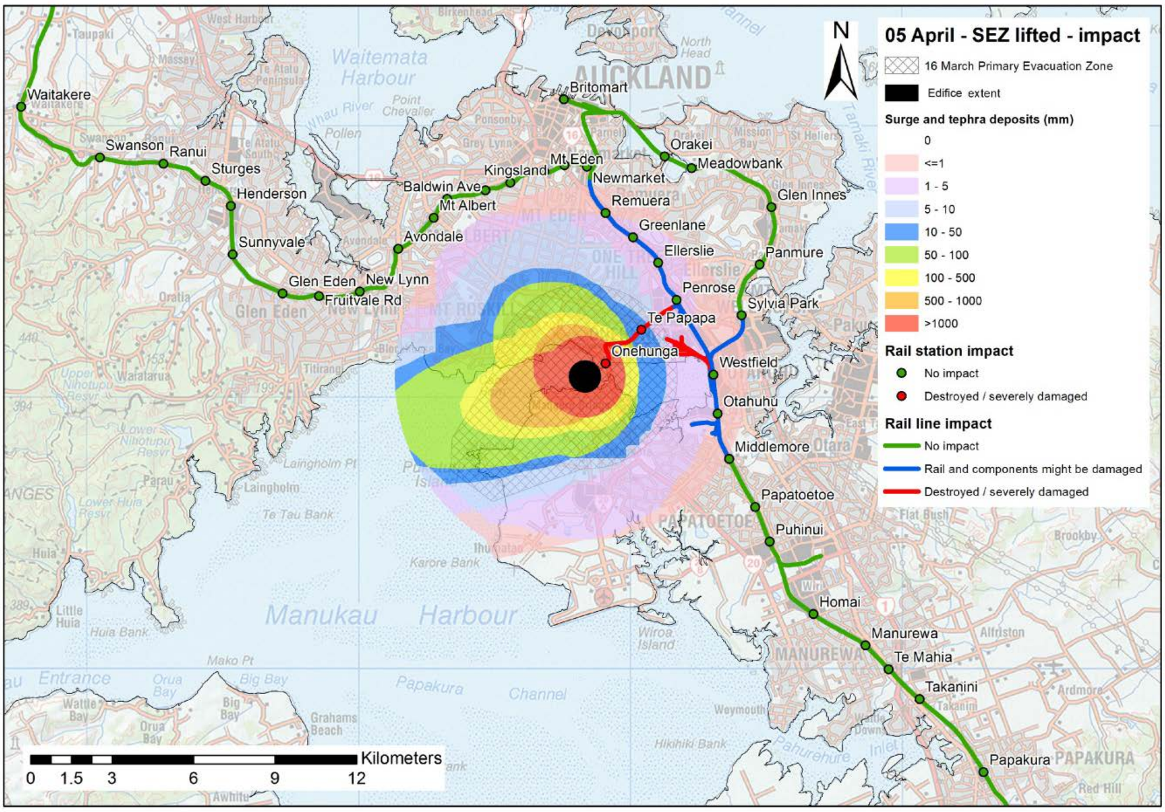


Figure 9.9 Physical impacts for rail network on 5 April following further clean-up and lifting of the SEZ; the PEZ (cross-hatched) is indicated. Stations are shown with circles and labelled. Hazard and damage state are coloured according to severity as in Figure 9.4.

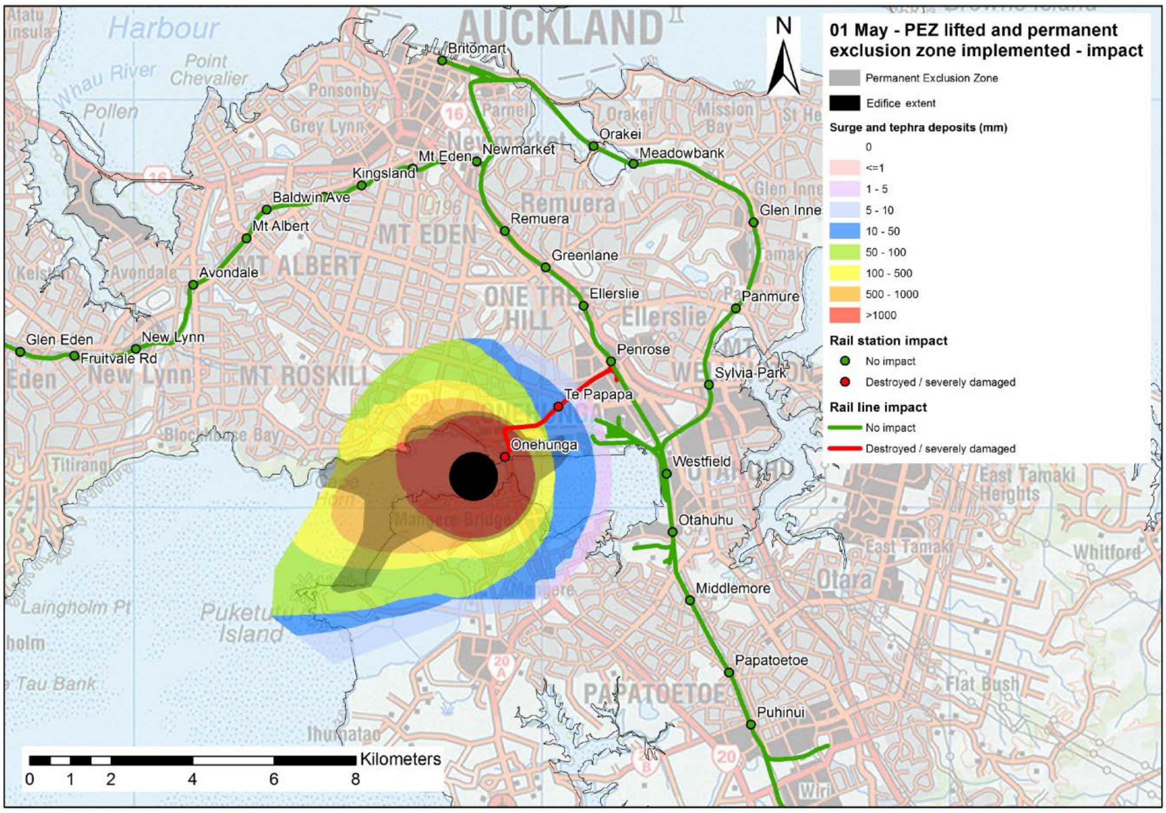


Figure 9.10 Physical impacts for rail network on 1 May following further clean-up, lifting of the PEZ and implementation of the new permanent exclusion zone (dark grey). Stations are shown with circles and labelled. Hazard and damage state are coloured according to severity as in Figure 9.4.

9.4.2 Auckland rail network level of service

Table 9.5 details level of service for the rail network over the course of the Mt Ruaumoko eruption, and Table 9.6 details level of service for the freight rail network. These are followed by maps (Figure 9.11 to Figure 9.19) showing these levels.

Table 9.5 Level of service for Auckland's suburban electric rail network over the course of the Mt Ruaumoko scenario. The table refers to the stations and lines covered by the Auckland electric suburban network.

Date	Relevant event details	Level of service summary	Figure
22 February	VAL increases from 0 to 1	Full level of service. *Note. Some self-evacuation may lead to increase in passengers and delays at stations (due to increased boarding time) but the implications are considered minor on overall service.*	N/A
08 March	08 March PEZ implemented	Rail stations: • Stations from Onehunga to Penrose on Onehunga Line, Greenlane to Westfield on Southern Line, and Westfield to Orakei on Eastern Line become entry only (no exit from stopping trains due to evacuation zone). Rail lines: • Onehunga Line between Onehunga and Penrose, Southern Line between Remuera and Otahuhu, and entire Eastern Line only operate as an evacuation service. • 40 km/h limit is introduced on these lines due to volcano-tectonic earthquakes increasing in magnitude and complications such as increased chance of obstructions at level crossings due to road evacuations. *Notes. Knock-on effects on the operability of the remainder of the suburban electric rail network are expected and new timetabling is anticipated for much of the scenario from this date. However, this is not displayed on the figures as the new timetabling details are unknown.* *Some trains are outstabled from Wiri to Henderson and Swanson to allow continued operation on the Western Line (including some diesel fleet from the Papakura to Pukekoe shuttle service).* *Relocation of KiwiRail operations and services from Westfield occurs (potentially to Stanley St and/or Avondale).*	9.11
11 March	11 March PEZ implemented	Rail stations: • Stations from Onehunga to Penrose on Onehunga Line, Greenlane to Westfield on Southern Line, and Westfield to Orakei on Eastern Line are now closed following evacuations.	9.12

Date	Relevant event details	Level of service summary	Figure
		• Otahuhu and Middlemore stations on the Southern Line become entry only (no exit from stopping trains due to evacuation zone). Rail lines: • Onehunga Line between Onehunga and Penrose, Southern Line between Remuera and Otahuhu, and entire Eastern Line are now closed to all rail services. • Southdown branch and Westfield sidings are closed. • Southern Line between Otahuhu and Papatoetoe only operates as an evacuation service (with 40 km/h limit due to the continued threat of earthquakes) *Notes. New timetabling comes into effect on Southern Line south from Papatoetoe and on entire Western Line.*	
12 March	12 March SEZ implemented	Rail stations: • Stations from Onehunga to Penrose on Onehunga Line, Greenlane to Middlemore on Southern Line, and Westfield to Orakei on Eastern Line are closed following evacuations. • Remuera, Papatoetoe and Puhinui stations on the Southern Line become entry only (no exit from stopping trains due to evacuation zone). Rail lines: • Onehunga Line between Onehunga and Penrose, Southern Line between Remuera and Papatoetoe, and entire Eastern Line are closed to all rail services. • Southdown branch and Westfield sidings remain closed. • Southern Line between Papatoetoe and Homai, and Remuera and Newmarket, only operate as an evacuation services (with 40 km/h limit) *Notes. New timetabling continues on Western Line and on Southern Line south from Homai.*	9.13
13 March	Volcanic gases detected. Shallow earthquakes (up to M4.5).	Rail stations: • Stations from Remuera to Puhinui on Southern Line, and all those on Onehunga and Eastern Lines are closed Rail lines: • Onehunga Line, Eastern Line, and Southern Line between Newmarket and Homai are closed to all rail services. • Southdown branch and Westfield sidings remain closed. • Remainder of electric suburban electric rail network experiences rolling outages (for hours) due to earthquakes and required inspections.	9.14

Date	Relevant event details	Level of service summary	Figure
		Notes. Limited service continues on Western Line and on Southern Line south from Homai between outages.	
14 March (AM and PM)	Base surge causes complete destruction 0–4 km from vent and some damage 4–6 km from vent. Tephra fallout to west. Shallow earthquakes (up to M4.8).	Level of service remains the same as 13 March as the volcanic events cause no new outages, and because the same evacuation zones apply. *Damage to parts of the network occurs due to base surge but closures are already in effect. Tephra does not cause additional outages at this stage.*	N/A
16 March	11 March PEZ and 12 March SEZ lifted. 16 March PEZ and 16 March SEZ implemented	Rail stations: • Stations from Remuera to Middlemore on Southern Line, Sylvia Park on Eastern Line, and all those on Onehunga Line remain closed. Rail lines: • Onehunga Line and Southdown branch remain closed. • A non-stopping service on the Southern Line between Newmarket and Papatoetoe through the new SEZ comes into effect restoring the north-south link on the rail network (with hazard thresholds for immediate reclosure established). As this route passes through outer surge deposits (between Remuera and Middlemore), a 40 km/h limit is in effect and rolling outages due to ash infiltration, associated component failure and required inspections occur. Any damage or obstructions from the surge are assumed to be cleared by this time. *Notes. New timetabling occurs on the Western Line, and Southern Line south of Papatoetoe. A limited service may be restored on the Eastern Line from Britomart to Panmure although low demand may deem this unnecessary at this stage.*	9.15
21 March	Tephra fallout to north west. Base surge.	Rail stations: • Stations from Remuera to Middlemore on Southern Line, Sylvia Park on Eastern Line, and all those on Onehunga Line remain closed. Rail lines: • Onehunga Line and Southdown branch remain closed. • A non-stopping service on the Southern Line between Newmarket and Papatoetoe through the new SEZ (with rolling outages due to surge and accumulating tephra, and 40 km/h limit) continues.	9.16

Date	Relevant event details	Level of service summary	Figure
		• Rolling outages occur on the Western Line from Britomart to Sturges due to tephra deposition and possible ash infiltration into components (40 km/h limit is introduced). *Notes. New timetabling remains on the Western Line, and Southern Line south of Papatoetoe. A limited service remains possible on the Eastern Line from Orakei to Panmure.* *Initial disruption to level of service on Western Line are expected to be short-lived (until late on 22 March). However, further outages are possible due to the resuspension and re-deposition of ash.*	
30 March	Tephra fallout to south east.	Level of service remains the same as 21 March except services (with new timetabling) are restored on the Western Line following ash clean-up outside of the SEZ.	9.17
05 April	Lava flows. 16 March SEZ lifted.	Rail stations: • Onehunga and Te Papapa stations remain closed. Rail lines: • Onehunga Line and Southdown branch remain closed. • Service is restored to all stations on the Southern, Eastern and Western Lines (with 40 km/h limit on Southern Line between Newmarket and Middlemore until minimal airborne ash). *Notes. New timetabling remains across much of the suburban electric rail network.* *Outstabling of trains and relocation of KiwiRail staff is reconsidered.*	9.18
01 May	16 March PEZ lifted. Permanent exclusion zone implemented.	Full service is restored to all stations and rail, with the exception of the Onehunga Line and Onehunga and Te Papapa stations which remain closed indefinitely.	9.19

Table 9.6 Level of service for Auckland's diesel freight rail network. Note that these are not specifically shown on the maps.

Date	Freight transportation level of service (for north-south flow and to and from Port)
8 March	Reduced service: Diesel freight through-traffic is expected to continue with delays.
11 March	No service: Diesel freight through-traffic ceases. Possible mitigative action is to relocate railhead to Wiri, but level of service is limited by the capacity of lifting equipment and dependence on road access to and from relocated railhead. Due to these limitations, freight transportation level of service is set at 'no service'.
16 March	Reduced service: Rail line open but subject to speed, evacuation, and/or no-stopping restrictions along parts.
1 May	Full services are restored.

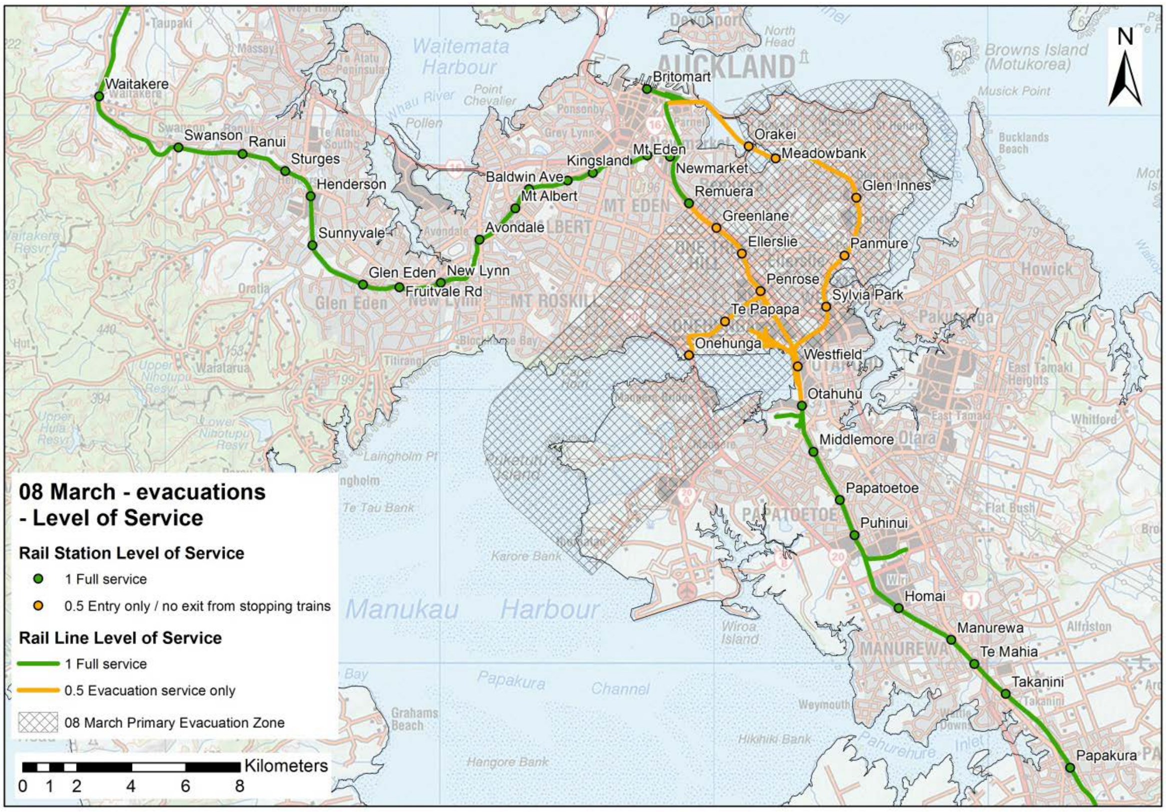


Figure 9.11 Rail network level of service on 8 March following implementation of the PEZ (cross-hatched). Full service stations and lines are green and stations and lines which can only be entered but not exited are orange.

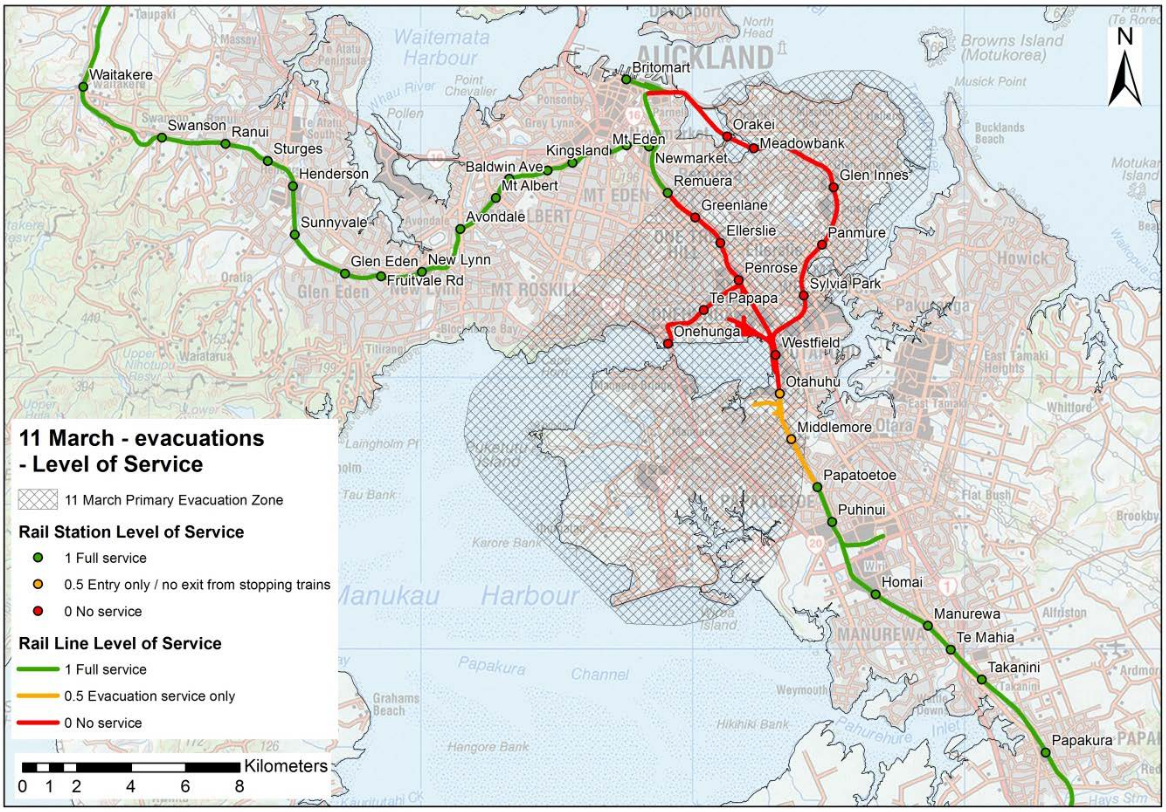


Figure 9.12 Rail network level of service on 11 March following implementation of a new PEZ (cross-hatched). Full service stations and lines are in green, stations and lines which can only be entered but not exited are orange, and stations and lines with no service are red.

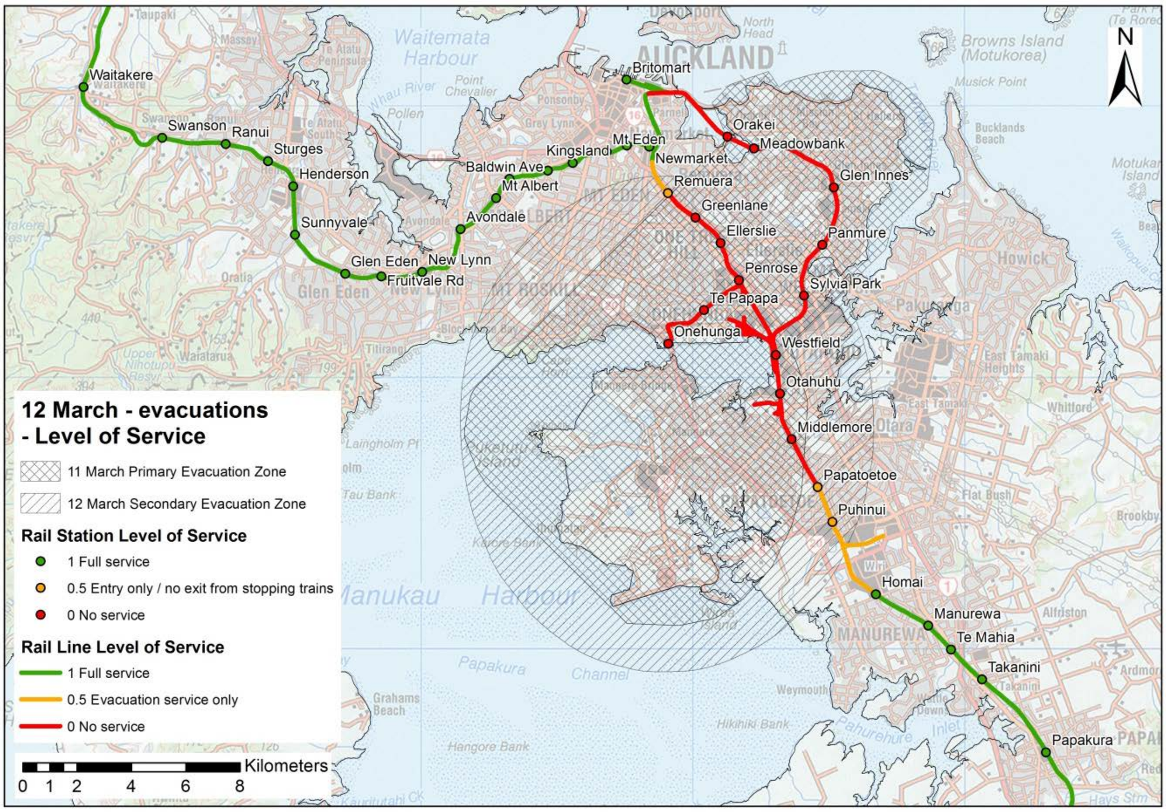


Figure 9.13 Rail network level of service on 12 March following implementation of the SEZ (hatched); the PEZ (cross-hatched) is also indicated. Stations and lines are coloured according to level of service as in Figure 9.12.

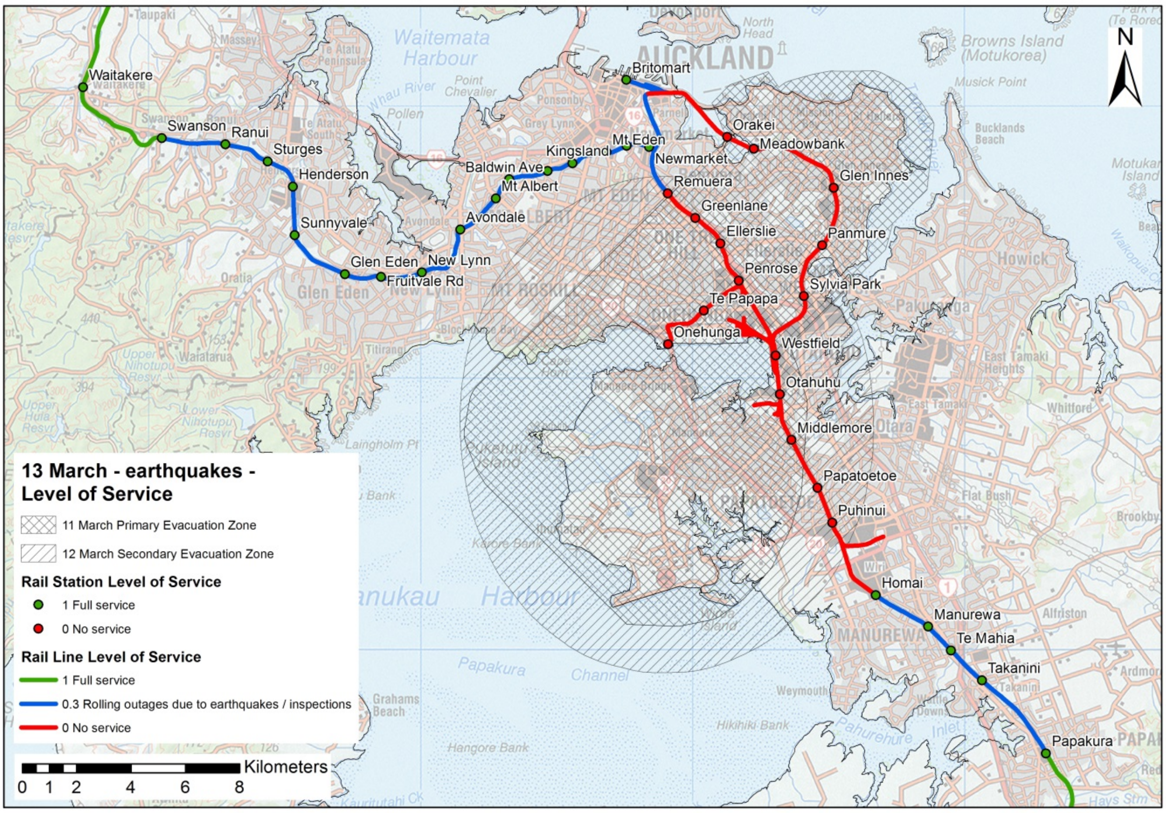


Figure 9.14 Rail network level of service on 13 March following M4.5 earthquakes; the PEZ (cross-hatched) and SEZ (hatched) are indicated. Full service stations and lines are in green, lines with rolling delays due to required inspections are blue, and stations and lines with no service are red.

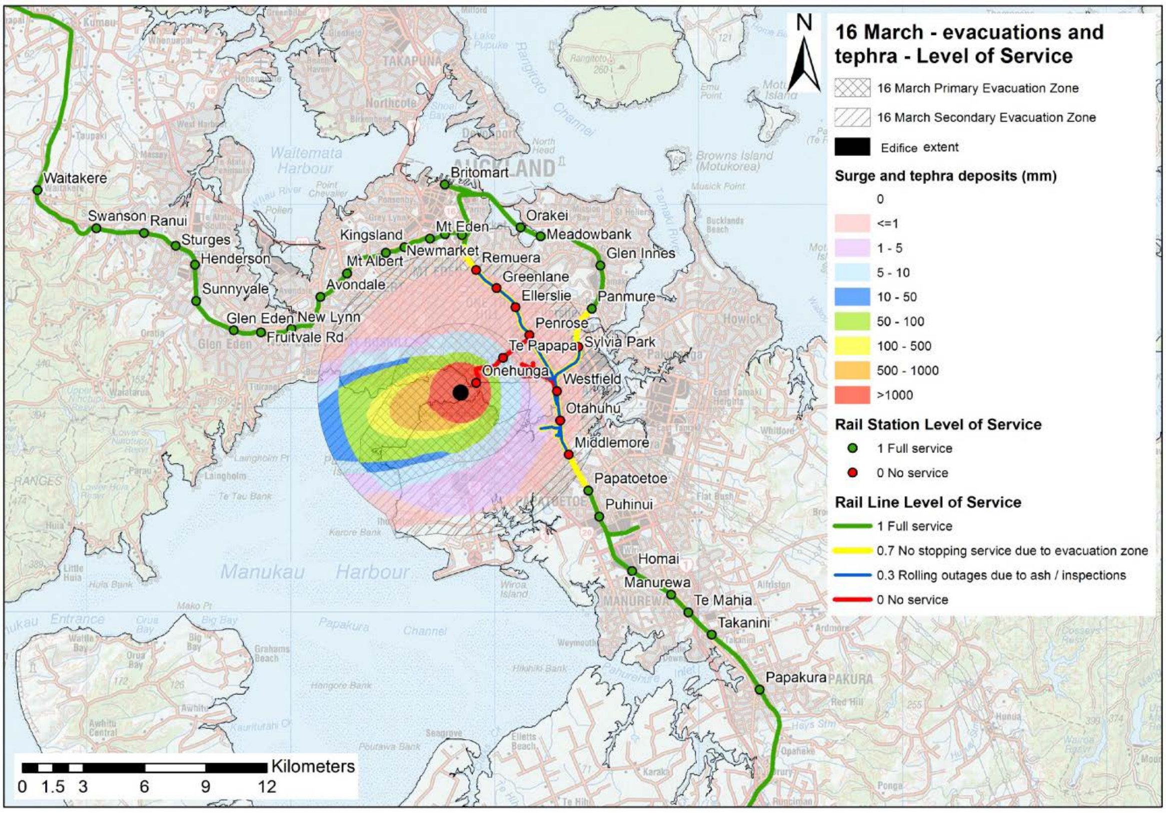


Figure 9.15 Rail network level of service on 16 March following clean-up and implementation of new evacuation zones; the PEZ (cross-hatched) and SEZ (hatched) are indicated. Uncleaned deposit thickness indicated (see legend) and the edifice is black. Full service stations and lines are green, lines with rolling delays due to required inspections are blue, lines with no stopping service are in yellow and stations and lines with no service are red.

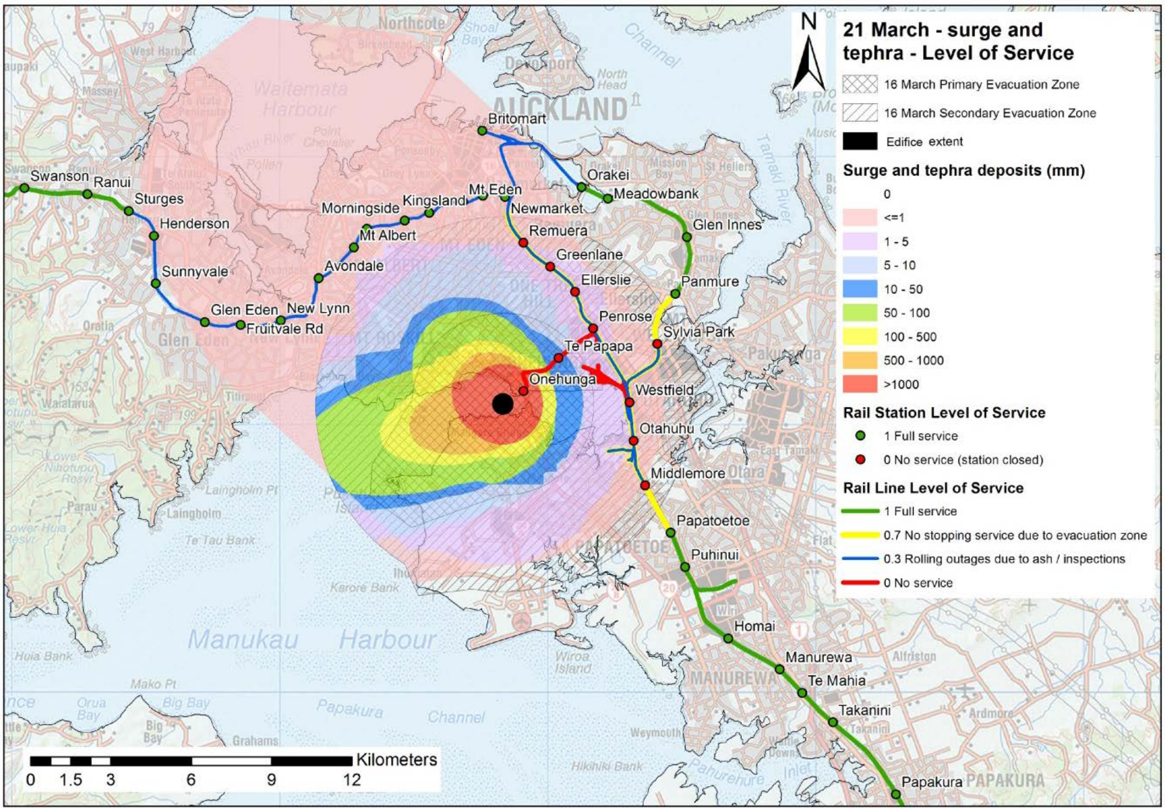


Figure 9.16 Rail network level of service on 21 March following average-case surge and new tephra fall; the PEZ (cross-hatched) and SEZ (hatched) are indicated. Hazard and level of service are coloured according to severity as in Figure 9.15.

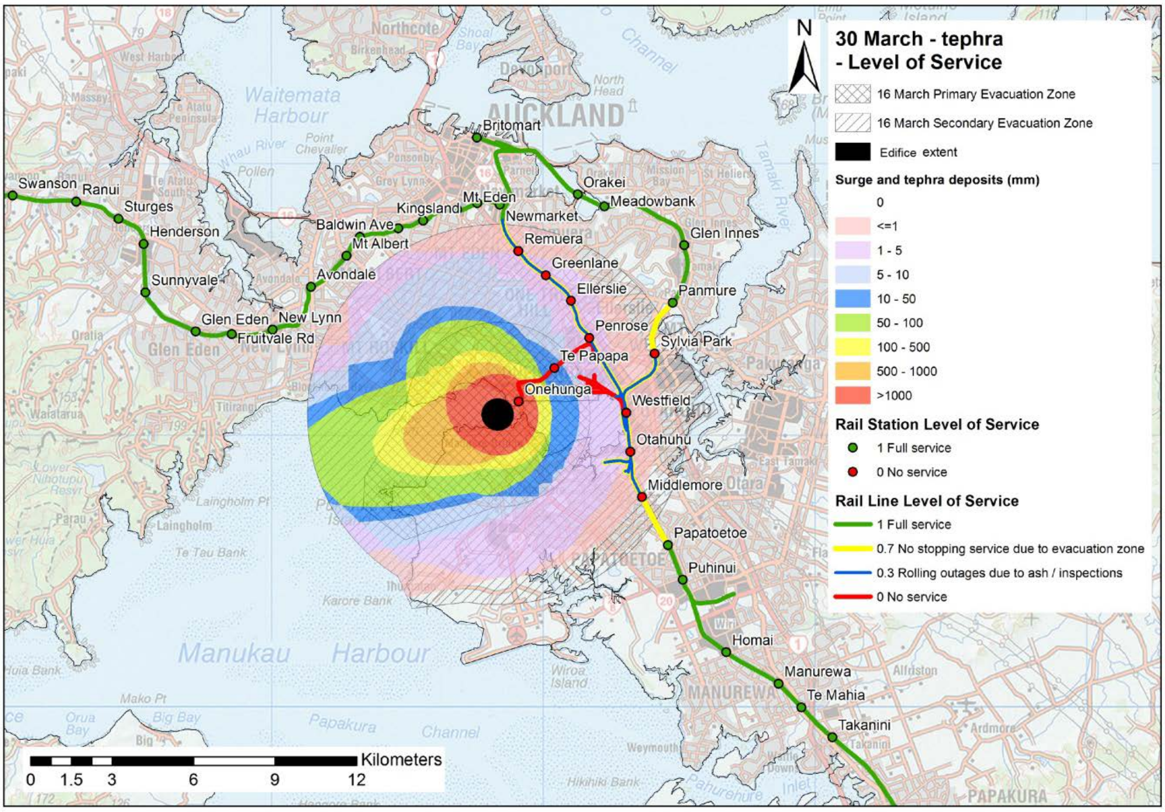


Figure 9.17 Rail network level of service on 30 March following further clean-up; the PEZ (cross-hatched) and SEZ (hatched) are indicated. Hazard and level of service are coloured according to severity as in Figure 9.15.

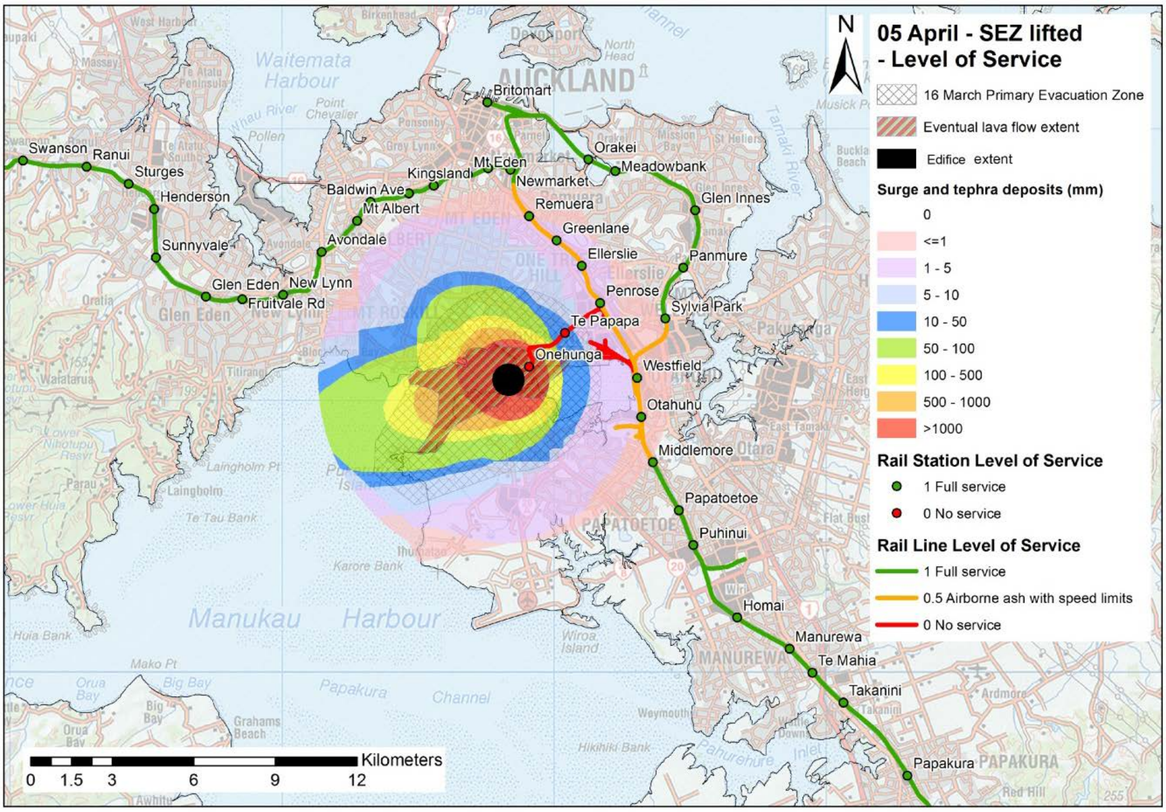


Figure 9.18 Rail network level of service on 05 April following further clean-up and lifting of the SEZ; the PEZ (cross-hatched) is indicated. Full service stations and lines are green, lines with reduced speed limits are orange, and stations and lines with no service are red. Hazard is coloured according to severity as in Figure 9.15.

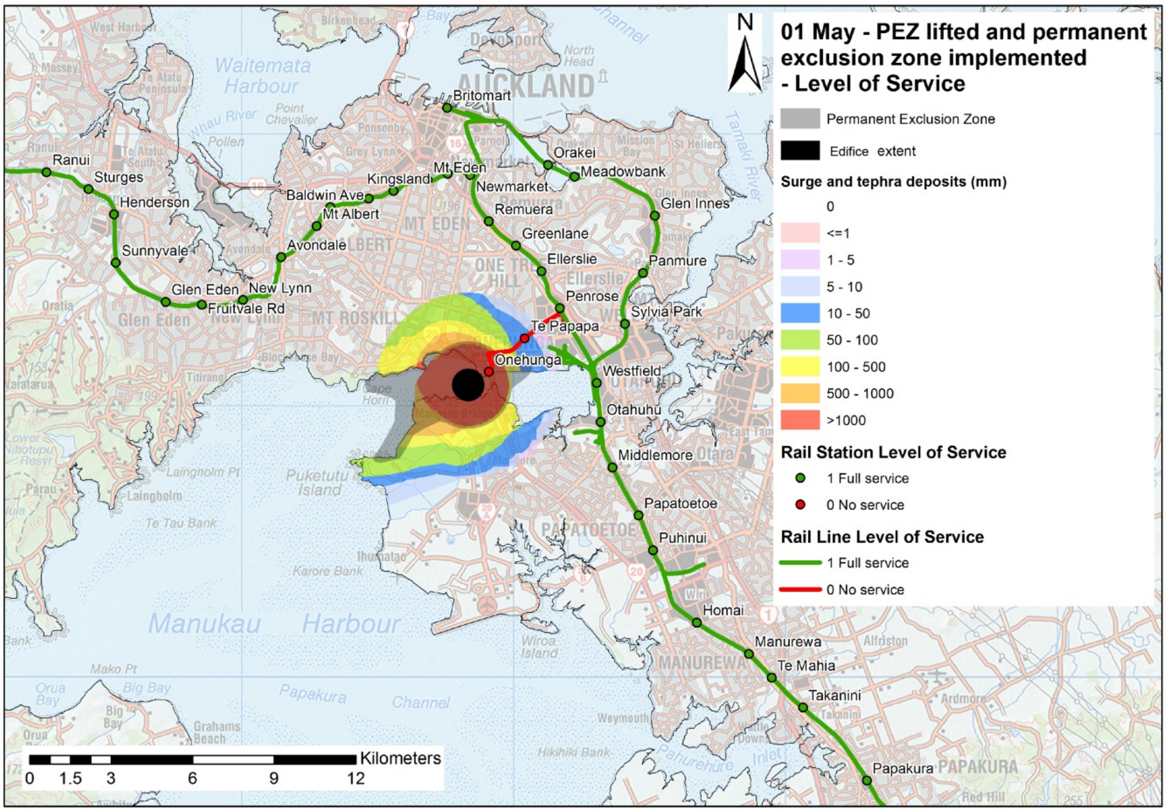


Figure 9.19 Rail network level of service on 1 May following further clean-up, lifting of the PEZ and implementation of the permanent exclusion zone (dark grey). Full service stations and lines are green and stations and lines with no service are red. Hazard is coloured according to severity as in Figure 9.15.

9.5 LIKELY INTERDEPENDENCIES

Electricity is a crucial interdependency for the suburban rail network of Auckland, with only Papakura to Pukekoe services operating by diesel power. KiwiRail and AT advised that a possible mitigative step to overcome this interdependency could be to redistribute the diesel fleet across the network, or even to hook up trains to diesel Mobile Maintenance Units (MMUs) for the transport of passengers. However, sufficient notice would be required for this to be achieved before links to the main overnight stabling area at Wiri are disrupted, and it would not be enough to maintain full capacity. This mitigative step has not been factored into the determination of reduced levels of service for the AVF scenario.

10.0 AVIATION

10.1 VOLCANIC IMPACTS TO AVIATION

Volcanic ash is extremely hazardous to aircraft, particularly those with jet engines, due to potential for engine failure and/or damage (Prata & Rose, 2015). Since 1953, there have been over 94 confirmed aircraft volcanic ash encounters, at least 79 of which had airframe or engine damage (Guffanti et al., 2010). On the ground, airports have been directly and indirectly impacted by volcanic hazards (Guffani et al., 2009). Direct impacts span from trace amounts of ash which must be removed from the airport, to destruction of an airport leading to abandonment or relocation. Indirect impacts are usually temporary airport closure due to closed airspace over the airport, as occurred at many European airports during the 2011 Eyjafjallajokull eruption (Bolic & Sivcev, 2011).

In ERI's MERIT model, the service provided by airlines in transporting people and goods will be captured through the status of the airports, the rationale being that if airports are temporarily closed or operating at reduced capacity the service provided by specific airlines and planes will likewise be unavailable or limited.

It is important to note that airports provide a service to airlines. Importantly, airports do not dictate whether a plane can or cannot land or whether conditions are too risky to fly. Furthermore, different airlines have different levels of risk tolerance or approaches to tricky situations. For example, during the 2011 Puyehue-Cordón Caulle, Chile, eruption, the ash cloud made its way around the hemisphere. Air New Zealand chose to fly some flights underneath the ash cloud on slightly different air routes (Air New Zealand media release, 2011), which required up to 10% more fuel, while other airlines opted not to fly. Finally, an airport may completely or partially close – e.g., not provide refuelling or a gate – but it is ultimately the pilot's decision whether or not to land.

All flights must identify alternate airports to land at in the case of an emergency, so in this scenario flights in the air when the situation changes (e.g., VAL changes, change in eruptive style) have plans in place to divert to alternate airports.

10.2 AVIATION LEVEL OF SERVICE METRICS

Auckland Airport identified three sub-sectors to consider for level of service considerations:

- Domestic air traffic. Domestic traffic is extremely responsive to local conditions and is dominated by Air New Zealand and JetStar.
- Local international air traffic. These primarily consist of flights from Australia. This traffic is moderately responsive to conditions, with a mix of airlines with various levels of risk tolerance.
- Wider international traffic. This traffic is least responsive. It would take a few days for international airlines start flying into Auckland again once they are allowed to land, in part due to the time it would take to reorganise schedules involving other hub airports from around the world. The wider international traffic might not return to full capacity for a while per demand and situation uncertainty.

For each of these sub-sectors the outage metric will be a percentage of normal capacity.

As the airport is a single site rather than a network, it is not possible to produce a spatial outage map. Rather, the outages are recorded in a table in a following section of this report.

10.3 Relevant Aviation Regulations

The International Civil Aviation Organization (ICAO) has ten airport categories with additional subcategories which detail what criteria an airport must meet to be able to accommodate specific aircraft and volume (Cooperative Development of Operational Safety and Continued Airworthiness, 1999). In addition to runway length and other considerations, firefighting capabilities is a key designator of airport category. Currently, Auckland Airport is a Category IIIc airport, the highest designation in New Zealand.

There are several aviation authorities and communication channels relevant for volcanic crises (Lechner, 2014):

- Airports issue a Notice to Airmen (NOTAM) to notify pilots of hazards and other relevant information, including runway or airport closures.
- Volcanic observatories (in New Zealand, GNS Science through GeoNet) issue a Volcano Observatory Notices for Aviation (VONA) to notify the aviation community of volcanic unrest and activity.
- Volcano Ash Advisory Centres (VAACs), one of which is hosted by the MetService in Wellington ('Wellington VAAC') produce Volcanic Ash Advisories (VAA) and Volcanic Ash Significant Meteorological Information (Volcanic Ash SIGMET).
- The New Zealand Civil Aviation Authority (CAA) can close parts of an airspace. There are default closures (Volcanic Hazard Zone designator; NZV) associated with various VALs for five New Zealand volcanoes, not including the AVF, and a requirement that if another volcano goes from VAL 0 to 1 an NZV be established.
- The Airways Corporation notifies airlines of routes and procedures that will be affected by various NZV as set by the CAA. Pilots must request special permission to enter these zones. Night flights are not permitted within NZVs.
- Military air traffic is not subject to CAA oversight, but any civilian aircraft operating out of a military base must following CAA regulations.

10.4 Auckland Area Airports

Aviation in Auckland primarily concerns Auckland Airport. The Auckland region is also home to the Ardmore Aerodrome and a Royal New Zealand Air Force (RNZAF) base at Whenaupai. There are also smaller airfields such as Dairy Flats on the North Shore.

Auckland Airport is New Zealand's largest and busiest airport. It has been identified as infrastructure of national significance. Auckland and Christchurch airports are the only airports in New Zealand capable of handling Boeing 777/747 and Airbus A380 planes; with regard to these largest planes, Auckland has four times the capacity of Christchurch. Auckland and Christchurch airports are also the only two international airports in New Zealand where Urban Search and Rescue (USAR) teams may enter the country and deploy. Although Auckland Airport has comparatively few dedicated cargo flights, it is a one of the larger cargo ports in New Zealand.

The Whenuapai military base has one main asphalt runway (2031 m) and two other concrete runways (Beca Planning, 2003). Whenuapai can handle the largest military aircraft (e.g., C5A Galaxy, C-141 Starlifter) provided they are not at full takeoff weight. There are presently no customs facilities at Whenuapai. We speculate in an emergency that Whenuapai would be used to transport emergency and relief aid (supplies and personnel), but not freight for commercial uses. Therefore, we do not consider it in this scenario for ERI as the flow of emergency supplies is outside the purview of the MERIT model.

Finally, the Ohakea military airport (30 km northwest of Palmerston North) could potentially be used as an alternate aerodrome international civilian passenger aircraft (up to two Boeing 747–400). However, we do not consider it in this scenario as it is outside of the Auckland region.

10.5 MT RUAUMOKO SCENARIO

Auckland Airport is not directly impacted by any volcanic hazard over the course of the Mt Ruaumoko scenario. However, it is indirectly impacted due to access, airspace restrictions, and impacts to other sectors.

10.5.1 Evacuation zones

Auckland Airport is within the PEZ from 11–15 March, but is outside of the evacuated areas for the remainder of the scenario (see Section 4). Ardmore and Whenuapai are outside evacuated areas for the duration of the scenario.

10.5.2 Airspace restrictions

The CAA sets a NZV based on VAL, i.e., for each VAL at a given radius from a volcano, planes are not allowed to fly below a certain level. For example, if a volcano is at VAL 2, a plane within 8 nautical miles of the volcano has to fly at or higher than Flight Level 150 (i.e., 15,000 ft or ~4.5 km above sea level). We follow CAA directives for establishing our hypothetical NZV (Lechner 2014; Figure 10.1). We stress that this is not a policy endorsement or recommendation by the authors, GNS Science, or the ERI program.

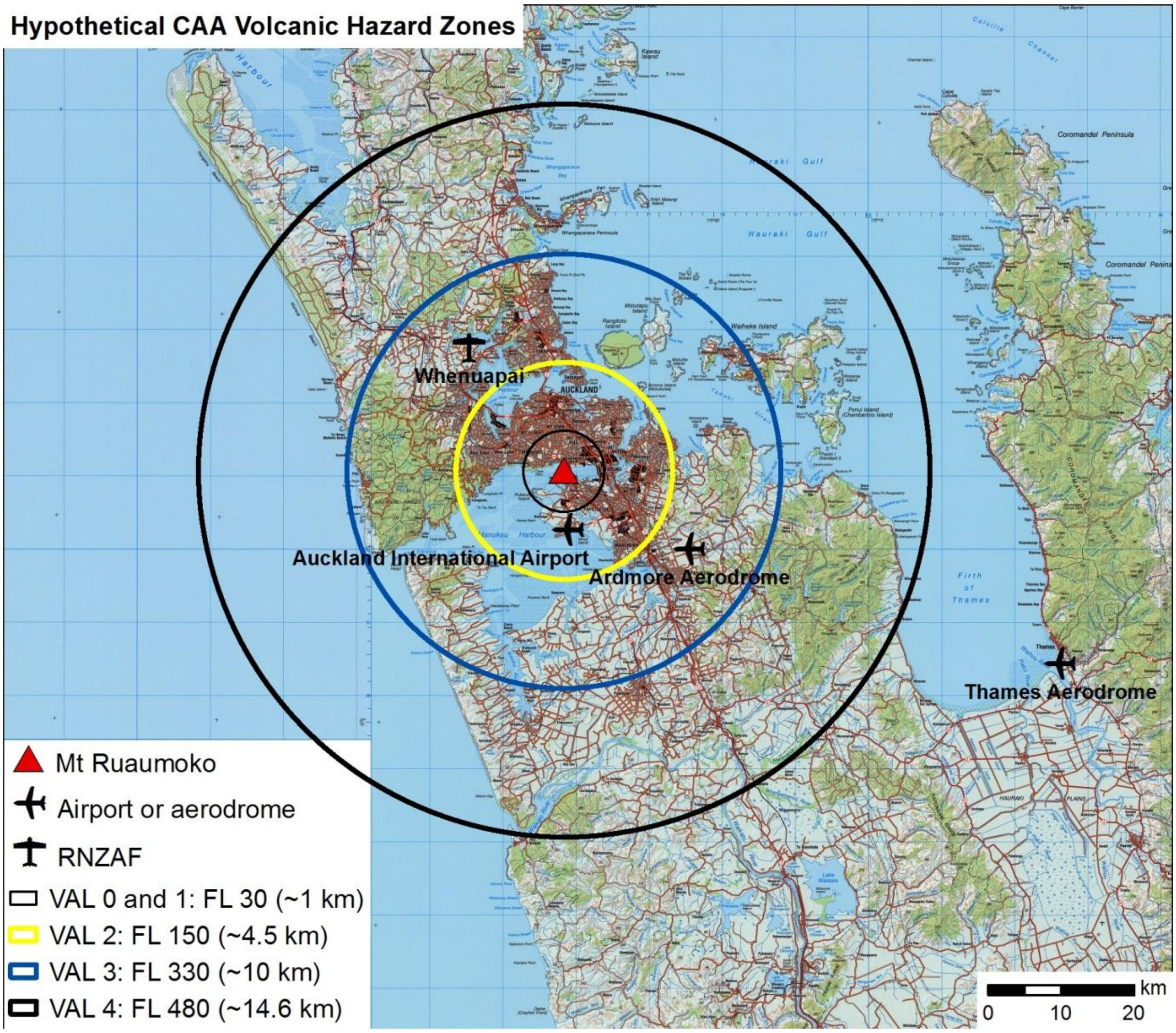


Figure 10.1 Hypothetical CAA Volcanic Hazard Zones for Mt Ruaumoko for the VALs, using zone radii of 3, 8, 16, and 27 nautical miles for VAL 0 & 1, VAL 2, VAL 3, and VAL 4, respectively. The legend indicates the flight level below which pilots require special permission to enter. Mt Ruaumoko is shown with a red triangle, and airports and aerodromes (from LINZ) are indicated with a plane.

The Mt Ruaumoko scenario ends on 16 April when the VAL drops to VAL 2. However, for the aviation sector VAL 1 and 0 are also important. We will assume VAL 1 is set on 1 May, and VAL 0 on 1 June (Table 10.1).

Auckland Airport is within the nominal CAA no-fly zone from 8 March to 1 May. As the runway is roughly oriented east-west and Mt Ruaumoko is to the north, the flight approach shouldn't be sustainably compromised at VAL 1.

Ardmore and Whenuapai are within the nominal CAA no-fly zone from 14–15 March and 18 March–16 April.

10.5.3 Aviation sector level of service

Table 10.1 provides aviation level of service for the Auckland region for domestic, local international and international air traffic for the ERI Mt Ruaumoko scenario. The following assumptions guided the development of this level of service table:

- Progressive Auckland Airport closure during the unrest leading to the Mt Ruaumoko eruptions.
- Auckland Airport is closed when it is in evacuated zones.
- All airports within a no fly zone are closed.
- During Auckland Airport closure, Whenuapai and Ardmore accommodate limited domestic and local international traffic, primarily for cargo.
- No consideration of interdependencies with other infrastructure sectors is taken.

Table 10.1 Auckland region aviation level of service, indicating percentage capacity at various stages of the Mt Ruaumoko scenario.

Date	VAL	Note	Domestic	Local international	International
22 February	VAL 1	Auckland Airport issues a NOTAM, would start making plans for a potential closure.	100%	100%	100%
8 March	VAL 2	Auckland Airport issues a NOTAM indicating airport closure. Minor domestic traffic at Ardmore Aerodrome. Most domestic traffic possibly diverted to Hamilton or Rotorua.	80%	50%	50%
11 March	VAL 2	Auckland Airport issues NOTAM indicating Auckland Airport within evacuation zone.	5%	0%	0%
14 March	VAL 3 and 4	Volcanic eruption begins. No air traffic in or out of Auckland.	0%	0%	0%
15 March	VAL 3		0%	0%	0%
16 March	VAL 2 and 3	Auckland Airport issue a NOTAM indicating it is no longer in evacuation zone but airport remains closed.	5%	0%	0%
21 March	VAL 3 and 4	Volcanic eruption resumes. No air traffic in or out of Auckland.	0%	0%	0%
5 April	VAL 3	Auckland Airport issue a NOTAM indicating it remains outside the evacuation zone with the new evacuation orders. Airport minimally opened. Some airlines request daytime access to no fly zone.	10%	0%	0%

Date	VAL	Note	Domestic	Local international	International
8 April	VAL 3	Auckland Airport full operations resume.	80%	25%	10%
16 April	VAL 2	Auckland Airport issue a NOTAM that VAL has decreased.	80%	30%	10%
1 May	VAL 1	Auckland Airport partially reopened	80%	50%	10%
1 June	VAL 0	Auckland Airport reopens	80%	80%	25%
15 June	VAL 0	Auckland Airport fully open, although some airlines and/or routes may take a while to re-establish	100%	100%	100%

10.6 LIKELY INTERDEPENDENCIES

Operationally, the aviation sector is reliant on fuel (Section 7), which is supplied to Auckland Airport via a pipeline from the Wiri Oil Services Limited (WOSL) terminal. There are five storage tanks at Auckland Airport, enough supply for three–four days at normal operation (three days during summer peak demand). It is unlikely that trucks would be able to supply the fuel required at current levels were the aviation pipeline damaged. In the fuel outage table (Table 7.1) no aviation fuel is delivered to Auckland Airport between 9 March and 15 June.

Auckland Airport is dependent on whether it is within evacuation orders, and is dependent on road access (also subject to evacuation orders) for personnel, passengers, and freight.

Auckland Airport requires staff to operate – airline personnel, pilots, cabin crew, airport staff, immigration staff, etc. Without immigration staff passengers may not disembark international flights – international flights would have to be processed at one of the other international airports (Hamilton, Rotorua, Wellington, Christchurch, Queenstown, and Dunedin).

Auckland Airport also relies on a functional water supply. Without firefighting capabilities the airport category is greatly downgraded and so is effectively shut. Passengers and hospitality businesses (e.g., airport eateries) also require potable water.

Passengers and staff require a working wastewater system. The internal backup wastewater arrangements during normal airport operations can meet demand for several hours, although there are contractual contingency plans in place to remove sewage prior to when the backup system is full, so it can potentially last longer. Raw sewage could be trucked to a facility in South Auckland or alternatively discharged to sea.

Auckland Airport has emergency generators and a diesel stockpile, which, when coupled with power saving measures such as reduced air conditioning, can generate the required power supply for at least a week.

11.0 PORT

11.1 VOLCANIC IMPACTS TO PORTS

There is documentation of volcanic eruptions causing port closure or damage due to tephra fall, lava flows and pyroclastic density currents and tsunami (Blong, 1984, Wilson et al., 2014). However, compared to other transportation networks these impacts are relatively infrequent. Site destruction is the most severe impact, engendered by PDCs, lava flows or tsunami. Disruptions may occur if tephra needs to be cleaned up. Presumably ports may be impacted due to interdependencies with other critical services, although there are no examples of this in a volcanic context.

11.2 PORT LEVEL OF SERVICE METRICS

We did not have the opportunity to meet with staff from Ports of Auckland. From an end-user point of view, the purpose of the Port is to send and receive goods. If the Port is closed for any reason related to the scenario, it will not be able to provide this service. In addition, there is limited physical damage to the Ports in this scenario. As such, we use only two metrics for Ports: open or closed.

As ports are single sites rather than networks, it is not possible to produce a spatial level of service map (similar to aviation). Rather, we note whether a port site is open or closed.

11.3 PORTS OF AUCKLAND

Auckland is serviced by Ports of Auckland, a council-owned company. Ports of Auckland has three sites: Port of Auckland, the main seaport, located in the Waitemata Harbour, Port of Onehunga, located in the Manukau Harbour, and the Wiri Intermodal Freight Hub, located in Wiri, South Auckland.

Marinas and boat ramps are not considered in this scenario, although some will be impacted.

11.4 MT RUAUMOKO SCENARIO

Only one of the Ports of Auckland facilities, the Port of Onehunga, the smallest and arguably least important of the three facilities, is directly impacted by the Mt Ruaumoko scenario. It is within the first and subsequent evacuation zones and is completely destroyed in the first eruption on 14 March. Table 11.1 provides a level of service table for the Port of Onehunga for the Mt Ruaumoko scenario.

Table 11.1 Port of Onehunga level of service table for the Mt Ruaumoko scenario. Other Ports of Auckland facilities are not directly affected.

Date	Port of Onehunga Status	Comment
7 March	Open	
8–11 March	Closed	Within evacuation zone. Vessels diverted to other ports, removal of stockpiled material.
12–13 March	Closed	Within evacuation zone. No personnel access.
14 March	Closed	Site destroyed, permanent closure.

The eruption changes the landscape where the Port of Onehunga used to be and also devastates the local built environment. A rebuild would not occur at the same site as the area becomes landlocked. However, it is possible that another port elsewhere in the Manukau Harbour, or indeed somewhere else in the Auckland region would be built.

11.5 LIKELY INTERDEPENDENCIES

As with other infrastructure, there may be reductions in capacity levels due to the (un)availability of staff.

Ports of Auckland is an important consumer of diesel fuel, accounting for nearly a quarter of diesel fuel used daily by CDEM-Critical Customers (e.g., Police, Health, Auckland Airport; Auckland Council, 2013b). During a power outage it requires additional diesel for power generators. It has no reliance on other types of fuel.

Rail is an important interdependency, particularly for the Wiri Intermodal Freight Hub (see Section 9). Likewise, a functional road network is critical for moving cargo from the port to consumers.

Finally, the long term discharge of wastewater into the ocean may deter certain sectors from using the port due to hygiene, reputation, or other concerns. For example, it is possible cruise ships may want to avoid raw sewage laden waters.

12.0 WATER SUPPLY

12.1 VOLCANIC IMPACTS TO WATER SUPPLY

Proximal volcanic hazards (lava flows, pyroclastic density currents and surges, and ballistics) can cause minor to severe damage or complete destruction of any exposed water supply assets. These can include water treatment plants, reservoirs and pumping stations. Reservoirs and pumping stations may be either above-ground (exposed) or below-ground (buried). Watermains (transmission lines) are generally buried and relatively invulnerable to direct damage from volcanic hazards, with the potential exception of lava flows and ground deformation associated with magma intrusion. Pre-emptive closure of sections of watermains where damage is anticipated may also occur, as breakages in transmission lines will cause depressurisation and allow contamination intrusion. If the area of depressurisation is larger than the treated area, then a precautionary boil water advisory and/or bacteriological testing should be considered.

Volcanic ash is generally the most disruptive and widely dispersed volcanic hazard, potentially falling hundreds to thousands of kilometres from its source. An ashfall can (Stewart et al., 2006; Wilson et al., 2012):

- Cause changes to water quality in raw water sources;
- Create high water demand during the cleanup phase, which can in turn lead to water shortages;
- Cause operational problems for water treatment plants.

In general, the major effect of ashfall on the water quality of raw water sources is likely to be increased turbidity (suspended solids) rather than changes in chemical composition. Increases in turbidity can cause problems for water treatment plants, although the extent to which this occurs is strongly dependent on the design of the treatment system. Resilient design features may help to mitigate against damage. An increased water demand is extremely common following an ashfall, as the cleanup phase begins, and should be anticipated and planned for.

12.2 WATER SUPPLY LEVEL OF SERVICE METRICS

Buxton et al. (2014) developed electricity and water outage scenarios for Auckland, with Watercare Services Ltd identifying areas with water supply outages as the result of an outage scenario involving the failure of both the Number 1 and Number 2 tunnels at Ardmore. This would result in an interruption to the southern Hunua's supply into Auckland for a two-week period. The supply level of service metrics developed by Buxton et al. (2014) and used here are:

- potable water;
- non-potable water;
- water restrictions; and
- no water.

12.3 WATERCARE WATER SUPPLY NETWORK

An overview of the Auckland metropolitan water supply network is as follows:

- Raw (untreated) water sources for the regions include abstraction from the Waikato River (11%); intakes on dams in the Hunuas (62%) and Waitakeres (24%), and from a groundwater source in Onehunga (~3%). Thus at least 70% of Auckland's water supply comes from the south of the city. Raw water is piped through raw watermains to water treatment plants.
- Water treatment plants serving the metropolitan network are Ardmore, Huia, Waitakere, Waikato and Onehunga. Ardmore has the largest production rate (350 ML/d) whereas Onehunga is just 20 ML/d and primarily supplies the local borough.
- Treated water is then piped into the city via dedicated watermains (bulk supply pipelines). From the south, there is a bottleneck in the bulk supply pipelines at Redoubt Road. After Redoubt Road, the supply divides into three bulk pipelines (Hunua 1 to Hunua 3). A fourth pipeline Hunua 4 is under construction and is scheduled for completion by 2020.
- The network has a number of storage reservoirs which may be either buried (below ground) or exposed (above ground), and control valves to balance needs of water users in different balance zones.
- Considerable lengths of the network are gravity-fed, but there are also pumping stations at key locations. Pump stations are either buried or exposed. A strategic pumping station at New Lynn has backup power generation capability that can be remotely activated, but most other pumping stations may require in-person starting of backup generators in the event of power outages.
- Local distribution networks deliver water to individual consumers.
- Resources required for water treatment include energy (power for water treatment plants and pumping stations) and chemicals for water treatment.
- The metropolitan water supply network is operated from Watercare's head office in Newmarket, with a backup facility at the Mangere wastewater treatment plant.

Watercare's water supply network, which services the entire Auckland Region, is shown in Figure 12.1. Key network assets (water sources, water treatment plants, watermains and reservoirs) are shown on the map, along with water balance zones.

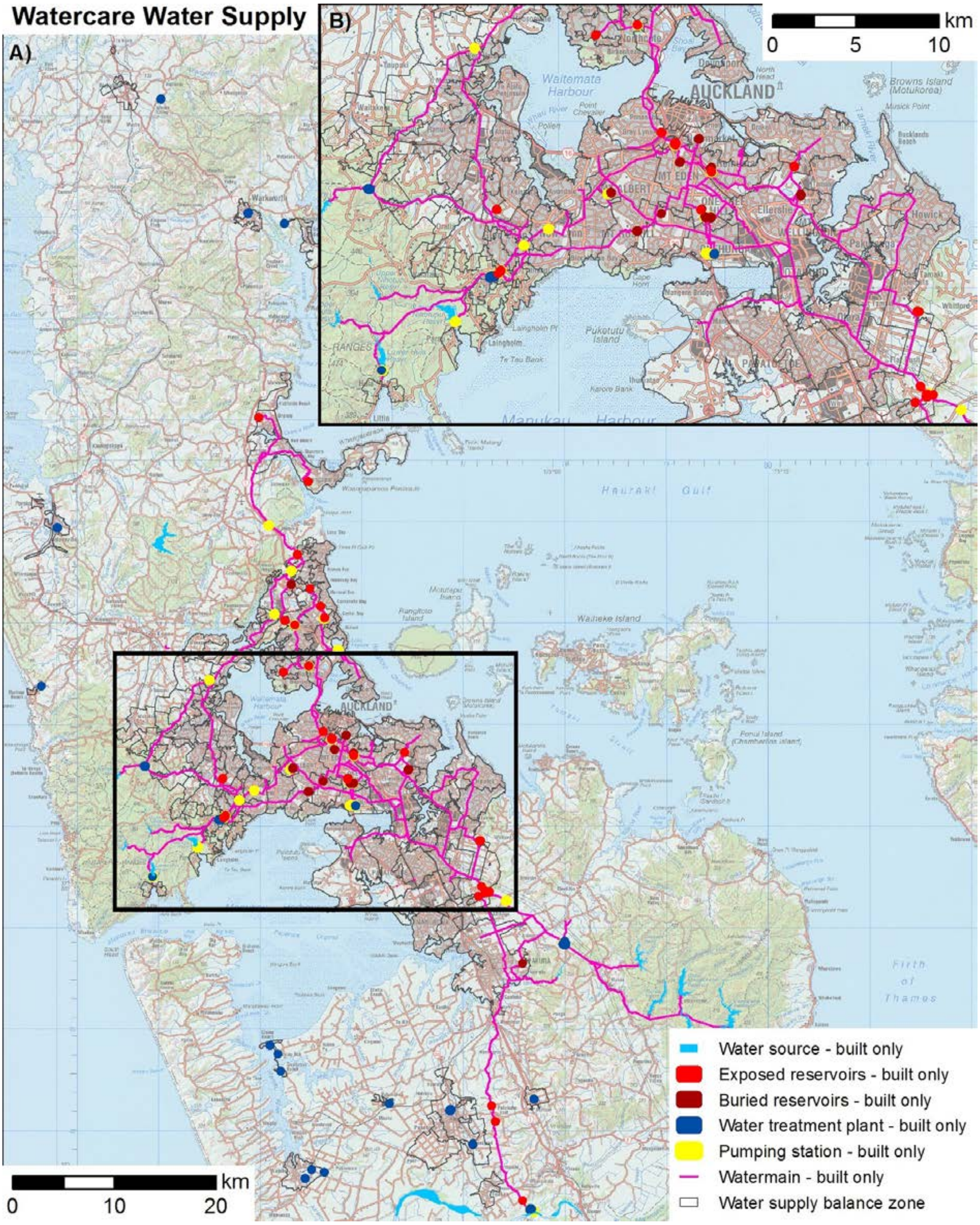


Figure 12.1 (A) Watercare water supply network, with (B) close up for the main population centre. Water sources are light blue, exposed reservoirs are in red, buried reservoirs are maroon, water treatment plants are dark blue, pumping stations are yellow, watermains are magenta, and water balance zones are outlined in grey.

12.4 MT RUAUMOKO SCENARIO

12.4.1 Assumptions about impacts on key network elements

12.4.1.1 Water sources

Dams in the Hunua and Waitakere ranges, together with their associated headworks, are assumed to be unaffected by events in this scenario. Very thin tephra falls (<1 mm) are expected to have a negligible impact (Stewart et al., 2006) either on raw water quality or the operation of the plant.

12.4.1.2 Water treatment plants

The Waikato, Ardmore, Huia and Waitakere plants are assumed to be unaffected by events in the scenario. The Onehunga plant is within the zone of complete destruction of all surface structures.

While the water treatment plants depend on electricity supply, all plants have onsite backup power generation, with sufficient fuel reserves for four days' operation. It is assumed that in the event of total power outages and road access being restricted, fuel would be airlifted into the Huia water treatment plant to ensure that it remained fully operational.

12.4.1.3 Water mains (transmission lines)

Figure 12.2 shows the location of watermains on the Auckland central isthmus. We note that the following watermains are listed as Criticality 1 assets (AELP-2, 2014): Hunua 2, Hunua 3, Huia 2, Epsom 1 and 2, and Northshore 1. Here we assume that the destruction of the Onehunga water treatment plant will compromise the integrity of the Onehunga 1 to 5 watermains; this will in turn force pre-emptive closures of adjoining watermains (Hunua 3, Epsom 1 and 2, and Campbell Rd 1 and 2). The assumption is that the junctions between Onehunga 1 to 5 and adjoining watermains may be damaged, which would in turn lead to a risk of breaching the other watermains causing depressurisation and allowing contamination intrusion.

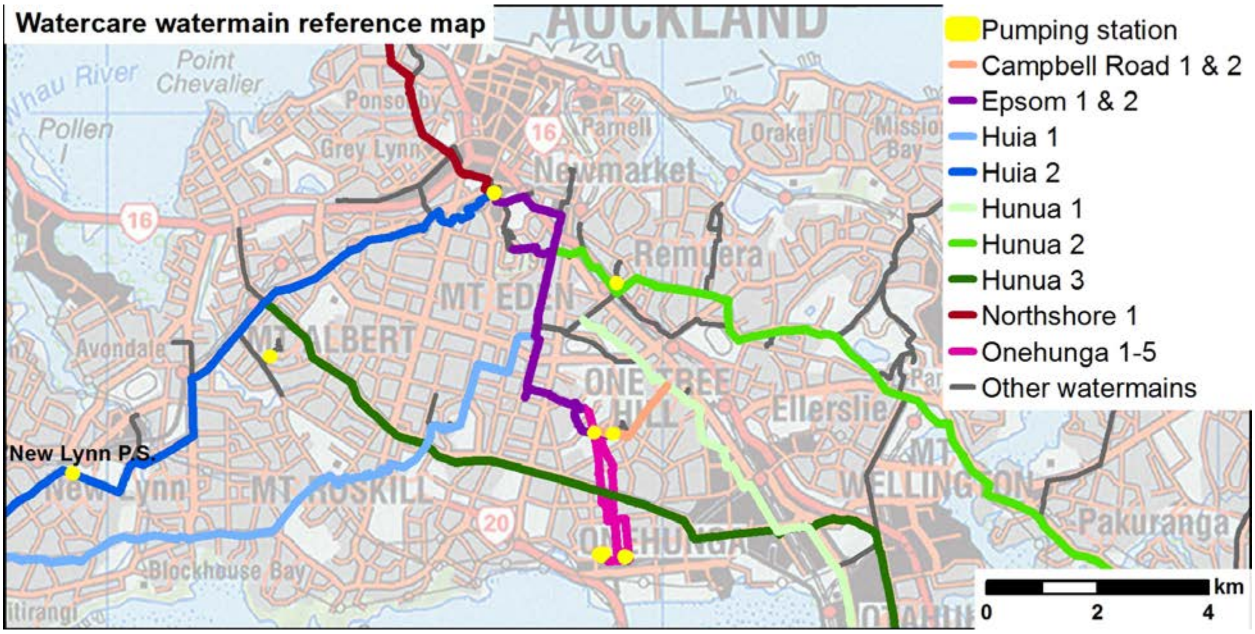


Figure 12.2 Water transmission lines on Auckland central isthmus colour coded by name (see legend).

Of these closures, the most significant is Hunua 3 as it is a major component of the supply into central Auckland. Taking Hunua 3 offline is expected to severely limit the supply into central Auckland and to the North Shore and Whangaparaoa. Widespread water restrictions would be the primary method of balancing the needs of users across the region. These restrictions would remain in place until repairs are completed, and for a further two weeks while decontamination measures are carried out.

12.4.1.4 Reservoirs

Here we assume that exposed reservoirs will be destroyed within the base surge zone of 'heavy structural damage' to buildings (buried infrastructure unaffected by the surge).

12.4.1.5 Pumping stations

We assume that exposed pumping stations will be destroyed within the base surge zone of 'heavy structural damage' to buildings (buried infrastructure unaffected by the surge). In terms of dependence on electricity, only the New Lynn pumping station has onsite backup power generation that can be activated remotely. Other pumping stations require manual start of generators, thus any located within the PEZ will not be able to be activated if they fail. Otherwise we assume that priority will be given to keeping pumping stations operational.

12.4.2 Impact maps

Table 12.1 summarises impacts to assets over the course of the Mt Ruaumoko eruption. We show both network status and damage in subsequent figures: Figure 12.3 for 12–13 March (pre-event mitigative measures), Figure 12.4 for 14 March (initial eruption impact), Figure 12.5 for 16 March (change in evacuation zones), and Figure 12.6 for 21 March (tephra fall).

Table 12.1 Impacts on the water supply network during Mt Ruaumoko scenario events.

Date	Relevant event details	Impact summary	Figure
12–13 March	13 March PEZ implemented, pre-event evacuation	Onehunga WTP taken offline Onehunga 1–5 watermains taken offline as damage expected Adjoining watermains taken offline to isolate damaged section: • Hunua 3 between Hunua 1 and Huia 1 • Epsom 1 from Onehunga low pump station to Huia 1 • Campbell Rd 1 and 2 Mangere is taken offline as Mangere Wastewater Treatment Plant watermain is offline	12.3
14 March AM	Base surge causes complete destruction 0–4 km from vent, minor damage to weaker structures 4–6 km from vent. Tephra fallout in afternoon	Onehunga WTP and associated pumping station destroyed One Tree Hill reservoir destroyed Four wells in Onehunga destroyed	12.4
16 March–4 April	New PEZ and SEZ established	No additional damage No access into PEZ for repairs	12.5
21 March	21 March: base surge and tephra plume to NW.	No additional damage	12.6

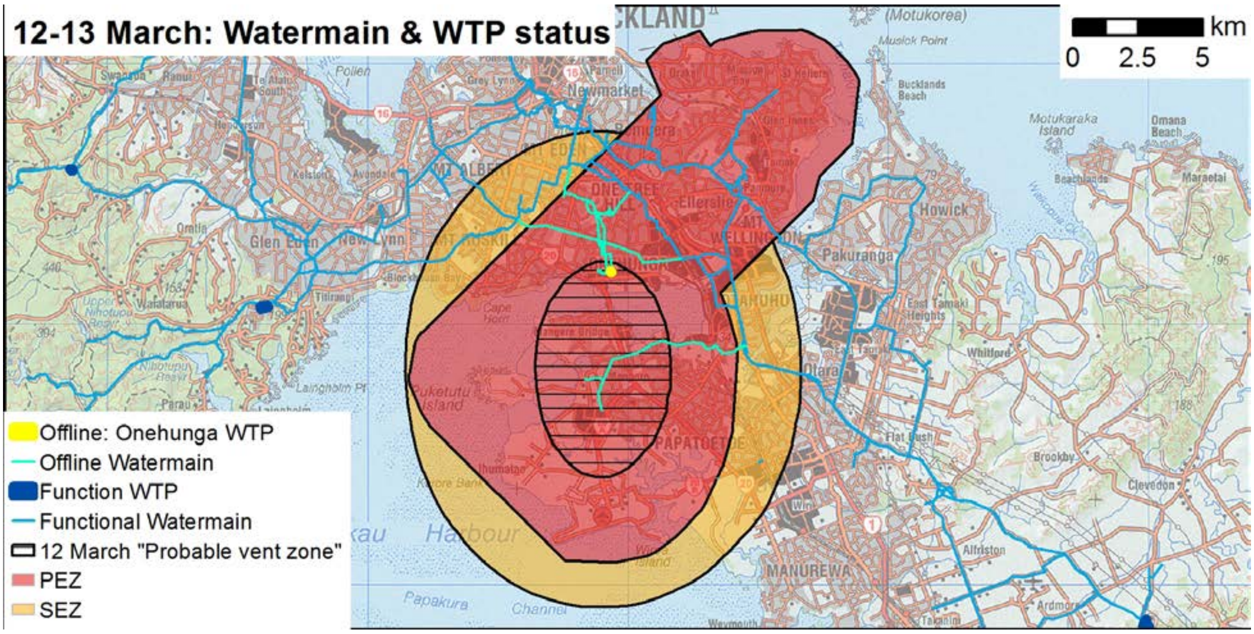


Figure 12.3 Water supply network status map for 12–13 March. Functioning watermains shown in light blue, offline pumping stations in teal, functioning water treatment plants in dark blue, and offline water treatment plants in yellow. The PEZ (red) and SEZ (orange) are shown along with the probably vent zone for 12 March (hatched).

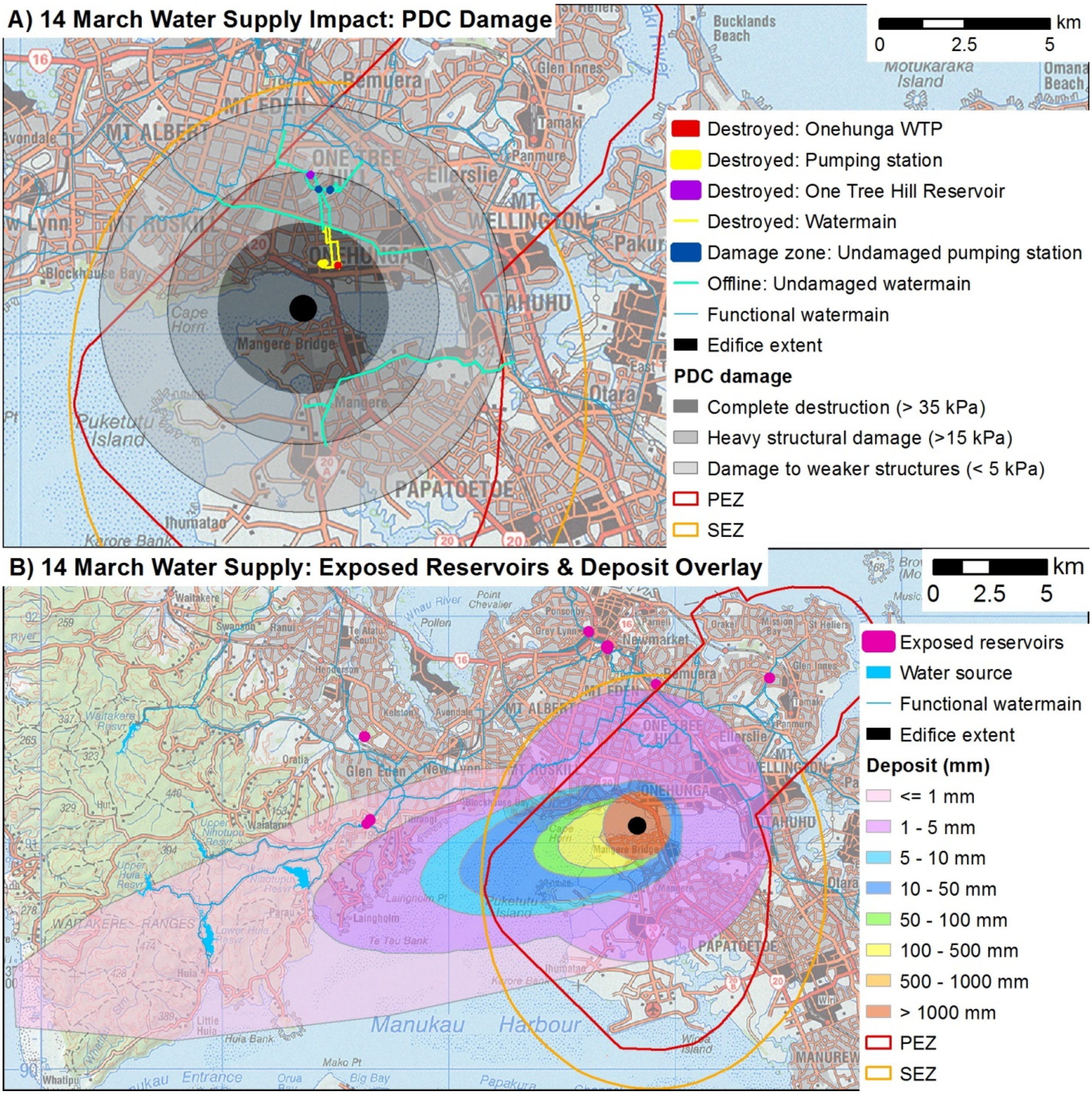


Figure 12.4 (A) Damage to water supply network assets on 14 March and (B) overlay of tephra fall deposit and exposed reservoirs (magenta) and water sources (light blue).

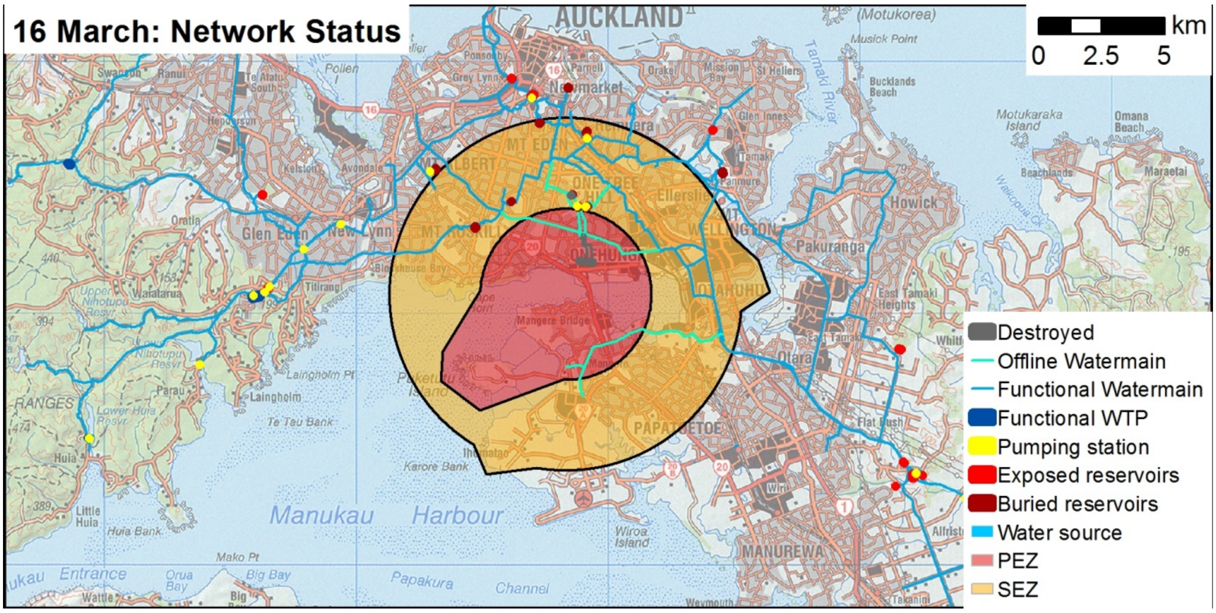


Figure 12.5 Network status in relation to PEZ (red) and SEZ (orange) established during 16 March–4 April.

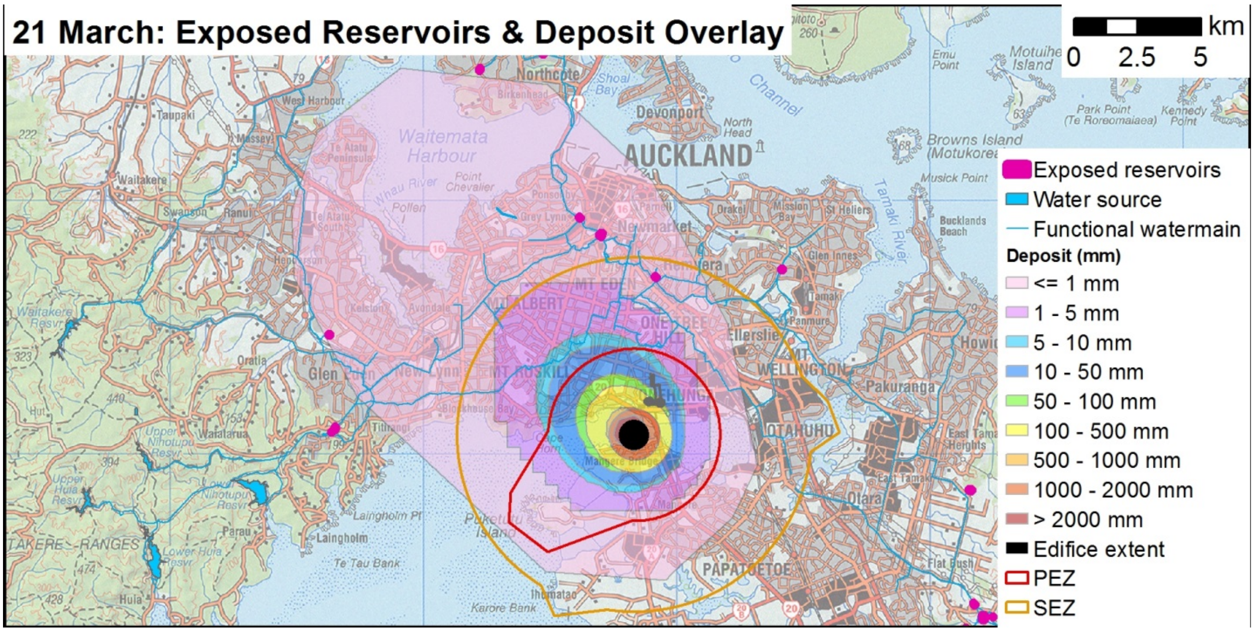


Figure 12.6 Overlay of 21 March tephra fall deposit and exposed reservoirs (magenta) and water sources (light blue) indicate no further damage is expected.

12.4.3 Watercare water supply network level of service maps

Expected water outages for different time periods are described in the following sections. Our general assumptions are that outages are dictated primarily by the reduced capacity of the water transmission system through the Auckland central isthmus, in conjunction with an increased level of water demand associated with cleanup of base surge and tephra deposits. Only a small area is expected to suffer total outages, but water restrictions and boil water advisories are expected to be widespread across the entire region for at least a year.

Water balance zones outside the map area are assumed to have potable water with no restrictions.

12.4.3.1 12 March–4 April

On 12 March, watermains will be pre-emptively isolated (Figure 12.3) as lifeline personnel are evacuated. Taking Hunua 3 offline prompts immediate and severe water restrictions of at least 50% (Figure 12.7). Total outages are expected in the areas where the watermains are isolated. However they are within the PEZ so no there should be no demand.

On 14 March, the eruption is expected to destroy some of the isolated pipes (primarily Onehunga 1 to 5), but the network should be protected from contamination. Thus there should be no change in the status of the network. Water demand for cleanup should be minor as the deposits are located within the evacuation zone. The establishment of the new PEZ and SEZ on 16 March should not change the water supply situation. Similarly, the new eruption (producing a base surge and tephra plume to the NW) is not expected to cause any additional damage. As tephra deposits >1 mm are restricted to within the SEZ, no additional demand for cleanup is expected.

Consequently, the level of service is the same for the period from 12 March to 4 April.

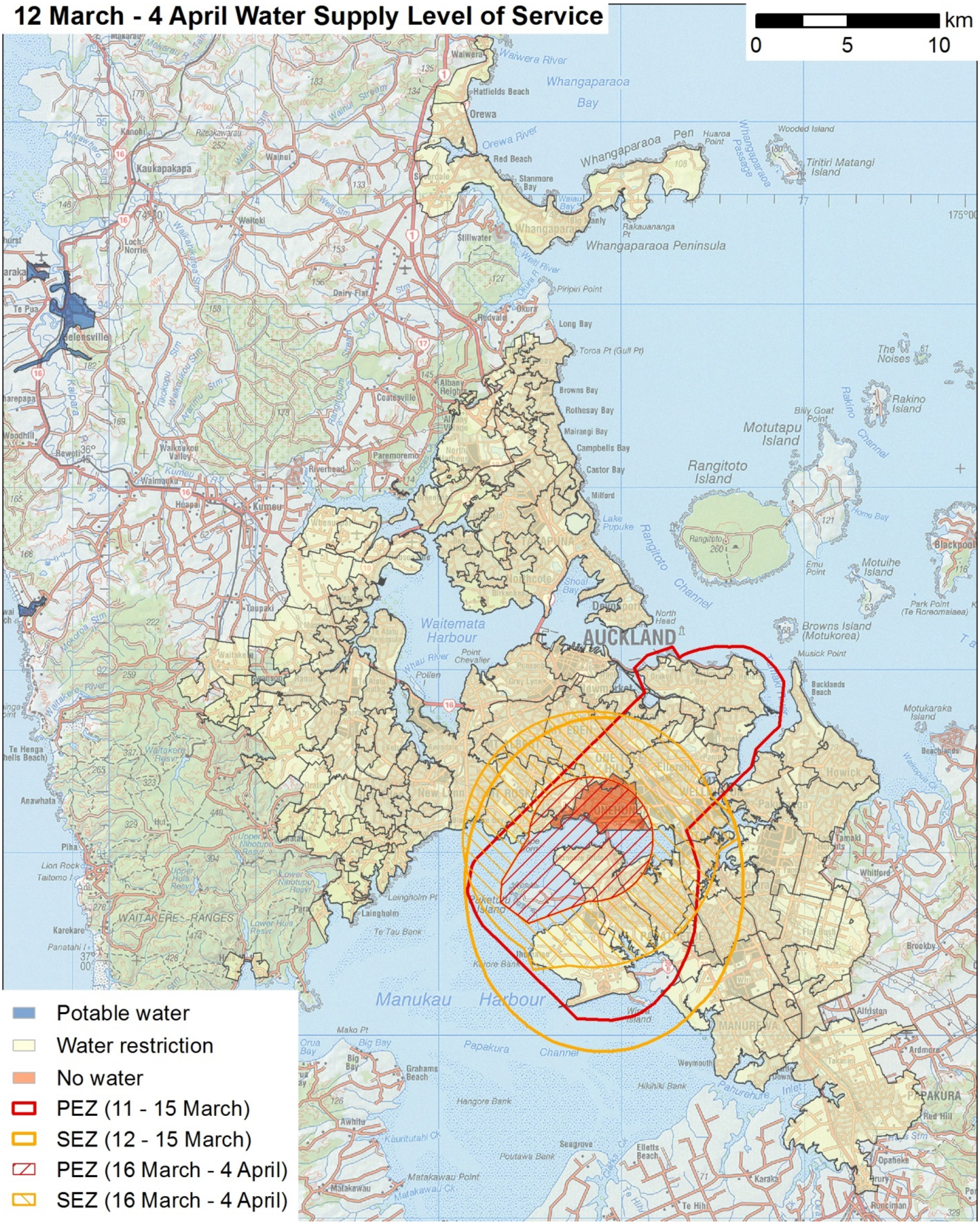


Figure 12.7 Water supply level of service map for period 12 March–4 April. Water balance zones are colour coded according to service level, with blue for potable water, yellow for water restrictions, and red for no water. The PEZs (red outline) and SEZs (orange outline) for this period are indicated, with outlined initial evacuation zones and hatched subsequent evacuation zones.

12.4.3.2 5–30 April

Water restrictions continue throughout this period (Figure 12.8). In addition, 'boil water' notices will be necessary in areas where isolated watermains that may have become depressurised are brought back online. The lifting of the SEZ on 4 April implies that large-scale cleanup will commence, which is expected to increase water demand. During this phase, we have assumed that the line to Whangaparaoa becomes depressurised, necessitating boil water notices in this area as well.

During this phase, it is likely that Watercare would be able to carry out inspections for damage, but it is unlikely that any repair work would be able to be carried out. Planning repair work and ordering replacement parts would likely commence at this stage.

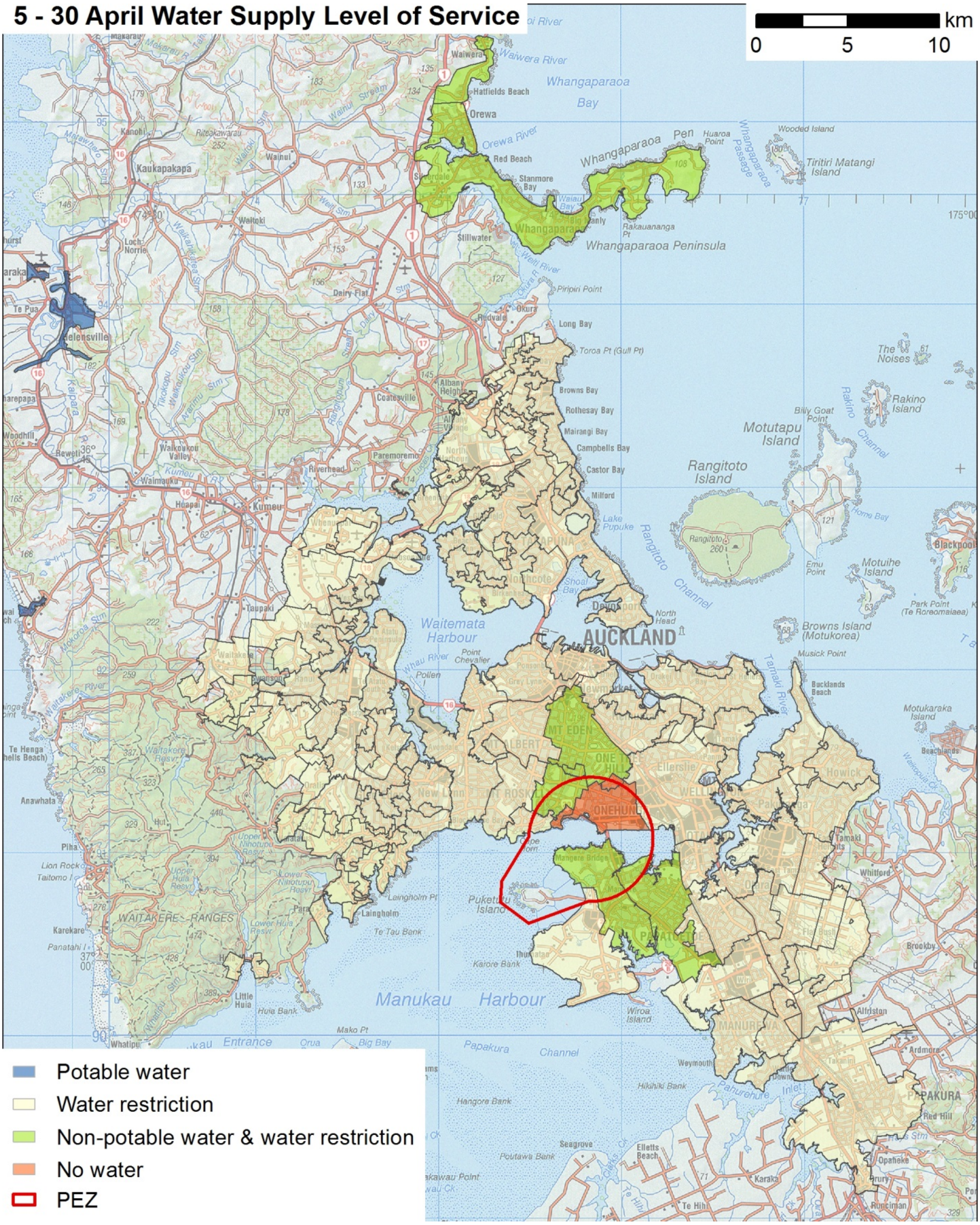


Figure 12.8 Water supply level of service map for period 5 April–30 April. Water balance zones are colour coded according to service level, with blue for potable water, yellow for water restrictions, green for non-potable water and water restrictions, and red for no water. The PEZ (red outline) for this period is indicated.

12.4.3.3 1 May–30 April (in Year 2) (Figure 12.9)

We assume that it takes a year to repair the junction of the Onehunga 1 to 5 and Hunua 3 pipeline, factoring in considerations such as the time required for cleanup and time taken to obtain replacement parts from suppliers. During this time, the water balance zones in the Onehunga area have no water (Figure 12.9). Water restrictions will remain in place during this period. Boil water notices will remain in place for Whangaparaoa, due to the likelihood of depressurisation episodes occurring because of the restricted supply and high demand.

Figure 12.9 Water supply level of service map for period 1 May–30 April of Year 2. Water balance zones are colour coded according to service level, with blue for potable water, yellow for water restrictions, green for non-potable water and water restrictions, and red for no water.

12.4.3.4 1–15 May (Year 2)

Following the restoration of the Hunua 3 watermain and return to full supply, a two week period will be required for decontamination measures and microbiological testing before potable water can be restored to the Whangaparaoa peninsula (Figure 12.10).

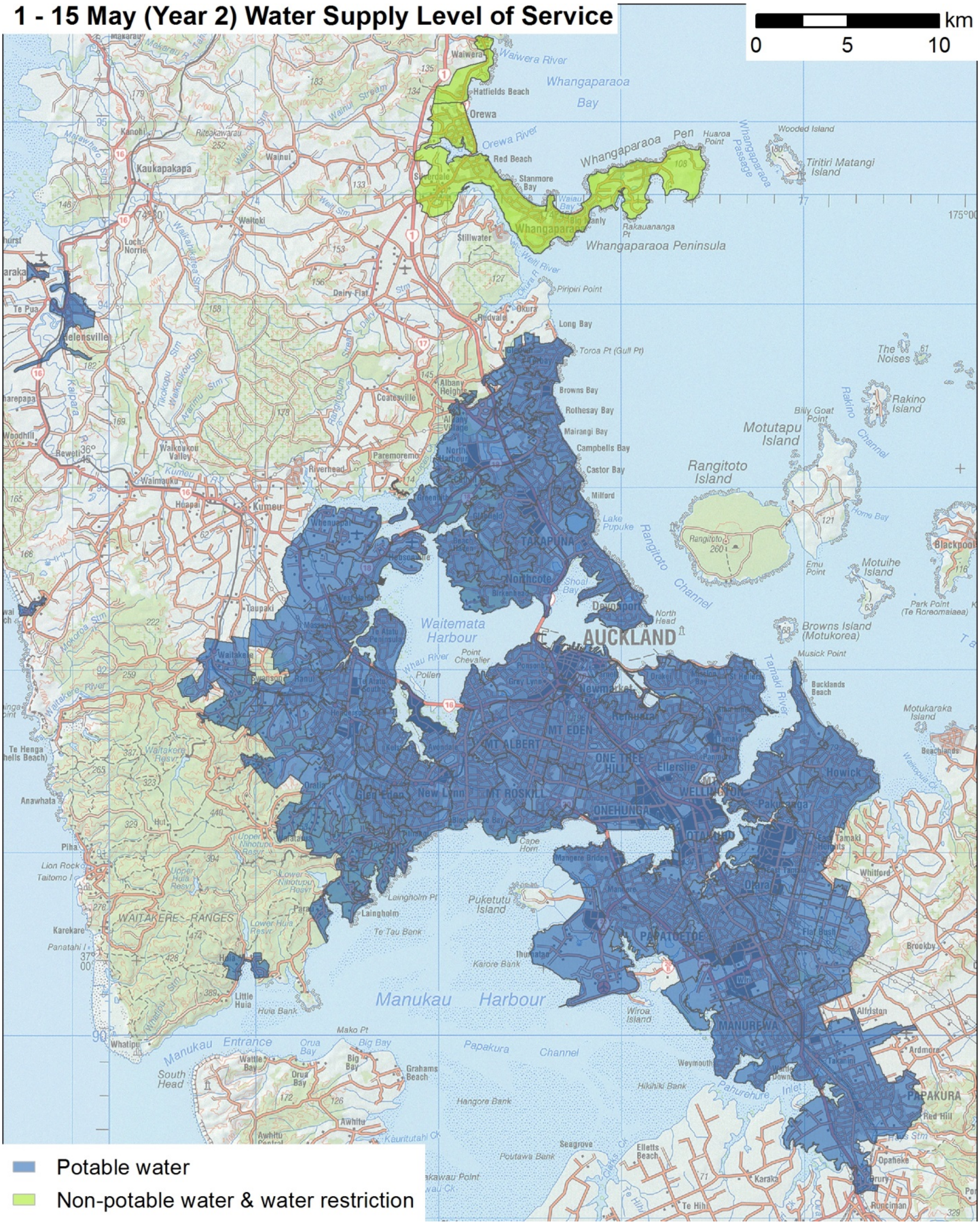


Figure 12.10 Water supply level of service map for period 1 May–30 April of Year 2. Water balance zones are colour coded according to service level, with blue for potable water and green for non-potable water.

12.5 LIKELY INTERDEPENDENCIES

Buxton et al. (2014) identified electricity as an infrastructure that water supply is highly dependent on in order to maintain supply. It is needed at water treatment plants and pumping stations. Watercare advised that their water treatment plants have their own back-up generators, along with a number of the pumping stations. However, not all pumping stations have on-site backup generators and would need to have generators taken to site. The generators would be able to overcome power outages during the rolling outages predicted for this scenario, provided they have fuel. Fuel availability and availability of access routes to the treatment plants and pumping stations for refuelling are therefore also critical.

Watercare advise that it has its own radio communication infrastructure, so water supply is not dependent on usual telecommunication networks.

Many key sectors are dependent on water supply. For example, wastewater removal from private properties relies on water being available. Water is essential for firefighting (usually via hydrants). Auckland Airport depends on water supply for firefighting.

13.0 WASTEWATER

13.1 VOLCANIC IMPACTS ON WASTEWATER NETWORKS

Proximal volcanic hazards (lava flows, pyroclastic density currents and surges, and ballistics) can cause minor to severe damage or complete destruction of any exposed (above-ground) wastewater network assets. These can include wastewater treatment plants and pumping stations.

Wastewater collection systems are highly vulnerable to damage from volcanic ashfall, as it can enter sewer lines where there is inflow or infiltration through illegal connections of building downpipes to the wastewater system, cross connections, gully traps, manhole covers and defective pipe joints. Combined sewer and stormwater collection systems are particularly vulnerable. Ash-laden sewage is likely to cause accelerated wear and tear damage to pump impellers.

Ash-laden sewage can cause extensive and costly damage if it enters a wastewater treatment plant. In particular, mechanical pre-screening equipment is highly vulnerable to damage. It may be preferable to bypass the treatment plant and discharge untreated or partially-treated sewage to the environment to protect the plant from damage. Very thin ashfalls of <2 mm should cause few problems for most waste treatment plants. However, an ashfall of only 10 mm (following the May 1980 eruption of Mt St Helens volcano) on the city of Yakima, Washington was sufficient to cause $US 4 million (1980 value) damage to the city's wastewater treatment plant, primarily because of damage to the mechanically-cleaned bar screen and grit classifier.

13.2 WASTEWATER LEVEL OF SERVICE METRICS

Even if the Mangere wastewater treatment plant is out of service, untreated wastewater can still be removed from individual properties. It will be discharged to the environment at some point, either at overflow points at pumping stations, or via the bypass at the Mangere plant. Thus, at the individual household level, service (wastewater removal) is primarily dependent on the household having sufficient water for toilet flushing. Tephra and surge deposit ingress into sewer lines may also restrict flow in gravity lines and cause wastewater to back up, which may lead to problems with drainage from individual properties. We propose the following level of service metrics:

- Full service;
- Intermittent service (due to drainage problems);
- No service (due to water outages to the property).

13.3 WATERCARE WASTEWATER NETWORK

The major wastewater treatment plant serving metropolitan Auckland is at Mangere. This site and key trunk sewers feeding it are Criticality 2 (regionally significant) assets. Failure of the treatment plant will not necessarily result in loss of service to individual customers, but is expected to cause extended duration discharge of untreated sewage to the Manukau Harbour with potential environmental and human health impacts (AELP-2, 2014).

Public access restrictions to waterfront areas and streams are likely to be utilised to minimise public health risks from the expected widespread discharges of untreated sewage to the environment following failure of the Mangere plant. Overflows and discharges of untreated sewage can be expected at any non-operational pumping station. Normal procedure in the event of a sewage spill (e.g., Whangarei District Council, 2013) involves a rapid notification of the Duty Health Protection Officer at the relevant District Health Board who then assesses the health risk and issues public health advisories as needed. These can take the form of signage at beaches advising against swimming and collecting shellfish, and/or closure of access points such as boat ramps and coastal walkways and reserves.

The key elements of the network are the Mangere wastewater treatment plant; the main (trunk) and local sewer lines; and pumping stations. Important assumptions for each of these elements are discussed in the following section. Protection of these key assets is of vital importance.

13.4 MT RUAUMOKO SCENARIO

13.4.1 Assumptions for impacts on key network elements

13.4.1.1 Mangere wastewater treatment plant

Shutdown procedures would be initiated at the plant prior to a major immediate threat, in order to protect the plant and its equipment to the maximum extent possible. A complete shutdown for an extended closure would take on the order of several days to a week, but if less time were available, worthwhile measures such as raising bar screens to protect them could still be taken.

The assumptions for this scenario are that immediately prior to the eruption the plant would be pre-emptively shut down; the 14 March base surge will cause heavy structural damage that will destroy the facility. The estimated time for full repair is approximately two to three years.

13.4.1.2 Trunk sewer networks

Wastewater networks use a combination of gravity lines and rising mains to convey wastewater from properties to the treatment plant. Pump stations are installed at low points in the network to lift wastewater to a higher point, in pressurised rising mains. From high points the wastewater flows downhill in unpressurised gravity lines. Storage in the network is provided at key critical locations at pump stations, which are built with a storage facility (wet well or stand-alone tank). Wet wells typically provide around four hours of storage in dry weather which reduces the likelihood of overflows from the network (Watercare, 2011).

Key assumptions are as follows:

- Gravity lines should continue to function without problems. Rising mains from non-functioning pumping stations will be undamaged but will not convey wastewater (not shown on the map as this information is not available as a GIS layer).
- Ingress of tephra into sewers (particularly smaller diameter local pipe networks) may cause partial flow restrictions through to total blockage, depending on deposit depth as well as local factors such as rainfall, any cleanup undertaken, and the extent of ingress points such as illegal connections from roofs into sewers. Our assumptions are that:

  - < 5 mm will cause no problems;
  - 5–100 mm will cause flow restrictions;
  - >100 mm will cause complete blockages.
- Wet well storage capacity will be overwhelmed and will not mitigate against untreated wastewater discharges.
- On a small scale, vacuum trucks can be used to remove untreated sewage from local wet wells, but this would be unlikely to be practical for a city-wide crisis.

We have used the following scheme for 'damage states' of sewer lines (Section 12.4.2):

- Green – normal functionality;
- Orange – restricted functionality;
- Red – no functionality (because of lack of pumping);
- Black – no functionality: destroyed.

13.4.1.3 Pumping stations

Pumping stations are important assets and are designed to fail safe and overflow untreated wastewater. They are dependent on continuous power supply. While in normal times there are arrangements in place for mobile backup power generation, it is unlikely that this option would be feasible under the conditions of this scenario because of issues such as road access and access to fuel. Our assumptions are as follows:

- Pumping stations will be destroyed in the zones of complete destruction and heavy structural damage from the base surges.
- No backup power generation will be available.
- Untreated sewage will be discharged to the environment from overflow points at pumping stations during power outages.
- While accelerated wear and tear on pump impellers (due to the abrasive nature of ash-laden wastewater) is likely to greatly increase maintenance requirements, we have not attempted to account for this in this scenario.

We have used the following scheme for 'damage states' of pumping stations (Section 12.4.2).

- Green – normal functioning;
- Orange – intermittent functioning;
- Red – not functioning because of power outage;
- Black – damaged or destroyed.

We note that untreated wastewater discharges to the Manukau and Waitemata Harbours on a large scale and for an extended duration will result from this scenario. While we have indicated likely discharge points on maps, we have not attempted to derive outage metrics such as beach closures and access restrictions.

13.4.2 Impact maps

Table 13.1 summarises impacts expected over the course of the Mt Ruaumoko scenario. We show both network status and damage in subsequent figures: Figure 13.1 for 13 March (pre-event mitigative measures), Figure 13.2 for 14 March morning (initial eruption impact), Figure 13.3 for 14 March afternoon (further impacts), Figure 13.4 for 21 March (tephra fall), Figure 13.5 (end of impacts) and Figure 13.6 (status after evacuation zones lifted).

Table 13.1 Impacts on the wastewater network for the Mt Ruaumoko scenario.

Date	Relevant event details	Impact summary	Figure
13 March	13 March PEZ implemented	Pre-emptive closure of Mangere wastewater treatment plant; bypassing of untreated sewage to Manukau Harbour (shutdown may begin earlier).	13.1
14 March AM	Base surge causes complete destruction 0–4 km from vent, minor damage to weaker structures 4–6 km from vent.	Impacts: Mangere Wastewater Treatment Plant is destroyed with all equipment and buildings being heavily damaged to completely destroyed. Heavy surge deposits near the vent causes flow restrictions in sewer lines. 8 pump stations within the zone of heavy structural damage due to the base surge are destroyed. 16 pumping stations along the Western Interceptor (north-west) lose pumping capacity due to electricity outages (interdependency). 16 pumping stations have partial functionality due to intermittent electricity outages (interdependency). Untreated waste is discharged into Waitemata and Manukau harbours from non-operational pumping stations.	13.2
14 March PM	Tephra fallout	Additional impacts/status changes: Heavy tephra deposits cause flow restrictions in sewer lines. Untreated waste is discharged into Waitemata and Manukau harbours from non-operational pumping stations.	13.3
21 March	Tephra fallout	Additional impacts/status changes Following rainfall, pipelines close to the vent become completely blocked due to heavy ash and surge deposit being washed into the pipelines. Additional tephra and surge deposits in plume to NW causes flow restrictions in some sewer lines. 5 pumping stations regain intermittent power, and so partial functionality (interdependency). Untreated waste is discharged into Waitemata and Manukau harbours from non-operational pumping stations.	13.4

Date	Relevant event details	Impact summary	Figure
30 March	Tephra fallout	Additional impacts/status changes: Following rainfall and additional tephra fall, pipelines close to the vent become completely blocked. There are flow restrictions along additional sewer lines 1 pumping station loses functionality due to loss of power (interdependency).	13.5
1 May	14 March PEZ lifted Permanent Exclusion Zone implemented	Additional impacts/status changes: Full restoration of power supply so all surviving pumping stations are fully operational. Pipeline with flow restrictions (not blockages) are cleaned and restored to full functionality. Discharge of untreated waste should be primarily limited to Manukau Harbour. This will continue until Mangere WWTP is repaired and online, approximately 2–3 years.	13.6

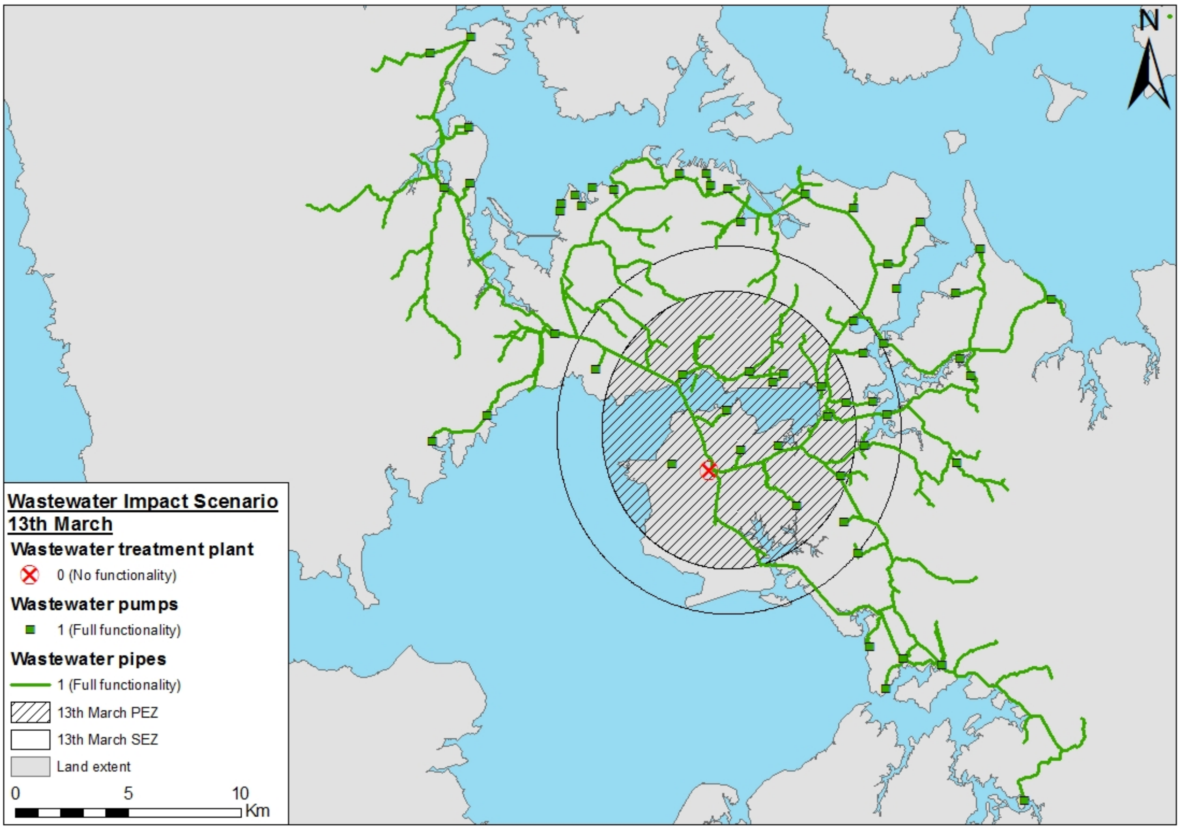


Figure 13.1 Wastewater status map for 13th March. In red is the Mangere Wastewater Treatment Plant (no functionality). Green squares are functioning water pumps and green lines are wastewater pipes. The PEZ (hatched zone) and SEZ (black outline) are shown for reference.

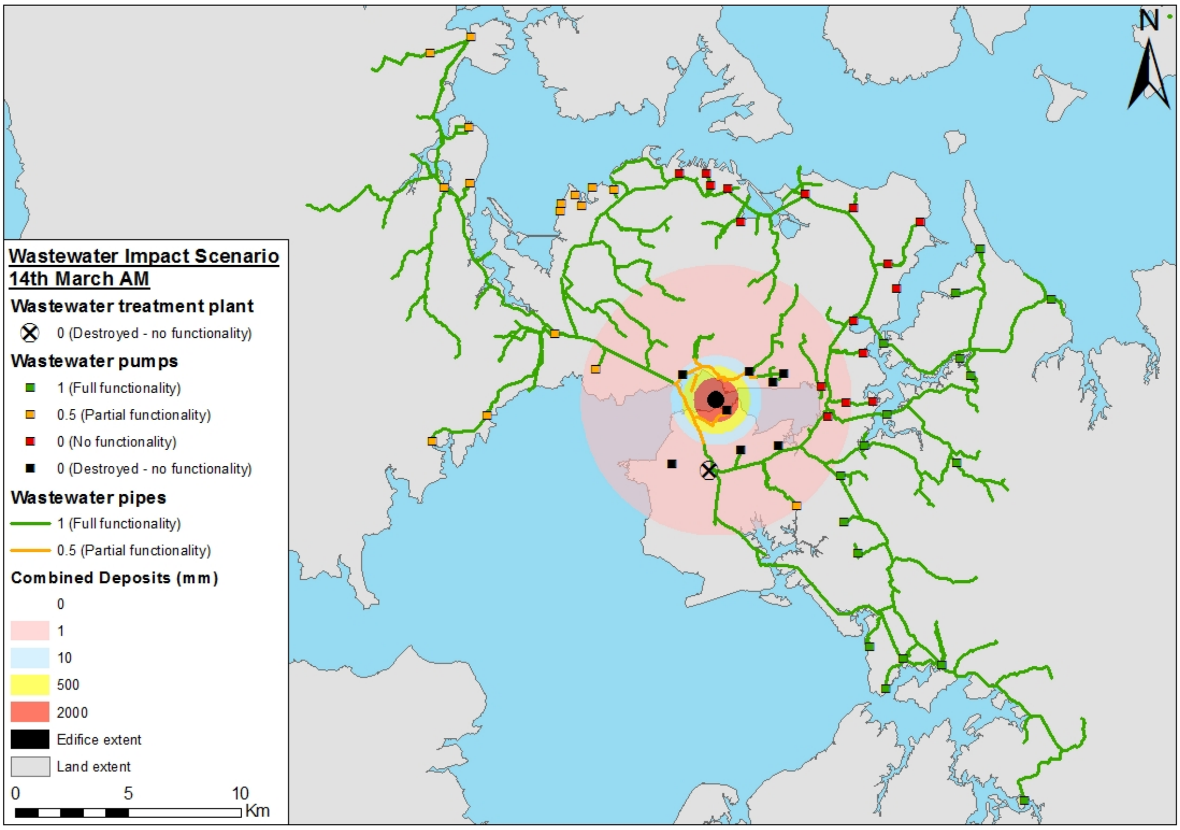


Figure 13.2 Wastewater impacts for 14 March AM, with deposit thickness coloured by thickness (see legend). The edifice is shown in black. Assets with full functionality are green, assets with partial functionality are orange, pumps with no functionality are red, and destroyed assets are black.

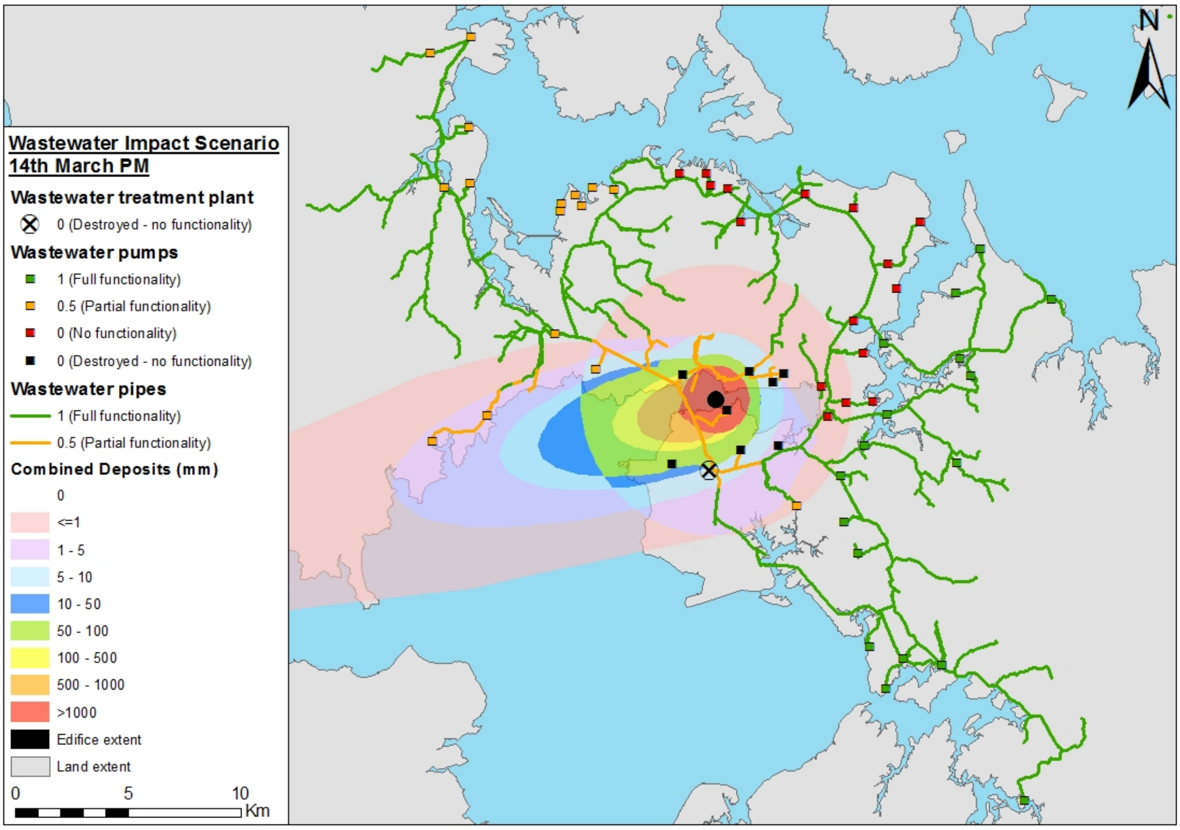


Figure 13.3 Wastewater impacts for 14 March PM. Hazard and asset state are coloured as in Figure 13.2.

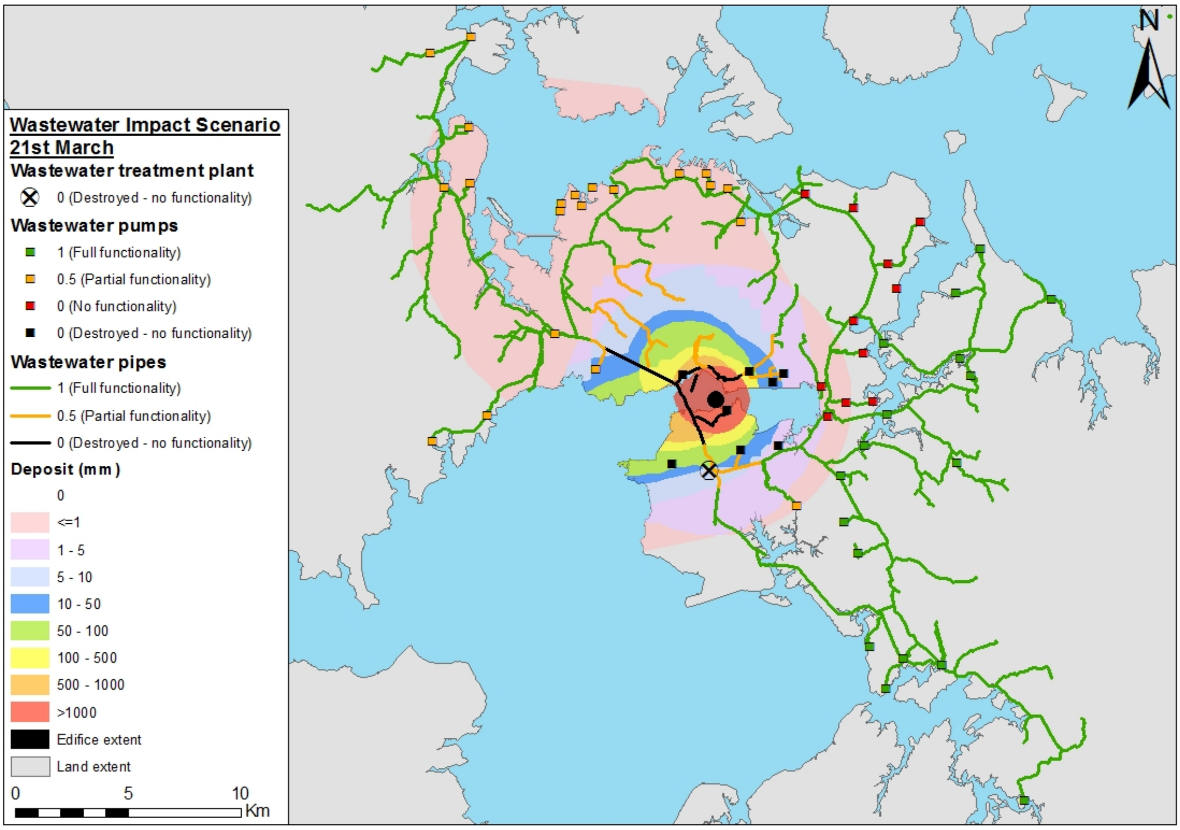


Figure 13.4 Wastewater impacts for 21 March. Hazard and asset state are coloured as in Figure 13.2.

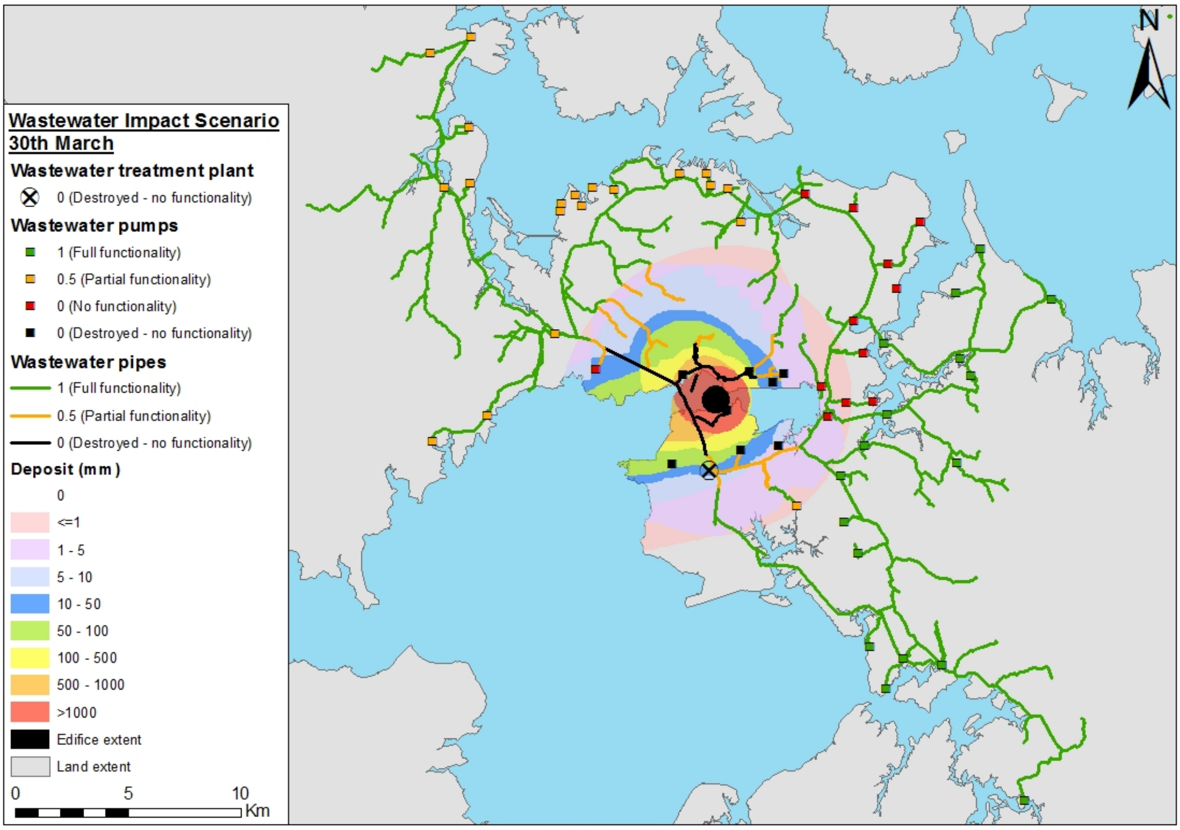


Figure 13.5 Wastewater impacts for 30th March. Hazard and asset state are coloured as in Figure 13.2.

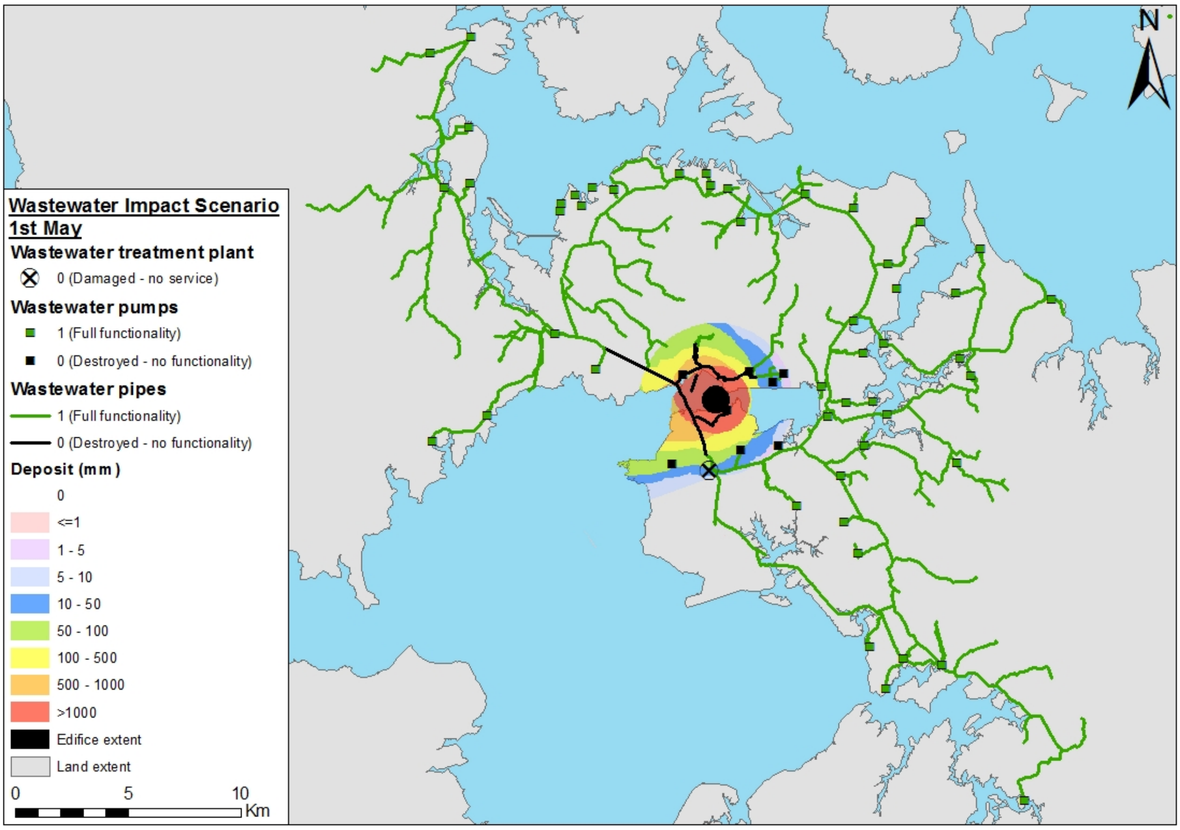


Figure 13.6 Wastewater impacts for 1 May. Hazard and asset state are coloured as in Figure 13.2.

13.4.3 Wastewater level of service maps

As noted in Section 13.2, wastewater services to individual customers are likely to depend primarily on the household or building having sufficient water for toilet flushing. Tephra and surge deposit ingress into sewer lines may also restrict flow in gravity lines and cause wastewater to back up, which may lead to problems with drainage from individual properties. Level of service maps (Figure 13.7 to Figure 13.12) have been constructed based on these two assumptions.

Figure 13.7 Wastewater level of service map for 13 March. In green are community boards with full service.

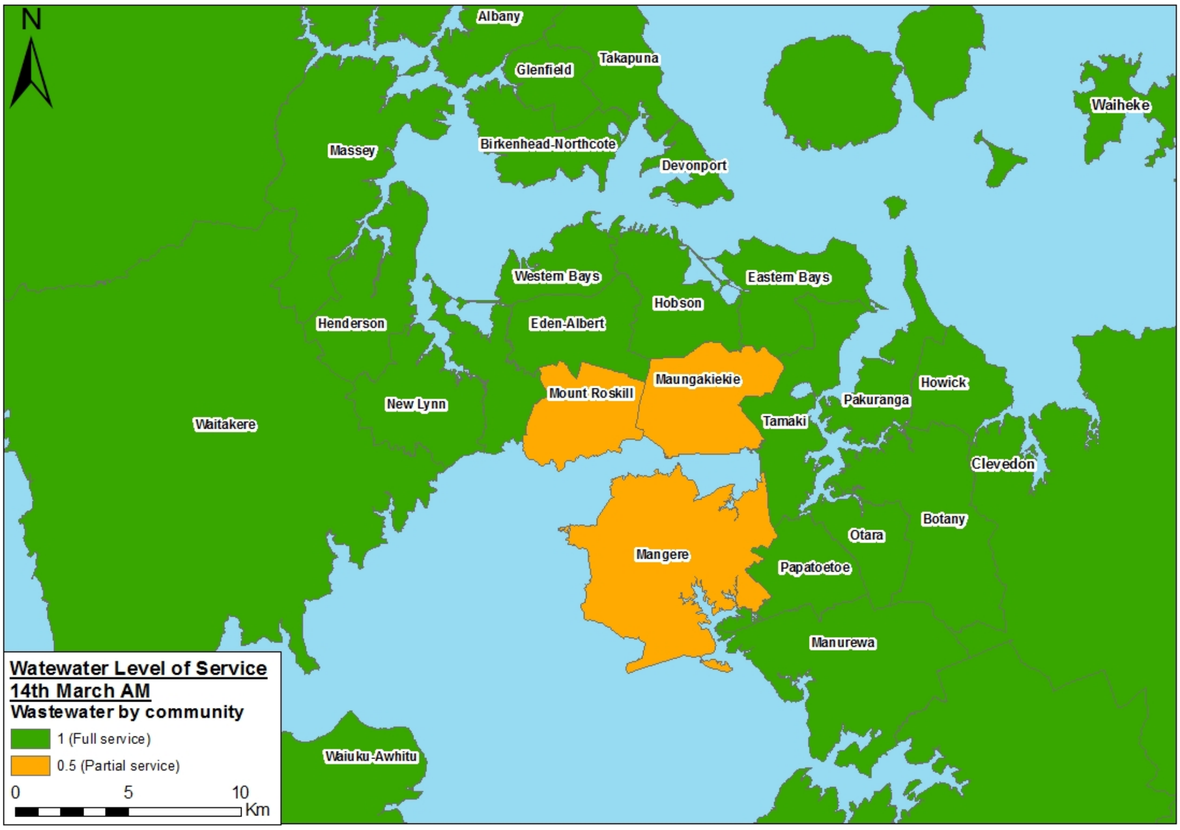


Figure 13.8 Wastewater level of service map for 14 March AM. In green are community boards with full service and in orange are community boards with partial service.

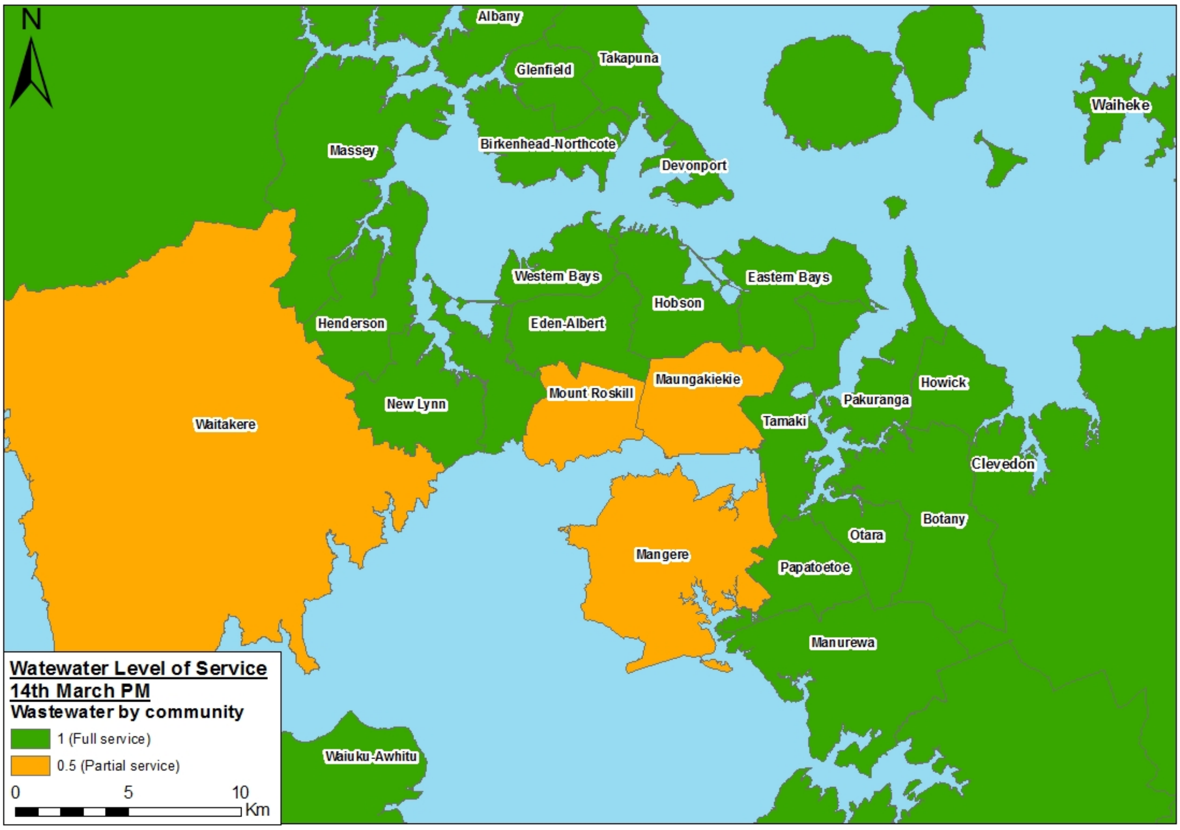


Figure 13.9 Wastewater level of service map for 15 March PM. In green are community boards with full service and in orange are community boards with partial service.

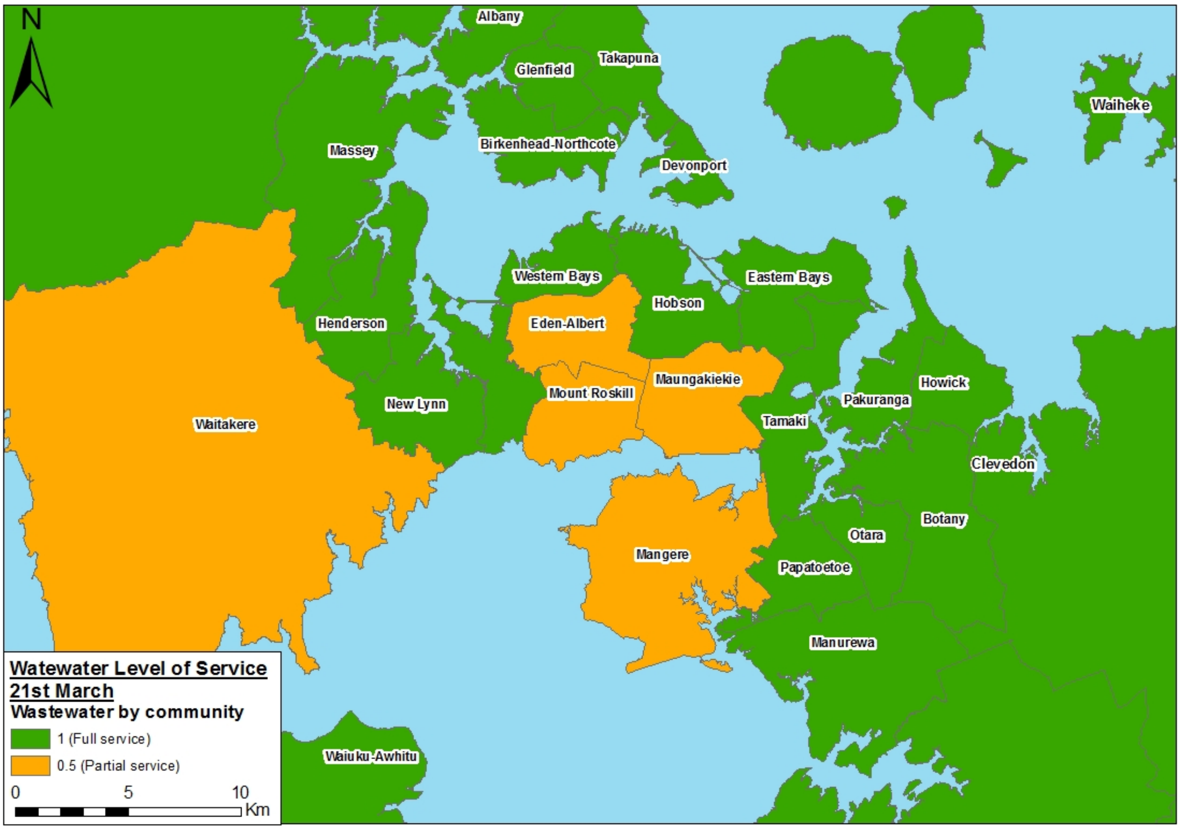


Figure 13.10 Wastewater level of service map for 21 March. In green are community boards with full service and in orange are community boards with partial service.

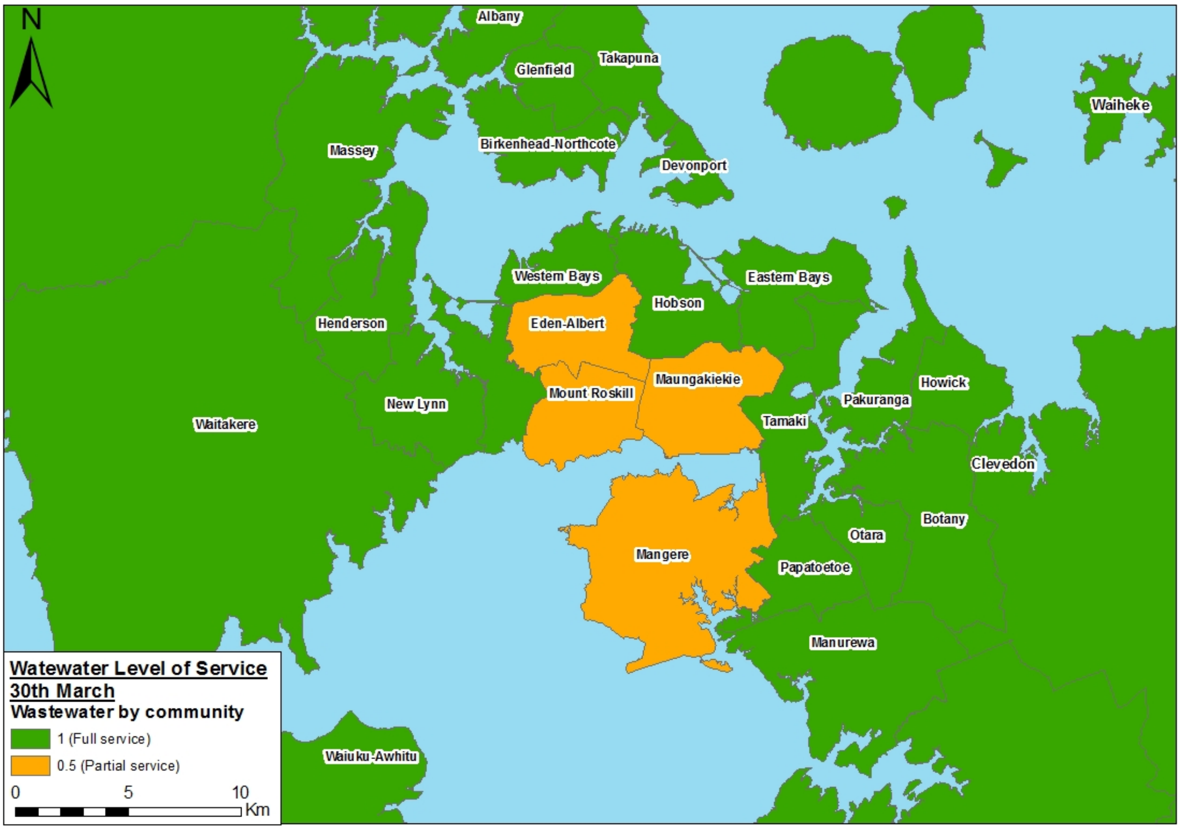


Figure 13.11 Wastewater level of service map for 30 March. In green are community boards with full service and in orange are community boards with partial service.

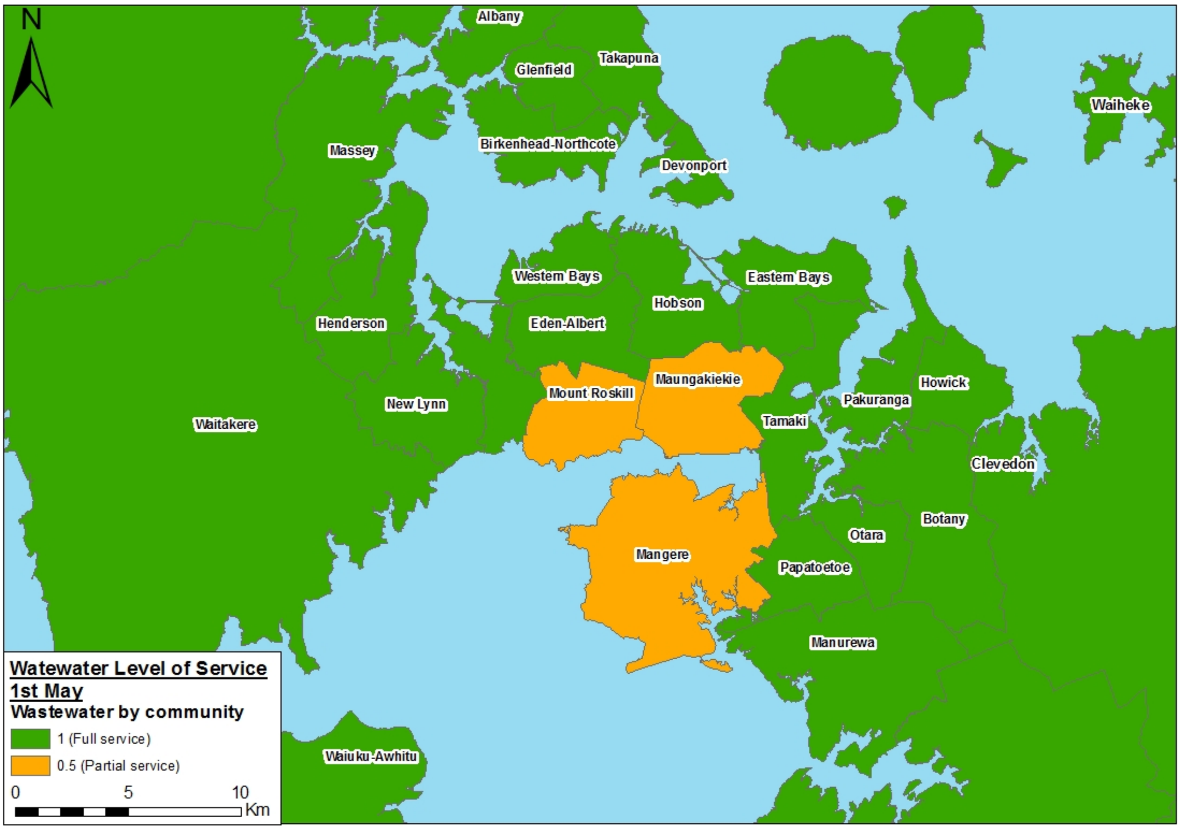


Figure 13.12 Wastewater level of service map for 1st May. In green are community boards with full service and in orange are community boards with partial service.

13.5 LIKELY INTERDEPENDENCIES

The functioning of the wastewater network has a critical dependence on electricity supply, as noted throughout this section. Wastewater services for individual customers also depend on a water supply to the property.

Repair of Mangere WWTP would probably depend on port access as there is a strong possibility that plant components would be built in Australia and shipped in.

14.0 STORMWATER

14.1 VOLCANIC IMPACTS TO STORMWATER NETWORKS

Stormwater systems serve to prevent surface flooding in urban areas. In the modern era, buildings, roads, and parking lots decrease the land's natural ability to absorb rainwater by covering large tracts of land with effectively impermeable surfaces (Frazer, 2005). Consequently, stormwater systems are crucial for rainfall removal and flood prevention or mitigation.

The main volcanic impact to stormwater systems is a reduction in capacity following volcanic ash ingress into the stormwater network (Wilson et al., 2012). Furthermore, as many stormwater and wastewater systems are connected (either as constructed, or due to illegal connections), ash ingress via stormwater drains often impacts wastewater capacity. Ash within stormwater pipes is extremely difficult to remove (Wilson et al., 2012) and can later result in pump failure and road or building flooding.

Volcanic eruptions may also impact the stormwater system by reducing (or possibly enhancing) surface permeability. Stormwater storage ponds or retainment dams may have reduced capacity due to ash or other volcanic material infiltration, which can compromise the network during intense rainfall events.

In general, an impacted stormwater network will result in increased localised flooding during rainfall events, which can temporarily compromise the road network and/or damage buildings and property.

14.2 STORMWATER LEVEL OF SERVICE CONSIDERATION

We will not provide separate stormwater outage maps in this report as the effects are quite localised and difficult to capture in terms of a user-experience outage. Rather, a stormwater network operating at a reduced capacity will likely flood more often, causing short term road use impacts, or will damage buildings and/or contents. This flooding will cover an area ranging from a single residential property to a few city blocks, and is highly dependent on local topography. Auckland Council (AC) Stormwater staff we consulted estimated that the scenario might increase the extent of local flooding for 1 in 10 year events, but that none of the rainfall events in our scenario would cause any stormwater-caused impacts. Rainfall intensities greater than 25 mm/hr might engender problems, but this is considerably more intense than what is present in the scenario.

If stormwater outages were to be re-examined in the future, a more comprehensive rainfall scenario would need to be included and impact modelling would have to be undertaken at a fine scale – LiDAR data would be used in this instance.

In the current scenario, we feel the current treatment of road network outages (Section 8) adequately covers impacts that may be incurred from an impacted stormwater system.

14.3 AUCKLAND STORMWATER NETWORK

Stormwater is managed by two entities in Auckland: Auckland Council Stormwater, who manage stormwater to protect buildings and properties, and Auckland Transport, who manage stormwater to prevent road flooding. Auckland Transport has access to national funds via NZTA, whilst AC Stormwater is solely council funded.

Roads in Auckland have stormwater drains, which connect to a gravity-driven buried network of stormwater pipes. There is just one stormwater pump in the entire region, situated in the Mt Wellington area for the Stonefields subdivision; it has a backup generator. A reticulation system is absent in some parts of the region, where soak holes into high permeability geologic units provide stormwater management.

AC Stormwater maintains retention dams and soakage ponds to manage high rainfall events. Many soakage ponds are located on top of high permeability basalts, with pipes at the base of the pond directing water into the basalt layers.

Stormwater and wastewater use the same pipe network in some parts of the city, particular in older neighbourhoods such as Ponsonby.

14.4 MT RUAUMOKO SCENARIO NETWORK IMPACT

Auckland Transport have indicated that prior to an eruption they would place filter membranes on drain covers to reduce the likelihood of ash ingress into the stormwater network, although they would likely be forced to prioritise based on road hierarchy and priority routes as there likely wouldn’t be sufficient supply.

PDC and tephra deposits can reduce permeability (and capacity) of storage ponds, reducing the return period flood a pond can manage. This would result in increased localised flooding, causing building and contents damage. However, this likely would occur in areas already highly impacted by the eruption – it wouldn’t cause additional damage but would need to be addressed along with other infrastructure for long term area restoration.

14.5 LIKELY INTERDEPENDENCIES

The status of the wastewater network is a major interdependency in parts of Auckland that have a shared stormwater/wastewater network. In these areas, stormwater drains provide an ash ingress point into the network, which can severely compromise the integrity of the system. In such compromised systems, comparably low intensity rain events (compared to pre-ingress events) can lead to flooding of raw sewage. This is of particular concern for Herne Bay, Ponsonby, Grey Lynn, and Westmere.

Stormwater network engineers are also reliant on a functioning road network for site access, and use telecommunication services to communicate with contractors.

15.0 TELECOMMUNICATIONS

15.1 VOLCANIC IMPACTS TO TELECOMMUNICATIONS

Proximal volcanic hazards (lava flows, pyroclastic density currents and surges, and ballistics) have the potential to cause minor to severe damage or complete destruction of above ground telecommunications infrastructure. Ash also has the potential to cause damage, depending on thickness, particularly to air-conditioning units associated with telecommunication exchanges and/or cell sites. More than 30 mm of ash is expected to cause some damage to air conditioning systems and above ground structures, as well as disruption of services, and structural damage to telecommunications infrastructure. Complete disruption of services is expected with more than 100 mm of ash (Wilson et al., 2014)

Spark New Zealand advise that experience during the Christchurch earthquakes of 2010 and 2011 showed that underground fibre optic cable is more resistant to damage from ground shaking/deformation than is copper cable.

15.2 TELECOMMUNICATION LEVEL OF SERVICE METRICS

It has been difficult to adequately develop a metric, which can be used by the economic model, to describe the level of service experienced by telecommunication end-users for telecommunications. This is due to the complicated nature of telecommunication services (mobile, fixed line and broadband services, each providing voice and data services, and each restored in different ways) and the more basic information being gathered by RA 2 researchers (business behaviours) that is focussed generally on voice and data services.

As research into telecommunication outages as a result of the AVF scenario progressed, it became clear that impacts to the telecommunications network were unlikely to be as severe as to other infrastructure services, in terms of degree of outage and spatial extent. Also, the impacts are either to all services, or just to mobile services. Therefore, the following metrics have been used to describe outages: no services (applies to all telecommunication services), reduced level of service (applies to all telecommunication services), and reduced mobile services only.

15.3 AUCKLAND TELECOMMUNICATION NETWORKS

There are three main networks that make up the overall telecommunications network in Auckland: mobile, fixed line, and broadband.

The mobile network is provided by cell sites located around the region, which each connect back to a core centre located on Mayoral Drive in the central city. Voice (including text messaging) and data services are provided by the mobile network.

The fixed line network is made up of copper cabling, down which telecommunications and power run, connected by a series of cabinets, and controlled by a series of exchanges. Analogue voice and data services are provided by the fixed line network.

The broadband network is provided by underground fibre optic cabling, connected by a series of above ground cabinets (sometimes the same cabinets that connect the copper network), and controlled by a series of exchanges. Data services, including voice over IP, are provided by the broadband network.

There are a number of different entities that control and/or provide services on each network. There are three main mobile service providers (Spark, Vodafone, and 2degrees). Spark is the primary provider of fixed line services. There are a number of broadband service providers. Chorus owns and maintains the copper line and broadband network infrastructure. We note that our assessment is based on conversations with Spark only, and therefore has to be taken as a generalisation of what is a much more complicated situation.

15.4 MT RUAUMOKO SCENARIO

15.4.1 Telecommunication network impacts

The base surge on 14 March is expected to result in the loss of the Onehunga and Mangere exchanges, and the loss of the fibre optic cable that crosses Mangere Bridge.

There is expected to be little impact to cell sites and their connectivity, as there will be no impact to the Mayoral Drive core site.

There is a potential for ash to impact cell sites in areas where ash depth is 5mm or more, by causing problems with the air conditioning units attached to each site. However, this potential impact will be mitigated by the units being turned off where possible, and more frequent replacement of filters where possible. As a result of these mitigative steps, impacts from ash are expected to be insignificant in this scenario.

15.4.2 Telecommunication level of service

Advice from Spark suggests that the loss of the Onehunga and Mangere exchanges would result in all telecommunication services being reduced to zero within the immediate suburbs (including the airport), and possibly wider, with some drop in levels of service around the fringes of this area. We note that these suburbs and surrounds are within the Primary Evacuation Zones at this point in time, and within the Primary or Secondary Evacuation Zones until 4 April (approximately three weeks). Spark advise that it would take a number of weeks to restore the exchanges. If service demand remained within this area, Spark would try to migrate services to other paths by laying new cables, in an attempt to reduce disruption to services during this time. However, this step seems an unlikely one for Spark to take, at least initially, given the extent of the evacuation zones during the three weeks following events on 14 March. The timing of restoration of telecommunication services to these areas will depend heavily on when and whether a population (and therefore demand) returns to these areas. Spark were clear that priority will be on ensuring services are available where they are needed (i.e., where the population is) and there would be little attention paid to areas where there is little or no demand.

Spark also advise that the loss of the fibre optic cable across the Mangere Bridge would result in an immediate drop in level of service in all telecommunications types for the area immediately to the south of the bridge, and that this effect would extend south of Auckland to at least Hamilton. This outage would last for only minutes for some services, which are setup to automatically redirect to a second fibre optic cable that travels through Otahuhu. However, some services would need to be manually shifted to this alternative cable, and this would take at least one day, possibly a number of days, depending on access status and staff and equipment availability.

A drop in level of service on the mobile network is expected as a result of a secondary impact – overloading as a result of increased numbers of people trying to contact others. Overloading is expected to be greatest at the time of, and immediately following, each new volcanic event. This means there would be a number of short (hours) episodes of overloading as the scenario unfolds.

These outages are summarised in Table 15.1.

Table 15.1 Summary of telecommunication level of service

Date	Level of service
14 March	No telecommunications services in Onehunga, Mangere. Reduced level of service south of the Mangere Bridge. Reduced mobile level of service over all of Auckland throughout the day (morning and afternoon volcanic events occurring).
18 March	Still no telecommunications services in Onehunga, Mangere. Full services restored south of the Mangere Bridge (assuming access to Otahuhu cable within Secondary Evacuation Zone is possible from 16 March).
21 March	Still no telecommunications services in Onehunga, Mangere. Reduced mobile level of service over all of Auckland for a number of hours due to new volcanic event.
22 March	Still no telecommunications services in Onehunga, Mangere. Reduced mobile level of service over all of Auckland for a number of hours due to new volcanic event.
30 March	Still no telecommunications services in Onehunga, Mangere. Reduced mobile level of service over all of Auckland for a number of hours due to new volcanic event.

15.5 Likely Interdependencies

Power was identified by Spark as a key interdependency for the telecommunications network. However, in the AVF scenario, where power is maintained (albeit with rolling outages) to much of the region, this interdependency was not expected to have any significant effect on levels of service. This is because cell sites have battery back-up and should therefore be largely able to cope with rolling outages. In addition, Spark advise that in preparation for the event, generators would be deployed to critical sites so they are able to keep going regardless of power supply reliability.

Fuel is an interdependency as generators are relied on to deal with reduced power supply.

Spark also noted that health and safety legislation could have an impact on getting staff to sites to do repair/maintenance work.

16.0 CONCLUSIONS

This report has presented a scenario detailing an AVF eruption and explored the ramifications to critical infrastructure providers. The scenario begins on 22 February when volcanic unrest is declared, with the eruption starting on 14 March. The eruption is over in a month, but the ramifications continue on for months and in some cases years.

Most of the damage results from the initial pyroclastic surge, modelled after Brand et al.'s (2014) worst-case scenario surge for an AVF eruption in the same substrate as the Mt Ruaumoko site. Later tephra fall causes further power disruptions and requires substantial clean-up efforts. Table 16.1 provides the overall disruption to consumers for the infrastructure sectors considered.

Table 16.1 Outage duration for sections considered in the Mt Ruaumoko scenario.

Sector	Overall outage duration
CDEM – evacuation	7 weeks
CDEM – cleanup	> 6 months
Electricity	> 1 year
Fuel	4 months
Roads	> 7 weeks
Rail	> 7 weeks, permanent closure of some lines
Aviation	3 months
Port	(Mostly negligible)
Water supply	Wide scale restrictions for > 1 year
Wastewater	> 2 years of raw sewage discharge
Stormwater	Reduced capacity in some areas
Telecommunications	< 2 weeks

We emphasise that interdependencies were not considered unless noted, as the ERI MERIT model will eventually consider interdependencies. However, we noted likely interdependencies throughout the report. In our sector meetings, it was clear that roads and power are two key sectors in terms of reliance by other infrastructure sectors, along with site access, which in some instances may require entering cordoned areas and extra consideration for worker health and safety. Infrastructure providers also depend on a workforce able to get to work and perform required duties.

Level of service metrics which may require more consideration are transportation, wastewater and telecommunication. Transportation is challenging as there are many ways to get from point A to point B in Auckland. Congestion may impact the usability of the network, and there may be different considerations for emergency/infrastructure services, commuters, and freight. We struggled with wastewater, as it is clear that destruction of the Mangere Wastewater Treatment Plant will have profound implications and will likely decrease both quality of life (and morale) for residents, and tourism, but given water, the ability to flush will continue. Telecommunications is also complex as it comprises many different types of services and is a rapidly changing sector.

Going forward, it is clear that a better understanding of surge impacts is required, along with raising awareness of what surges can do in the critical infrastructure community. Likewise, a better understanding of how evacuation zones will be identified and enforced is needed, along with what health and safety considerations will be necessary for workers entering cordoned areas. Much work has been done on pre-eruption evacuation and response – a similar amount of work is required for restoration and recovery.

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NID coordinated the report, adapted the Mt Ruaumoko scenario, created hazard layers, was the lead for the evacuation, fuel, aviation, and stormwater sections, contributed to the electricity and water supply sections, and edited the final report. She attended sector meetings with AC CDEM, AC Stormwater, Air New Zealand, Auckland Airport, Transpower, Vector, and Watercare, and corresponded with Refinery NZ. DMB coordinated a preliminary version of the report (EQC workshop scenario), was the lead on the road and rail sections and contributed to the evacuation section. He also edited much of the final report and attended sector meetings with AC CDEM, Auckland Transport (AT), KiwiRail, NZTA and staff at the Auckland Transport Operations Centre (ATOC). AJD led preliminary work on the electricity transmission, water supply and wastewater sectors, and heavily contributed to the final wastewater section. He assisted with final editing. ESG coordinated with other research aims of the ERI research programme, led development of outage metrics and the telecommunication sections, contributed to the road, rail, and water supply sections, and organised the majority of sector meetings. She attended sector meetings with AT, AC Stormwater, KiwiRail, NZTA, Transpower, Vector, and Watercare, and corresponded with Spark. JH led the cleanup section, contributed to the fuel section and attended the sector meeting with ATOC. SP undertook preliminary work on the evacuation zone designation. CS led the water supply and wastewater sections, including developing outage metrics, and attended the sector meeting with Watercare. GW undertook preliminary work on the electricity and wastewater sections. TMW coordinated the overall UC contribution, contributed to the electricity section, attended the sector meeting with Transpower, and edited the final report.

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APPENDICES

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A1 APPENDIX 1: LIST OF SECTOR MEETINGS AND PARTICIPANTS

- 14 November 2014, Auckland Airport: Roy Robertson (Auckland Airport, Compliance and Quality Assurance Manager), Natalia Deligne (GNS Science)
- 3 August 2015, Opus, Manukau: Murray Parker (NZTA, Senior Traffic and Safety Engineer), Peter Scott (Auckland Transport, Southern Road Corridor Delivery Manager), Daniel Blake (University of Canterbury), Emily Grace (GNS Science)
- 3 August 2015, KiwiRail Westfield Depot: Peter Ramsay (KiwiRail, Asset Engineer), Mark Goodman (KiwiRail, Traction Service Manager), Paul Jenkinson (AT, Senior Asset Management Project Lead), Daniel Blake (University of Canterbury), Emily Grace (GNS Science)
- 12 August 2015, ATOC Smales Farm, North Shore: David Murphy (ATOC), Daniel Blake (University of Canterbury), Josh Hayes (University of Canterbury)
- 14 August 2015, Transpower, Wellington: Graeme Ansell (Transpower), Natalia Deligne (GNS Science), Emily Grace (GNS Science), Tom Wilson (University of Canterbury)
- 21 August 2015, Elliott Stables, Auckland: Richard Woods (AC CDEM, Head of Emergency Management Planning), Daniel Blake (University of Canterbury), Natalia Deligne (GNS Science). Apologies: Tom Wilson (University of Canterbury)
- 24 August 2015, Bledisloe House: Helen Chin (AC Stormwater, Stormwater Asset Management), Simon Aiken (AC Stormwater, Growth and Renewals Planning), Phillip Johansen (AC Stormwater, Manager Central Stormwater Operations), Uys de Wet (AC Stormwater, Central Stormwater Ops), Natalia Deligne (GNS Science), Emily Grace (GNS Science). Apologies: Dukessa Blackburn-Huettner (AC Stormwater), Tom Wilson (University of Canterbury)
- 24 August 2015, Vector, Newmarket: John Welch (Vector, Manager of Planning/New Network Solutions), Rick Liew (Vector, Manager Electricity Operation Planning/Network Services), Harley Brown (Vector, Group Risk Manager/People, Safety & Risk), Scott Muspratt (Vector, Senior Engineer/Asset Resilience), Tiena Teariki Mana (Vector, Business Risk Manager), Natalia Deligne (GNS Science), Emily Grace (GNS Science). Apologies: Tom Wilson (University of Canterbury)
- 25 August 2015, Ministry of Food, Wellington: Peter Halliwell (Air New Zealand, Senior Business Continuity Management Advisor), Natalia Deligne (GNS Science)
- 28 August, Auckland Airport: Roy Robertson (Auckland Airport, Compliance and Quality Assurance Manager), Natalia Deligne (GNS Science)
- 28 August 2015, Watercare, Newmarket: Priyan Perera (Watercare, Operations Manager, Water Supply), Mark Bourne (Watercare, Operations Manager, Wastewater), Natalia Deligne (GNS Science), Emily Grace (GNS Science), Carol Stewart (Massey University/GNS Science)
- 7 September 2015, teleconference: Darren Beattie (Spark, Service Delivery Manager, Energy, Health and Local Environment, Auckland Lifelines Group Rep) and Brian Potter (Spark, National Lifelines Group Rep), Emily Grace (GNS Science) and Charlotte Brown (Resilient Organisations).

A2 APPENDIX 2: METSERVICE WIND DATA FOR TEPHRA2 MODELLING

As explained in Section 3.1.3, we use real wind data provided to the GeoNet volcano monitoring team by MetService as input into Tephra2 modelling of ash dispersal. Tables A2.1 – A2.4 contain the data provided by MetService and direction and speed conversions to properly input it into Tephra2.

Table A2.1 Preferred model of day GFS MetService wind data forecast for 14 March 2014 at 18:00 NZDT. The first three columns are from MetService and the last two are converted data for TEPHRA2 input.

Height above sea level (m)	Velocity (knots)	Wind direction (from; degrees)	Velocity (m/s)	Wind direction (to; degrees)
1000	10	085	5.1	265
2000	13	080	6.7	260
3000	16	080	8.2	260
4000	18	095	9.3	275
6000	15	015	7.7	195
8000	17	350	8.7	170
10000	26	350	13.4	170
12000	36	325	18.5	145

Table A2.2 Preferred model of day UKMO MetService wind data forecast for 21 March 2014 at 06:00 NZDT. The first three columns are from MetService and the last two are converted data for TEPHRA2 input.

Height above sea level (m)	Wind direction (from; degrees)	Velocity (knots)	Wind direction (to; degrees)	Velocity (m/s)
1000	145	5	325	2.6
2000	165	6	345	3.1
3000	180	4	0	2.1
4000	240	3	60	1.5
6000	270	6	90	3.1
8000	295	18	115	9.3
10000	295	21	115	10.8
12000	280	18	100	9.3

Table A2.3 Preferred model of day UKMO MetService wind data forecast for 22 March 2014 at 18:00 NZDT. The first three columns are from MetService and the last two are converted data for TEPHRA2 input.

Height above sea level (m)	Wind direction (from; degrees)	Velocity (knots)	Wind direction (to; degrees)	Velocity (m/s)
1000	110	3	290	1.5
2000	115	6	295	3.1
3000	100	6	280	3.1
4000	100	9	280	4.6
6000	095	13	275	6.7
8000	075	19	255	9.8
10000	125	8	305	4.1
12000	235	12	55	6.2

Table A2.4 Preferred model of day GFS MetService wind data forecast for 29 March 2014 at 06:00 NZDT. The first three columns are from MetService and the last two are converted data for TEPHRA2 input.

Height above sea level (m)	Wind direction (from; degrees)	Velocity (knots)	Wind direction (to; degrees)	Velocity (m/s)
1000	300	6	120	3.1
2000	260	3	80	1.5
3000	245	1	65	0.5
4000	195	3	15	1.5
6000	215	9	35	4.6
8000	185	18	5	9.3
10000	190	29	10	14.9
12000	195	33	15	17.0

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