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PLANNING FOR RESILIENCE OF WATER NETWORKS UNDER EARTHQUAKE HAZARD: A CASE STUDY FOR ROTORUA DISTRICT, NEW ZEALAND

S.R. Uma[1], Finn Scheele[2], Elizabeth R. Abbott[3] and Jose M. Moratalla[4]

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ABSTRACT

Water networks are vulnerable to earthquakes and failures of network components can result in a lack of availability of services, sometimes leading to relocation of the community. In New Zealand, there are statutory requirements for the water network providers to address the resilience of infrastructure assets. This is done by identifying and managing risks related to natural hazards and planning for appropriate financial provision to manage those risks. In addition to this, the impact from the Canterbury region earthquakes has accelerated the need for understanding the potential risk to critical infrastructure networks to minimise socio-economic impact. As such, there is a need for developing pragmatic approaches to deliver appropriate hazard and risk information to the stakeholders.

Within the context of improving resilience for water networks, this study presents a transparent and staged approach to risk assessment by adopting three significant steps: (i) to define an earthquake hazard scenario for which the impact needs to be assessed and managed; (ii) to identify vulnerable parts of the network components; and (iii) to estimate likely outage time of services in the areas of interest. The above process is illustrated through a case study with water supply and wastewater networks of Rotorua Lakes Council by estimating ground motion intensities, damage identification and outage modelling affected by number of crews and preferred repair strategies.

This case study sets an example by which other councils and/or water network managers could undertake risk assessment studies underpinned by science models and develop resilience management plans.

INTRODUCTION

Planning for the resilience of water networks under earthquake hazard has drawn increasing levels of attention amongst councils and other organisations who manage those networks. In New Zealand and in other parts of the world, water networks have been notoriously vulnerable to significant earthquakes and have resulted in severe damage leaving the community with a lack of water supplies for several days [1-3]. Lessons from such real events demonstrate the importance and urgent need for resilience planning for critical as well as vulnerable infrastructure networks. As a statutory requirement, the Local Government Act 2002 with ACT 2014 amendment includes a section on “infrastructure strategy” which states, “provide for the resilience of infrastructure assets by identifying and managing risks relating to natural hazards and by making appropriate financial provision for those risks”. In addition, the 2015 National Infrastructure Unit’s (NIU) thirty-year infrastructure plan 2015 [4] supports the following viewpoint: “There is a need to increase the sophistication of how we think about resilience, shifting beyond a narrow focus on shock events or infrastructure failure and thinking more about interdependencies, levels of service and community preparedness”. In this context, councils consider taking initiatives to implement resilience review programmes of water infrastructures in different capacities, such as criticality and vulnerability assessment exercises to reduce impact from infrastructure failure.

A framework to establish resilient infrastructure networks includes : (i) a risk assessment to understand the overall post-earthquake performance in terms of damage to the network components and extent of disruption to levels of service (LOS); (ii) defining post-earthquake performance goals in terms of LOS to the customers; (iii) developing mitigation measures in terms of intervention options, estimate related cost and timeframe to bridge the gap in meeting service goals; and (iv) defining seismic design standards for significant/critical components of the network to achieve new performance objectives. Note that some of the above actions could be driven by the professionals and stakeholders in their respective fields, however, defining post-earthquake performance goals for resilience require collective input and acceptance from different stakeholders, city leaders and the community.

Recently, Rotorua Lakes Council (RLC) engaged researchers from GNS Science to carry out a systematic risk assessment study to evaluate potential impact of earthquake hazards on their water supply and wastewater network assets with a goal to improve the resilience of their networks and the findings were reported [5]. The study generated information useful to RLC in many ways including to support decision making regarding resilience investment projects; and enabling conversations with other stakeholders in order to agree on the LOS for the provision of water after a major earthquake event. It is worth mentioning that, over time, RLC has undertaken several projects including vulnerability studies of their infrastructure network components and resilience review programmes in various capacities. Generally, 30-year infrastructure strategy plans are developed and revised periodically. In the 2015 and 2018 versions of their infrastructure strategy plans, RLC

[1] *Corresponding Author, Risk and Engineering Team Leader, GNS Science, Lower Hutt, s.uma@gns.cri.nz (Member)*

[2] *Risk Specialist, GNS Science, Lower Hutt, f.scheele@gns.cri.nz*

[3] *Seismic Hazard Specialist, GNS Science, Lower Hutt, e.abbott@gns.cri.nz*

[4] *Risk Engineer, GNS Science, Lower Hutt, j.moratalla@gns.cri.nz*

identified key risks to its water infrastructure components from natural hazards.

The study involved tasks related to: (i) the identification of vulnerable components and systems in the water supply and wastewater networks under a selected earthquake scenario; and (ii) the determination of service outages to various wastewater catchment and water supply zones. The risk assessment was a desk-top study, not including site visits or site-specific assessments. As part of the study, we used existing resources as provided by RLC regarding the network assets and established fragility functions to predict likely damage in the network components. GNS Science and RLC worked in a participatory style to provide information and feedback at various stages of the study to increase efficiency and to deliver results that are useful and usable. This paper builds on the consultancy report submitted to RLC [5].

RISK ASSESSMENT FRAMEWORK

The risk assessment framework adopted for analysing RLC water networks follows a staged approach and is shown in Figure 1. This framework has been previously applied in another project namely "Wellington Resilience Programme business case" [6], It includes three stages: (i) earthquake hazard modelling; (ii) developing network asset models and damage models; and (iii) modelling recovery and estimating time-stamped outages for affected areas. The hazard modelling stage involves defining a fault source event scenario with an understanding of earthquake hazard in the region and micro-zonation effects. The damage modelling uses network information in terms of their significant components as well as connectivity and their respective fragility functions to predict the likely damage. Recovery and service outage modelling deals with estimation of spatial and temporal extent of disruption to services taking into account of the damage to the assets and their functional dependencies.

Earthquake Hazard Analyses and Scenario Identification

Investigations from earlier studies revealed the presence of many active faults that could contribute to the earthquake hazard for Rotorua Lakes District [7]. It was reported that the active faults could generate peak ground accelerations (PGA) varying between 0.2 g and 0.5 g for 10% probability of exceedance in next 50 years calculated based on an earlier version of seismic hazard map [7]. For the purpose of the study, it was necessary to identify one single fault rupture scenario generating shaking intensity that could cause reasonable levels of damage to the water network components. The preferred earthquake scenario was identified in two steps: (i) the calculation of probabilistic hazard values; and (ii) the disaggregation of the probabilistic hazard values to identify independent contributions to the hazard by different fault sources.

Probabilistic earthquake hazard analyses were performed using version 2.7 of the OpenQuake Engine. OpenQuake is a suite of open-source software developed by Global Earthquake Model (GEM) Foundation to promote consistent use of data and facilitate best practices in seismic hazard and risk calculation [8]. The most recent version of GNS Science's National Seismic Hazard Model (NSHM) [9] and a suite of ground motion prediction equations (GMPEs) were used to calculate the hazard results. The GMPEs were selected based on the recommendations from previous studies [10,11]. For active shallow crust sources, totally five GMPES [12,13], [14-16] were considered; two GMPEs were used for volcanic sources [15,16] and four GMPEs were used for subduction interface and subduction slab sources [16-19]. Hazard results were calculated on a 5 km grid across the Rotorua Lakes District. They were calculated for return periods of 100-, 500- and 2500-years, with average shear velocities to 30 m depth (Vs30) of 1000 m/s, 450 m/s, and 200 m/s, representing New Zealand Site Classes B (rock), C (shallow soil), and D (deep/soft soil) respectively [20,21].

In order to determine the scenario earthquake for this study, the class B (rock) probabilistic seismic hazard estimates for a single point of reference selected by RLC (176.25° E, 38.14° S) in the Central Business District (CBD) of Rotorua was disaggregated. A single point was considered sufficient to provide, high-level understanding of the contributing earthquake sources in the area, in order to produce scenario hazard analyses as input for the subsequent risk analyses. Class B conditions were only used to disaggregate the earthquake sources in the NSHM that would be contributing most to a probabilistic hazard analysis, such that we could then produce scenario spectra for the highest contributing sources. The make-up of key contributing sources does not tend to change much from site class to site class. The scenario spectra were produced for site classes B, C and D. Most of Rotorua is identified with site class D.

The top four fault sources contributing to the hazard at the site of interest are as listed in Table 1 and shown in Figure 2, and the highest contribution is ranked number 1.

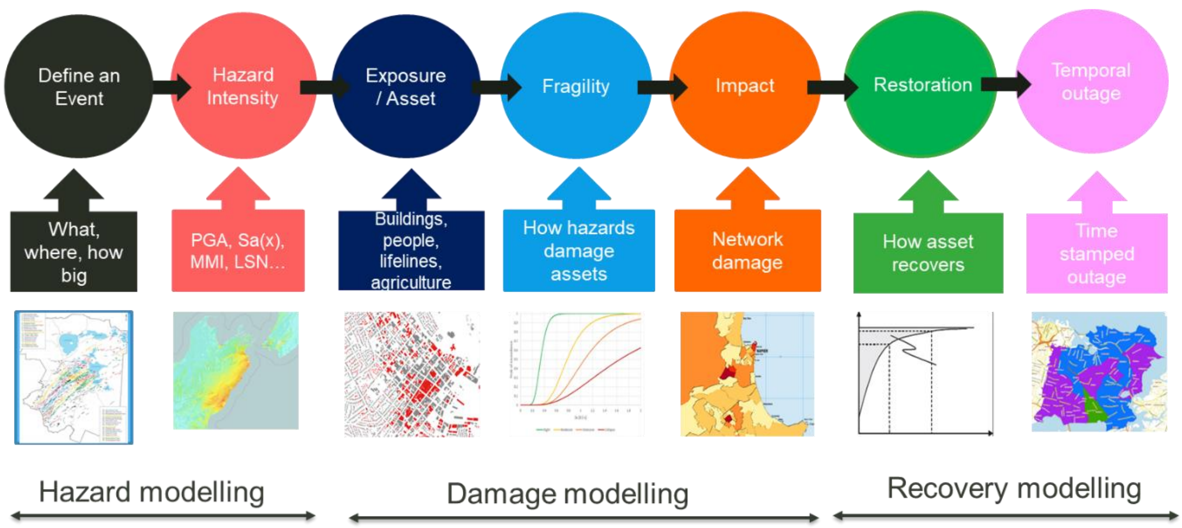

Figure 1: Stages involved in risk assessment framework adapted from [6].

Table 1: Top four fault source contributors to the PGA hazard for 100, 500 and 2500-year return period at Rotorua CBD for class B rock with Vs30=1000 m/s conditions.

Fault	Magnitude	Mechanism	Recurrence Interval (years)	Shortest Distance to Site (km)	Source Contribution Rank		
					100 Years	500 Years	2500 Years
Ngakuru Southwest	6.0	Normal Volcanic	970	8	1	1	1
Maleme	6.4	Normal Volcanic	310	16	2	3	4
Ngakuru New	6.5	Normal Volcanic	2300	9	4	-	-
Horohoro	6.5	Normal Volcanic	7400	4	-	4	2

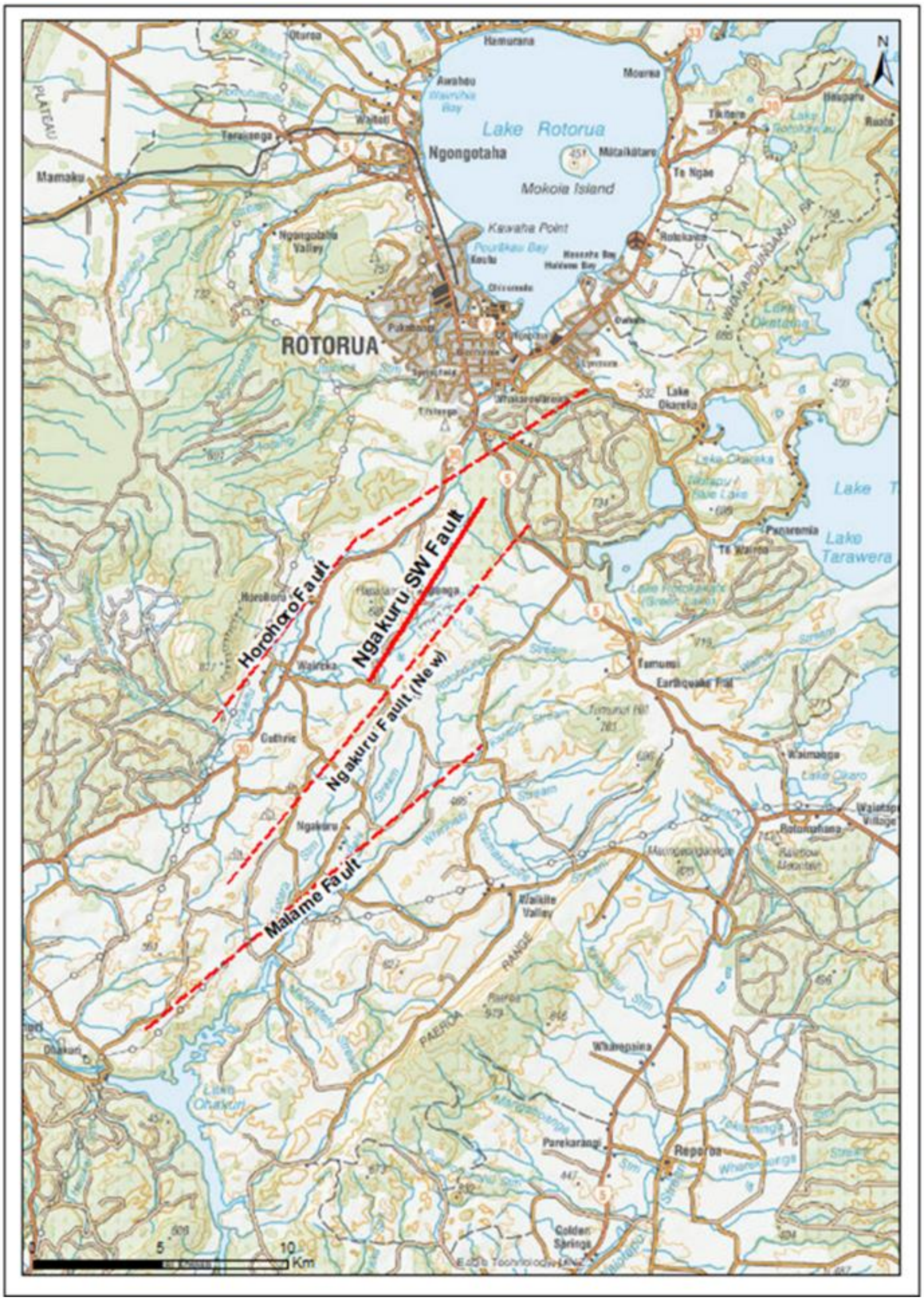

Figure 2: Top four contributing faults to seismic hazard in Rotorua CBD.

From Table 1, it can be seen that Ngakuru Southwest fault source shows consistently maximum contributions to the hazard for all the three return periods considered. This fault has a modelled recurrence interval of 970 years and is located at 8 km from the reference point in the CBD. The Horohoro fault source is closer to the reference point in CBD by 4 km and has a modelled recurrence interval of 7400 years, and has the second largest contribution at the 2500-year return period. The Ngakuru New fault source and Maleme fault source are located at increasing distances from Ngakuru Southwest fault source and their contributions are lower at the 2500-year return period.

To evaluate the potential hazard produced by each of the top contributors from the disaggregation, 84th-percentile deterministic (scenario) spectra with 5% damping were calculated for all 4 earthquake sources at the reference site. Figure 3 shows a comparison of the deterministic spectra for all four sources for site class D (Deep Soft Soil). The Horohoro fault source generated the highest motions, and therefore, could be considered as the "maximum credible event" scenario. Ngakuru Southwest fault source is the second-most dominant at lower periods up to about 0.2 s, after which Ngakuru New produced the second highest values. The Maleme fault scenario generated the lowest spectral acceleration values.

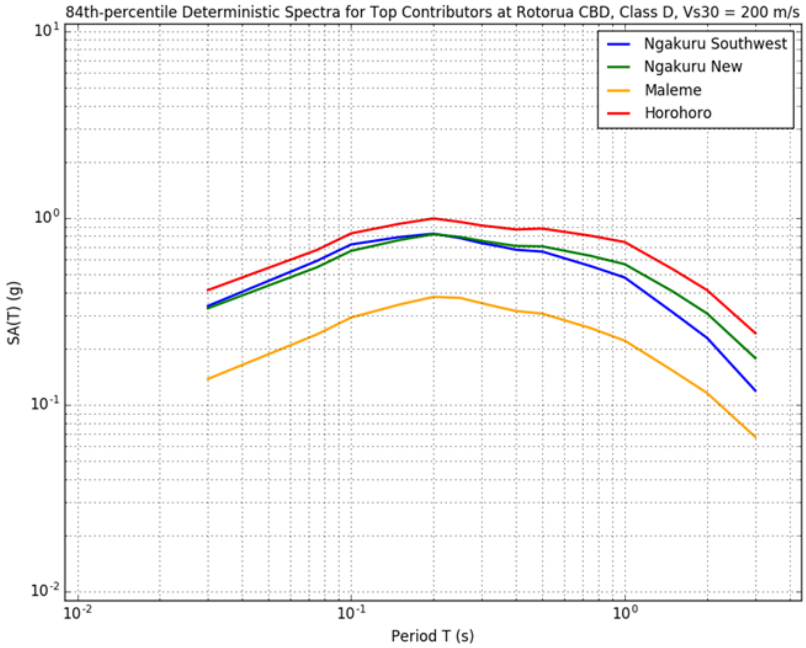

Figure 3: The 84th-percentile deterministic spectra with 5% damping for the top four fault source contributors at Rotorua CBD for Site Class D deep or soft soil with Vs30 = 200 m/s.

The decision to use the Ngakuru Southwest as the preferred fault source scenario was made through a discussion with RLC. The Ngakuru Southwest fault source: (i) is consistently the highest contributor to the hazard at different return periods compared to the other 3 faults; (ii) generated the second highest motion at low periods (which are of greater interest for pipeline infrastructure); and (iii) is expected to rupture more often than Horohoro fault because of its shorter recurrence interval of 970 years. Further, the RLC team expressed a preference to plan for resilience with a scenario with more moderate impact than for a "maximum credible event" scenario.

MMI maps on a 5 km grid across the Rotorua Lakes District were also calculated using the current version of the NSHM [9] in OpenQuake. The intensity prediction equation (IPE) [22] was used to estimate MMIs at different locations away from the source of rupture. The IPE accounts for the earthquake magnitude, location, focal depth, mechanism and the orientation of the fault source.

Microzonation Modelling

Local ground characteristics can greatly modify the seismic shaking and damage that are experienced at a specific site and is referred to as microzonation. Various phenomena can be involved, with those having most relevance to seismic risk assessment studies being amplification of shaking by soft or deep soils, liquefaction, landslide, and topographic enhancement of shaking. In a few locations the tectonic movement, i.e. uplift or subsidence of large tracts of ground can be important. Only soil amplification, liquefaction and its related lateral spreading were accommodated in the present modelling. The impact of landslides on the network performance and ground subsidence was not modelled. Although landslide susceptibility has been mapped for the whole country, it is currently based only on the slope angle and simple geological characteristics. The true potential for slope failure depends on numerous factors including soil and geological conditions, vegetation, rainfall, and shaking level, among other factors. Sophisticated models can be developed using fundamental principles when all the necessary information is available for a given region [23]. These models are computationally intensive and require evidence-based data to generate reasonably reliable landslide scenarios. For the above reasons, landslide modelling and impact on the two networks was not considered within the scope for the present study.

The underlying geology of Rotorua is highly complex and has evolved through volcanic activity. As part of the surficial geology Mesozoic greywacke forms the basement rock in the area. Younger formations are predominantly rhyolite ignimbrites, rhyolite and dacite lava domes and lacustrine and alluvial sediments derived from those volcanic lithologies [24]. In the marginal areas around the lake, the geology is Holocene lacustrine sediments of the Tauranga Group, with surficial alluvial sand, silt and clay sediments and peat layers overlying the pumiceous sandy and silty lacustrine sediments of the Rotorua Basin. These are, in turn, underlain by the intra-caldera portions of the Mamaku Ignimbrite [25,26]. Anywhere between 50 and a couple of hundred metres of lake sediments are of pumice, gravel, sand and peat, on top of the last ignimbrite. The ignimbrite is porous, but quite hard, so it has shear wave velocities from the high hundreds to low thousands of m/sec. However, most of the lake sediments are identified with low shear wave velocity around 200 m/s representing site class D [27].

Ground Shaking and its Amplification Effects

Amplification of seismic shaking by soft soil often occurs, but not always. Certain type of soils can amplify the low levels of input rock motion, but the soil remains elastic. Once the soil is excited beyond its elastic range, soft soils can isolate surface structures from the strong shaking. In the present study, the OpenQuake engine as used in the hazard analysis has explicitly accounted for the site amplification effects for PGA estimations as well as the MMI predictions. For PGA estimations, the appropriate shear wave velocity (Vs30) values for each site class were used within the GMPEs adopted. For MMI predictions, suitable factors [28] were included in the [22] expressions to adjust the MMI values. The estimated PGA in Rotorua CBD varies between 0.3 g and 0.4 g and the CBD zone is predicted with an intensity of MMI 9.

Liquefaction and Lateral Spreading

Liquefaction is the term used to describe the loss of bearing strength experienced when uniformly graded, saturated sand and silt are subjected to dynamic shaking. Certain soils are more susceptible to liquefaction than others. Different liquefaction susceptibility classes have been derived and mapped for the whole of New Zealand but with varied resolutions with a map scale of 1:25,000 for some significant urban areas to 1:1,000,000 for rural and remote locations. For Rotorua, the available data is at 1:250,000 scale. Descriptions of the way in which the susceptibility ratings were derived can be found in studies [29] including some recent studies for Wellington Region [30-32]. Liquefaction severity and the extent of land damage at a location depend on the liquefaction susceptibility class and shaking intensity experienced at that location.

Previous studies [29] suggested that at intensities of MM6 to MM7 the effects of liquefaction are nearly always small and rarely cause significant damage. At higher intensities, MM8 and above, ground damage (settlement, spreading or displacement) often occurs and can result in substantial damage. Figure 4 shows areas of 'moderate' liquefaction susceptibility and the zones of lateral spreading considered for modelling. During the Canterbury earthquake sequence, several areas in the Christchurch region were affected by moderate to severe liquefaction and in areas close to waterways (rivers and streams) the liquefaction was accompanied by lateral spreading [33] resulting in ground displacements. The lateral ground displacements extended from tens of centimetres to several metres. In this study, we have explicitly modelled the damage near the waterways and around the lake to account for heightened potential for damage to infrastructure components. Around the lake about a 200 m wide band was assumed to be affected by lateral spreading (Figure 4), accounting for the higher water table in this area. Along waterways, either a 25 or 50 m wide band was assumed to be affected by lateral spreading, depending on the size of the waterway. Larger streams had a larger buffer, and the size was determined based on topographic information (stream significance) and aerial imagery.

Asset Modelling of Water Network

RLC provided the asset data for the water supply and wastewater networks and was largely complete in terms of key information required for damage modelling. The data included the assets' geographic co-ordinates (i.e. latitude and longitude), the year of construction, the material of construction, the pipe length and the diameter. RLC shared the data in a GIS format which was highly valuable for this project.

The assets of water networks are broadly classified into two groups: (i) point assets (those represented by a single location) such as storage reservoirs and pump stations; and (ii) line assets representing the pipes. Different approaches were adopted to model damage to these assets.

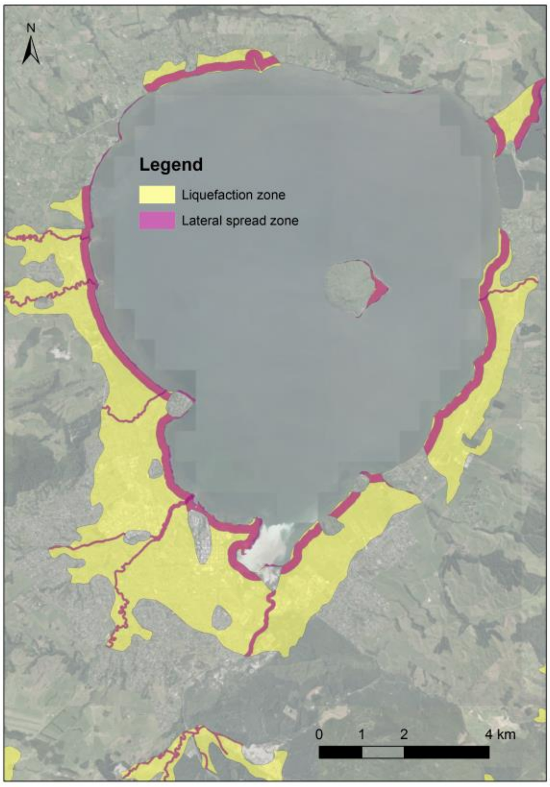

Figure 4: Zones with 'moderate' liquefaction susceptibility class and potential lateral spreading.

RLC also shared a report [34] which provided an overall view of the two networks and described the status of the facilities at critical sites (e.g. headworks and pump stations) and included descriptions around the general conditions of the facilities supported by some photographs which were useful for damage modelling.

Water Supply (WS) Network

RLC's water supply network has different components including water source (springs), water treatment plants, pump stations, storage reservoirs, and pipelines. The assets considered for modelling were discussed with RLC and agreed on. Typically, for risk assessment of a large distributed network, it is important to focus on modelling the vulnerability of the components that are of: (i) high value; and/or (ii) critical to the functionality of the network, which included headworks (intake sources, storage reservoirs and pump stations) and the pipe network. Other assets in the network such as the ultraviolet (UV) and chlorine (Cl2) treatment plant structures, pressure valves, meters, lateral pipes connecting to the households, pipe joints and inlet/outlet connections to other structures were excluded from the damage modelling. Ultraviolet and chlorine treatment plant structures are light structures (for example, with sheet metal cladding and roof) constructed between 2008 and 2010, and therefore these structures were assumed to be seismically resilient and would likely not be functionally compromised. Other assets were not modelled due to a lack of information. It is worth mentioning that pipe joints and pipe inlet/outlet structures are vulnerable to failure due to ground movement. Even though these assets were not modelled explicitly, it is believed that such potential failures were accounted within pipe damage modelling. The pipe failure rates per unit distance used for pipe damage modelling are based on empirical repair data capturing failures within the pipe segment length as well as at the joints. The pipes installation year ranges between 1916 and 2017. About 50% length of the pipes are older pipes installed prior to 1980. A summary of the asset information for water supply network with respect to the four designated supply zones as received from RLC is given in Table 2.

Water Supply Zones

Four water supply zones and respective springs (intake sources) are identified within the Rotorua Lakes District by the council: (i) a Central supply zone with Karamu-Takina springs; (ii) an Eastern supply zone with Waipa springs; (iii) a Western (Ngongotaha) Supply Zone with Taniwha springs; and (iv) a Northern (Hamunarana and Kaharoa) supply zone with Rewarewa springs as shown in Figure 5. The mains and submain pipes are part of the system connecting the headworks as well as the reticulation distribution network.

Table 2: Summary of water supply assets by supply zone.

Water Supply Zone	Water Intakes	Reservoirs	Pump Stations	Pipes (km)
Central	1	10	7	345
Eastern	2	4	2	121
Western	1	2	1	67
Northern	1	6	3	87
Total	5	22	13	618

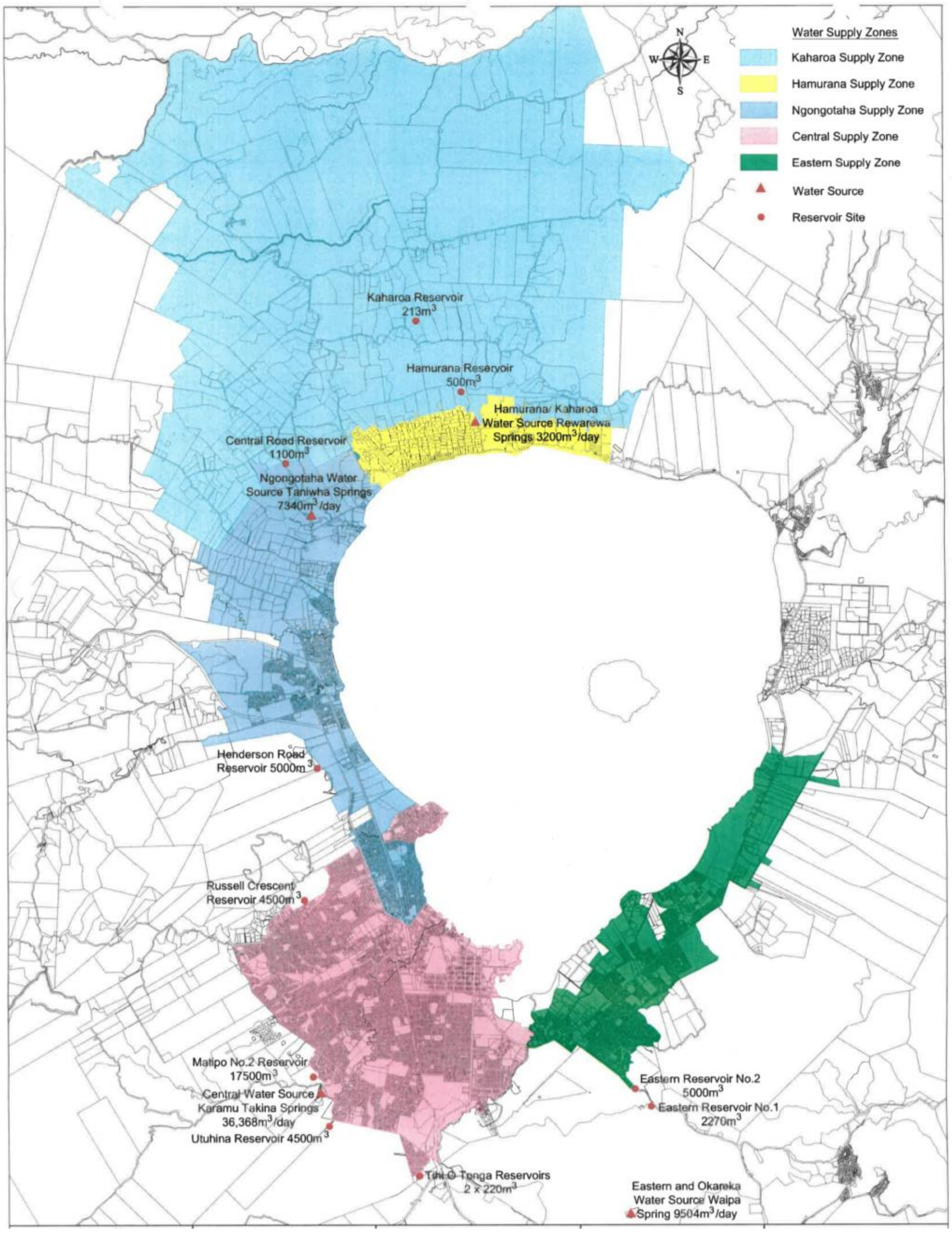

Figure 5: Water supply zones in Rotorua Lakes District (Courtesy: RLC).

Wastewater (WW) Network

The Rotorua wastewater reticulation network covers approximately 3150 ha, from the airport through to the suburban areas including Ngongotaha and the Atiamuri Landfill. RLC has identified 10 catchment zones that collect wastewater around the region, through pump stations (lift stations), manholes and pipelines to deliver waste to one wastewater treatment plant located at Te Ngae Road, Rotorua. The asset details are listed in Table 3. The key components of the network considered for damage modelling include: (i) 79 pump / lift stations; (iii) 7789 manholes; (iv) 534 km pipes. The potential damage to manholes were modelled for RLC needs, however, their impact is not included in this paper as the recovery time of wastewater supply would not be largely affected by the repair time required for manholes. It was identified that only less than 1% of the total number of manholes suffered moderate damage with a potential uplift between 50 mm to 200 mm. It was assumed that these manholes and any damage to inlet/outlet pipe connections at those manholes could be restored during recovery of other components of the network.

Table 3: Summary of wastewater assets per catchment area.

Wastewater Catchments	Pump Stations	Manholes	Pipes (km)
W-CBD	3	255	14.6
W	8	898	54.4
W1	6	788	44.5
W2	13	2850	151.8
W3	15	683	45
Wn	1	30	29.1
S	4	338	22
E	8	1261	88.1
E1	4	229	17.6
En	17	457	66.9
Total	79	7789	534

The wastewater treatment plant (WWTP) has many physical and chemical unit processes including a 5-stage Bardenpho process and clarifiers connected in series to treat and eliminate the contaminants of the wastewater collected (Figure 6). The contents are further treated through a land irrigation system before it is safely fed into the lake.

Figure 6: Aerial view of the wastewater treatment plant in Rotorua (Source: RLC website).

Wastewater pump stations are critical components in a wastewater network as they raise wastewater from lower elevation catchments. The Rotorua region has about 80 pump stations and 80-90% of them use submersible pumps. The collection pipes transport waste to low elevations where it is then pumped back up-gradient to the WWTP. Some of the rural areas of the region rely on on-site disposal; septic tanks or community package wastewater treatment plants, and such areas are not considered for this study. Typically pump stations were built as concrete block structures with cladding and steel sheet roof. The pump chamber is a reinforced concrete structure constructed below ground. Figure 7 shows a typical pump station and a below ground pump chamber.

Figure 7: Typical wastewater pump station and chamber (Photos: [34]).

The year of construction of the pump stations ranges between 1939 and 2013 with almost 75% of them built/refurbished after 1980. Newer submersible pump stations basically consist of two chambers which are non-symmetrical, i.e. the circular sump with the pumps and the square chamber for the valves as shown in Figure 8. Typically, the valve chamber is about 1350 mm deep and the sump chamber is about 3500 mm below the ground level. A reinforced concrete slab covers both of the chambers. As part of new construction methods, the pipes through the concrete walls are preferably with fibreglass material to accommodate any strain due to differential settlements between the chambers.

Damage Modelling

The assets of water networks were broadly classified into two groups representing point assets and line assets. Fragility functions with five different damage states were used to model damage to the point assets. The damage states were considered representing various levels of damage and functionality of the asset and are noted as: DS1 for 'None', DS2 for 'minor', DS3 for 'moderate', DS4 for 'extensive' with damage beyond repair and full loss of functionality and DS5 for 'complete' with collapse of the building/ reservoir and full loss of functionality [35]. Detailed descriptions of damage states specific to different types of assets were developed in discussions with RLC asset engineers and are presented in the Appendix.

The fragility functions were expressed in terms of ground shaking level (PGA) and the probabilities of exceeding different damage states. A single damage state was assigned to the asset and it was based on the 84^{th} percentile for a given PGA value, which is one standard deviation above the mean. Therefore, 84% of the time the asset can be expected to experience less damage, and 16% of the time it can be subjected to a higher damage state. Using the damage state at the 84th percentile is a conservative estimate of damage. For water source intakes (springs), pump stations and storage reservoirs published fragility functions [35] were used. Figure 9 shows an example of fragility curves derived for a typical water supply pump station [35] with a pumping capacity less than 38 m^3/s and anchored with seismic restraints. Note that these fragility functions were calibrated to suit the expected performance of pump stations with input from RLC asset engineers.

Figure 8: Two types of chambers (square and circular) in submersible pump station. (Photos courtesy: RLC).

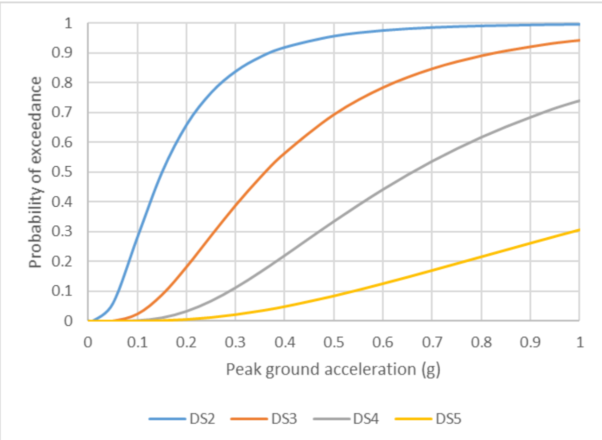

Figure 9: Fragility functions for pump stations (with seismic restraints [35].

Damage Modelling for Pipes

Water supply and wastewater pipes are generally buried underground, and they are vulnerable to shaking related ground damage in the form of ground displacement/strain, liquefaction and lateral spreading. During the 2010-11 Canterbury Earthquake Sequence (CES), buried infrastructure sustained severe damage [36]. CES provided a wealth of information on ground motions experienced and network damage data to quantify ground damage and to establish fragility functions (in terms of repair rate or break rate per unit length) for buried pipes (e.g. [37-40], among several others). Various factors including pipe size, material, and their supporting ground conditions in terms of susceptibility to liquefaction and lateral spreading, permanent ground displacement (PGD)/ground strain and peak ground velocity (PGV) experienced were considered in deriving fragility functions.

The pipe types in Canterbury were similar to those installed around the country, including Rotorua, and consist of a mix of materials and diameters. In this study, suitable empirical fragility functions relating break rates per km length with Modified Mercalli Intensity (MMI) were used [40,41]. These fragility functions were derived combining the global damage data [42] and Canterbury damage data. MMI is used as the intensity parameter for convenience to build on the existing models while acknowledging the fact that MMI inherit the subjective-ness of the macro-seismic scale unlike the other engineering demand parameters (e.g. PGV, PGD). The break rate information distinguishes between pipe types and sizes, as well as the ground conditions that led to failure. Pipe types are categorised based on flexibility, as either brittle, ductile, or semi-ductile, depending on the required categorisation in the particular break rate equation applied.

For pipe damage modelling, the pipes were segmented into approximately 50 m lengths. By considering smaller segments, it was possible to account for the effects due to varying shaking intensities and ground damage caused by liquefaction and lateral spreading. For both water supply and wastewater pipes, segments are classified for the application of fragility functions by diameter, specifically >400 mm, 100–400 mm, and <100 mm. Pipe segments are further categorised as ductile, non-ductile or galvanised iron. The liquefaction severity (as determined by MMI experienced and liquefaction susceptibility) and lateral spreading potential determine the hazard parameters for each pipe segment. There are a multitude of different break rate equations applied, depending on these attributes. Only a few expressions are included in this paper and for further details are reported elsewhere [41]. Earlier studies [32] have noted that, at MMI7, the effects of liquefaction are low; whereas at MMI 8 the liquefaction severity is moderate and MMI9 or above the liquefaction severity is high or very high.

Empirical expressions of fragility functions (break rates per km distance) based on MMI were used for two categories: (i) for pipes of size larger than 400 mm diameter considering modification factors for cast iron material, coupling age factor and liquefaction hazard factor; and (ii) for pipes of size less than or equal to 400 mm diameter for region with only shaking and no liquefaction and lateral spreading effects. The liquefaction and lateral spreading zones are shown in Figure 4. Pipes located in areas of liquefaction and lateral spreading susceptibility are assessed for damage based on the MMI level and discrete values of break rates were applied as given in Table 4 for water supply and wastewater pipes and Table 5 for wastewater pipes in lateral spreading zone only. Based on engineering judgement, it was assumed that in areas with lateral spreading potential, 15% of pipe segments were assumed to experience lateral spreading, with the remainder experiencing high liquefaction.

Two types of failure modes were assumed in this study: (i) breaks; and (ii) leaks. If failures to the pipe segments were only due to ground shaking, 80% of them were considered to be ‘leaks’ and rest of them were considered to be ‘breaks’. However, if the failures to the pipe segments were due to liquefaction or lateral spreading, 80% of them were considered to be ‘breaks’ and the rest as ‘leaks’. Differentiating the failure into ‘breaks’ and ‘leaks’ is useful as it affects the time required to repair the pipe for restoring the services. The proportions of breaks vs leaks were adopted based on the earlier study [6].

Table 4: Break rate per kilometre for pipes in areas of liquefaction or lateral spreading.

Liquefaction Severity	Ductile ≥100 mm	Non-Ductile ≥100 mm	Ductile <100 mm	Non-Ductile <100 mm
Low	0.11	0.58	0.23	2.26
Moderate	0.42	1.80	0.46	5.21
High	0.61	2.21	0.62	5.49
Lateral spreading (water supply pipes only)	2.57	5.65	1.88	9.30

Table 5: Break rate per kilometre for wastewater pipes in lateral spreading zones.

Ground Conditions	Pipe Material	Breaks/km
High liquefaction severity	Brittle	25
	Semi-ductile	7
	Ductile	2
Lateral spreading	Brittle	50
	Semi-ductile	16
	Ductile	5

Outage/Recovery Modelling

Outage or recovery modelling of damaged infrastructure network is recognised to be a complex problem requiring knowledge on: (i) the performance of network components related to their severity of damage and their extent of spatial distribution over the supply region; (ii) the priority and order of recovery of service in the region; and (iii) the resources available. Several research studies have attempted to treat outage/recovery modelling with complex algorithms considering prioritisation of inspection and repair scheduling criteria and use of available resources and repair crews to achieve optimised recovery time (e.g. [43] and [44], among others). These approaches can become computationally intensive if the network connectivity is complex with multi-varying factors and the recovery information is computed at household level. Therefore, in dealing with such real-world problems where lots of uncertainties are involved, it is prudent to make reasonable assumptions in the modelling process to suit the objective of the study. In this study, the focus was to derive outage/recovery time at the pre-defined water supply zones and wastewater catchment zone level and to adopt a strategic approach by identifying priority and order of recovery to reduce the region's socio-economic impact.

Performance of Water Supply Network

In the water supply network, 5 source intake structures, 13 pump stations and 22 storage reservoirs were assessed for their likely damage states. A prominent observation was that the assets to the South of Rotorua and closer to the Ngakuru Southwest fault line showed the likelihood of experiencing greater damage compared to the assets to the North and West of Rotorua that are far away from the fault line. The damage scenario for these critical assets indicated that at least about 8 pump stations (62% of the total); 3 water intakes (60% of the total); and 10 reservoirs (42% of the total) were likely to suffer, at least, moderate damage.

Figure 10 shows a damage scenario map with the distribution of pipe segments that were predicted to have failed as a result of a single simulation process using break rates from Table 4. The damage scenario for the pipe network would be different for another simulation with different number of failures and their locations in the network due to the random number process involved. Hence, several pipe failure simulations were run and the mean of the cumulative aggregate of failures was observed for convergence. The total number of failures showed a distribution with the 50th percentile value of 426 failures and 84th percentile value of 464 failures.

The map shown in Figure 10 should be considered as an indicative damage scenario that was used for risk assessment in this study and not to be used for any other purposes. The main pipes were identified with 130 failures (i.e. either in the form of break or leak) and the submain pipes were identified with about 300 failures giving a total estimate of about 430 failures in the water supply network. Pipes in certain zones in the Central scheme were predicted with more than 200 failures collectively, both mains and submains.

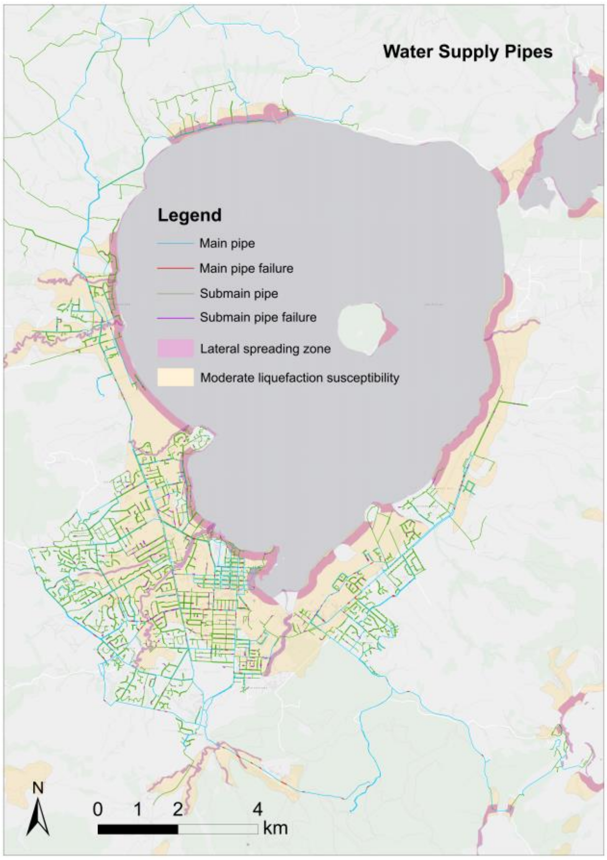

Figure 10: Water supply pipes break locations.

The damage results to pipes are tabulated with respect to the areas subjected to only shaking, liquefaction and lateral spreading for all the supply zones collectively in Table 6. The damage summary of all the modelled components in the network is provided in Table 7.

Table 6: Water supply summary: all Rotorua. Length in km.

Total Rotorua Water Supply	Main Pipes				Submain Pipes				Total	
	Ductile		Brittle		Ductile		Brittle			
	Length	Failures	Length	Failures	Length	Failures	Length	Failures	Length	Failures
Lateral spreading zone	7.7	4	1.3	4	17.1	9	3.8	10	29.9	27
Liquefaction zone	40	27	26.3	63	99.6	58	68	166	233.9	314
Shaking only	56.4	11	62.3	21	158.3	16	77.4	43	354.4	91
Total	104.1	42	89.9	88	275	83	149.2	219	618.3	432

Table 7: Summary of damage and outage time for the water supply network. ER = emergency response.

Phase	Priority	Order	Primary Infrastructure/ Supply Zones	Time to Restore Services	Time until Pipe Repairs	Pump Stations	Water Intakes	Reser voirs	Pipe Failures – Mains	Pipe Failures – Submains	Pipe Failures – Total
ER	ER	1	Central Headworks	2 weeks	2 weeks	3x DS3	1x DS3	-	-	-	-
ER	ER	2	Eastern Headworks	4 weeks	4 weeks	1x DS3	1x DS4	-	-	-	-
ER	ER	3	Mains to incl. Matipo and Utuhina Reservoirs	4 weeks	2 weeks	-	-	3x DS3	0	0	0
ER	ER	4	Mains to incl. Hemo Res	5 weeks	4 weeks	-	-	1x DS3	3	0	3
ER	ER	5	Mains to CBD	5 weeks	4 weeks	-	-	-	15	0	15
ER	ER	6	Mains to incl. Tarawera Reservoirs No1 and No2	5 weeks	4 weeks	-	-	1x DS2, 1x DS3	2	0	2
Basic	1	7	Western Headworks	1 week	1 week	1x DS1	1x DS2	-	-	-	-
Basic	1	8	Mains to incl. Pukehangi Booster, Russel Res	7 weeks	4 weeks	1x DS2, 2x DS3	-	1x DS3	2	0	2
Basic	1	9	Mains to incl. Henderson Reservoir	2 weeks	1 week	-	-	1x DS2	5	0	5
Basic	1	10	Mains to incl. Central Reservoir	1 week	1 week	-	-	1x DS1	0	0	0
Basic	2	11	Mains to incl. Okareka Tank	10 weeks	5 weeks	1x DS3	-	2x DS3	2	0	2
Basic	2	12	Northern Headworks	1 week	1 week	1x DS1	1x DS2	-	-	-	-
Basic	2	13	Mains to incl. Hamurana Reservoir	1 week	1 week	-	-	2x DS1	0	0	0
			Supply Zones								
Full	1	1	CBD Zone	6 weeks	5 weeks	-	-	-	25	34	59
Full	1	2	Area covering Lynmore, Ngapuna, Owhatiura, Owhata, Hinemoa Point, Holdens Bay and Rotokawa zones.	7 weeks	5 weeks	-	-	-	23	47	70
Full	2	3	Rest of the zones in Central scheme	9 weeks	4 weeks	1x DS3	1x DS4	3x DS2, 2x DS3	47	203	250
Full	2	4	Area covering Eastern High Pressure and Forest Place zones.	6 weeks	5 weeks	-	-	-	0	2	2
Full	2	5	Ngongotaha	2 weeks	1 week	-	-	-	4	12	16
Full	3	6	Okareka	10 weeks	10 weeks				0	1	1
Full	3	7	Hamurana	2 weeks	1 week	2x DS1	-	4x DS1	2	3	5
					Totals	4x DS1, 1x DS2, 8x DS3	2x DS2, 1x DS3, 2x DS4	7x DS1, 5x DS2, 10x DS3	130	302	432

Priority and Recovery of Water Supply Network

Three different recovery phases were identified by RLC: (i) emergency recovery (ER, for the most important assets); (ii) basic (for minimum functionality); and (iii) full (for full recovery). In addition, RLC determined the priority and order of recovery of different parts of the network to assist in the recovery of the supply zones in the preferred order. For outage modelling, the assets were first assigned a recovery phase, priority and order according to data provided by RLC (ref: Table 7).

It was assumed that pipe repairs would not begin until a minimum flow of water was available. This assumption was based on the fact that the water flow was necessary for finding breaks and leaks in the pipes. Therefore, the headworks including source intakes, reservoirs and pump stations were to be restored to provide water for damage detection in pipes. The restoration time for the headworks were best estimated rationally based on the rebuild and recovery process observations reported following the 2010-2011 Canterbury earthquakes [45] and shown in Table 8. This was necessary to begin the repair for each of the target recovery areas listed in Table 7.

The priority and order were followed for repairing the pipe network, unless the requisite water supply was not yet available, in which case repairs began on lower priority pipes. In this way, the network service was restored as efficiently as possible, while still targeting the areas of highest priority when it was possible to do so.

Computation of Outage Time for Water Supply Zones

Some of the key factors and the basis for consideration within this study are described below.

Number of crews available: There should be an understanding of the number of crews available immediately after the event, and how many additional crews outside the Rotorua district will be required for weeks following the event. In discussions with RLC, 6 crews were assumed to be available for the first two weeks and it was assumed to be increased to 12 crews after the third week until all the repairs were completed. These crews were expected to be mainly available to repair the pipes. It was assumed that special crews would be available to repair the point assets and the restoration of point assets could occur in parallel. It is appreciated that as Rotorua is geographically well connected with other regions (Hamilton, Auckland etc), it is possible that adequate crews can arrive earlier than the assumed time frame in this study to manage the restoration process so that the outage time can be reduced.

Repair rates for fixing the pipes: The repair rates for the breaks and leaks were arrived in discussions with RLC. In a week, all 7 days were considered to be as working days. Two different repair rates were applied for mains and submains: 2.5 days per break in the mains and 0.5 days per break for submains. For fixing leaks, the repair rate for the mains was doubled, i.e. 1.25 days per leak, although the same repair rate was retained for fixing the leaks in the submains. Note that the repair rates can be affected by the availability of materials for construction after a real event. Also, in the future improved repair technologies could be in practice that could have better efficiency in reducing the repair time.

Interdependencies on other networks: The transport, electricity and fuel supply services that are relevant for the water network restoration were assumed to get restored in short time frames so as not to have significant impact on the restoration of water services. However, after a real event, interdependencies on other lifelines could play a significant role in outage time of the water services particularly in terms of availability of road access to the repair site and electricity/fuel supply to run pump stations or generators. Modelling interdependencies of critical infrastructure networks has been an active research area at least for the past two decades and several methods addressing different levels of complexities and their appropriateness have been investigated ([46-48], among others). In addition, there is new interest and need for developing decision support tools to test different intervention options and their effects on improved network performance. Recently, a research study has been completed to develop a decision support tool with capabilities for handling large size of network data and information including user interactive features to test different intervention options and compare outage times [49]. Further work is ongoing to model infrastructure outage within probabilistic approach where two networks can be spatially correlated for generating combined outage [50].

Table 8: Restoration time for water supply assets depending on the damage states.

Damage State	Pump Stations	Water Intakes	Reservoirs
DS2	0.5 weeks	1 weeks	1 week
DS3	2 weeks	2 weeks	4 weeks
DS4	4 weeks	4 weeks	20 weeks
DS5	12 weeks	12 weeks	24 weeks

The priority and orders of each item listed in Table 7 were followed to compute the outage time for each item. The supply zone headworks and mains to reservoirs were given priorities for emergency and basic recovery. Then, full recovery to the supply zones was undertaken. Knowledge around the network connectivity and operation is fundamental to identify priorities and the order of restoration for the components. Repairs would start with the headworks, pump stations, mains and reservoirs, followed by trunk distribution mains in the supply zone. For example, to compute the outage time for the CBD supply zone, it was required to identify the components of the pipe network and the point assets that supply water. In this case, the restoration time for mains to CBD, mains to the reservoirs and the central headworks were added to the restoration time for pipes in the CBD supply zone. To determine restoration times, pipeline failures were manually tabulated for each zone, allowing crews to be assigned based on availability over time.

To calculate the restoration time for the pipes in each zone, the steps involved are: (i) aggregating the total number of damaged segments of mains and submains in the zone of interest to get the total number of failures; (ii) dividing the total number of failures into potential ‘breaks’ and ‘leaks’ as discussed earlier; (iii) applying the repair rates and find the number of ‘crew days’ as the ratio of total number of breaks (or leaks) to the time required to repair per crew; (iv) allotting the crews in the defined restoration order, after considering the necessary waiting time; and calculating the minimum number of weeks required to restore full functionality (i.e. pre-event level of service) using the number of crews allotted and the repair rates.

A temporal outage map for the water supply zones is shown in Figure 11. The outage times for primary water network components and water supply zones are summarised in Table 7. The CBD supply zone, which is the highest priority, was estimated to take about 6 weeks for full functionality to be restored, as the headworks and the mains to CBD could take about 5 weeks to restore and one more week to restore the reticulation pipes within the zone. The Eastern supply zone was estimated to have an outage time of about 7 weeks and that for the Central zone was about 9 weeks. Ngongotaha and Hamurana supply zones could take about 2 weeks to restore, as they experienced less damage and crews were available to restore the services, even though the priority and order was relatively low for those zones. Okareka supply zone took the longest at about 10 weeks. This is because the maximum time for pump restoration and reservoir restoration in the Okareka region was 5 weeks and crews would be busy with restoration for higher priority areas. Many times, the recovery process is about optimising the resources and increasing efficiency. Nevertheless, the outage times predicted from this risk assessment will be useful to appreciate the relative severity of outages for different supply zones.

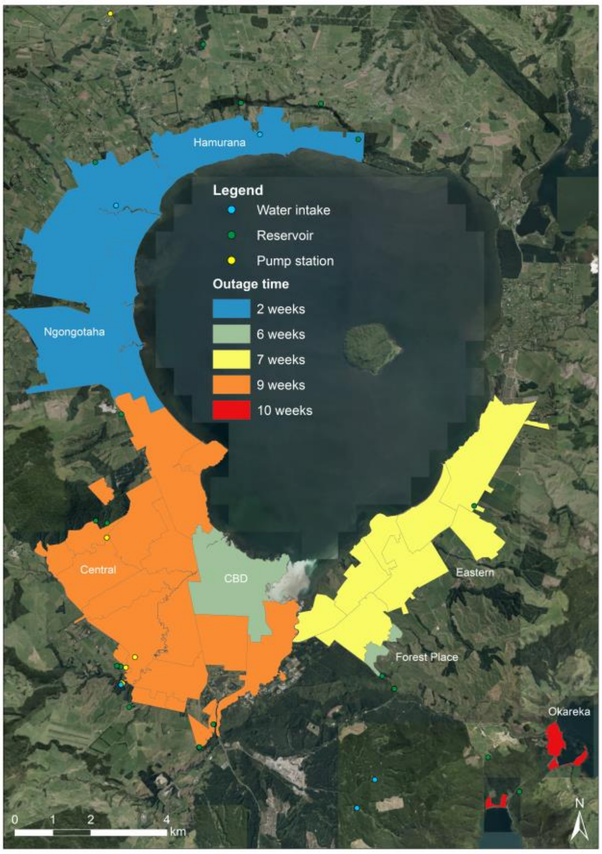

Figure 11: Outage time for water supply zones.

Performance of Wastewater Network

In the wastewater network, pump stations were modelled for damage. However, the wastewater treatment plant was not modelled for the reasons explained earlier in the report and the treatment plant was assumed to be partially operational under the current scenario chosen.

Out of total 79 pump stations, about 50% of them are in less than or equal to DS2 and about 40% of them are in DS3 and 6% of them are in DS4. Unlike water supply pump stations, many of the wastewater pump stations are below the ground level with submersible pumps and situated in the liquefaction and lateral spreading zones. As observed during the CES, these pump stations could suffer from various effects including differential settlement, uplift of the chambers, shearing of inlet-outlet pipes due to settlement around the structure. RLC was interested to know the damage states for 14 key wastewater pump stations (PS) serving significant catchment zones, in which 8 of them (PS34, PS36, PS44, PS45, PS46, PS47, PS54 and PS56) were predicted to sustain only minor damage and 6 of them (PS4, PS6, PS7, PS9, PS13 and PS31) to sustain moderate damage.

The distribution of damage to wastewater pipes is shown in Figure 12. The main pipes were identified with about 250 failures and the submain pipes were identified with about 470 failures giving a total estimate of about 720 failures over 534 km length pipe. About 1/3rd of the total pipe breaks were observed only in the Western region. The damage results to pipes are tabulated with respect to the areas subjected to only shaking, liquefaction and lateral spreading for all the catchment zones collectively in Table 9. Table 10 provides the damage summary of all the modelled components in the network.

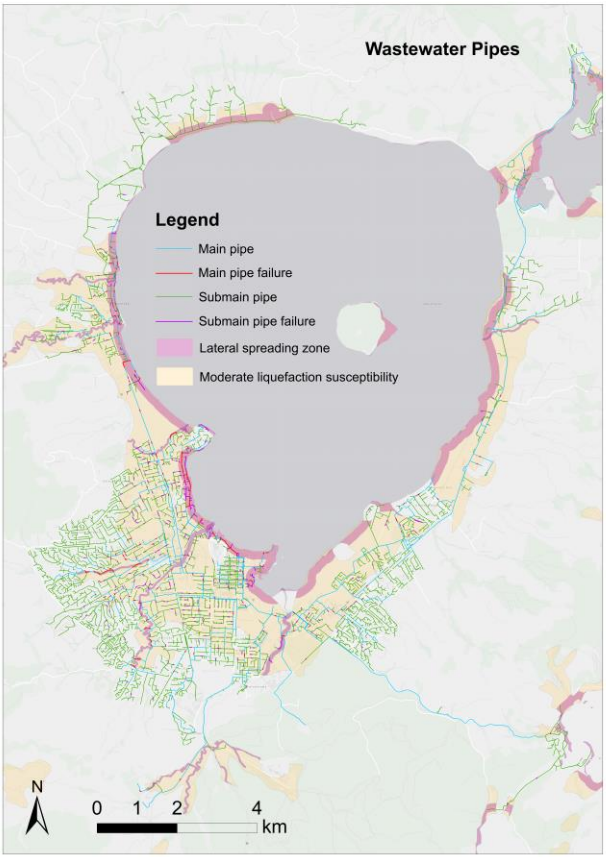

Figure 12: Wastewater pipe break locations.

Table 9: Wastewater catchment summary: all Rotorua. Length in km.

All Wastewater Catchments	Main Pipes				Submain Pipes				Total	
	Ductile		Brittle		Ductile		Brittle			
	Length	Failures	Length	Failures	Length	Failures	Length	Failures	Length	Failures
Lateral spreading zone	9.1	12	10.1	141	18.2	13	11.2	184	48.6	350
Liquefaction zone	43.1	19	40	68	43.5	24	92.6	207	219.2	318
Shaking only	28.6	1	19.3	13	101.6	10	116.7	30	266.2	54
Total	80.9	32	69.3	222	163.3	47	220.5	421	534	722

Table 10: Summary of damage and outage time for the wastewater network.

Phase	Priority	Order	Primary Infrastructure/ Supply Zones	Time until Minimum Function	Time until Pipe Repairs	Pump Stations	Pipe Failures – Trunk	Pipe Failures – Mains	Pipe Failures – Submains	Pipe Failures – Total
ER	ER	1	WWTP	Reduced functionality	-	1x DS3	0	0	1	1
ER	ER	2	Mains to CBD	6 weeks	6 weeks	-	0	0	0	0
ER	ER	3	Mains to hospital, PS2, PS28, PS5	7 weeks	6 weeks	3x DS3	0	16	2	18
Basic	1	4	Mains to PS6 Depot St	8 weeks	6 weeks	1x DS3	1	0	0	1
Basic	1	5	Mains to PS4 Elisabeth St	6 weeks	6 weeks	1x DS3	0	0	0	0
Basic	1	6	Mains to PS31	8 weeks	6 weeks	1x DS3	1	0	0	1
Basic	1	7	Gravity trunk main South Fenton	10 weeks	9 weeks	1x DS3	0	2	0	2
Basic	1	8	Mains to PS44 Parawai	10 weeks	9 weeks	1x DS2	0	14	0	14
Basic	1	9	Mains to PS7; Mains to PS13	10 weeks	9 weeks	2x DS3	0	1	0	1
Basic	2	10	Mains to PS45, PS46, PS47	8 weeks	6 weeks	3x DS2	0	4	1	5
Basic	2	11	Mains to PS76, PS77	6 weeks	6 weeks	1x DS1, 1x DS2	0	0	0	0
Basic	2	12	Mains to PS36, PS56, PS55, PS54	8 weeks	7 weeks	4x DS2	0	2	0	2
Basic	2	13	Mains to PS34, PS35	8 weeks	7 weeks	2x DS2	0	6	0	6
Basic	3	14	The rest of the primary mains and pump stations	11 weeks	6 weeks	13x DS1, 14x DS2, 25x DS3, 5x DS4	0	96	0	96
			Catchments							
Basic	1	1	PS28, PS2, PS5 (W-CBD)	8 weeks	6 weeks		0	10	37	47
Full	2	2	W	12 weeks	6 weeks	5x DS3, 1x DS4	0	7	39	46
Full	2	3	W2	14 weeks	9 weeks	2x DS1, 1x DS2, 7x DS3	0	60	195	255
Full	2	4	W1	15 weeks	9 weeks	4x DS3, 1x DS4	0	16	58	74
Full	2	5	W3	16 weeks	6 weeks	3x DS1, 7x DS2	0	4	57	61
Full	2	6	S	16 weeks	9 weeks	2x DS3, 2x DS4	0	6	15	21
Full	2	7	E	16 weeks	7 weeks	6x DS3, 1x DS4	0	4	33	37
Full	2	8	E1	17 weeks	7 weeks	1x DS2, 1x DS3	0	2	19	21
Full	3	9	Wn	17 weeks	6 weeks	-	0	0	3	3
Full	3	10	En	17 weeks	7 weeks	8x DS1, 5x DS2	0	2	8	10
					Totals	14x DS1, 25x DS2, 35x DS3, 5x DS4	2	252	468	722

Priority and Order of Recovery of Wastewater Zones

The approach for determining priority and order of recovery for the wastewater network is the same as for the water supply network. For outage modelling, the priority and order were broadly followed, unless it was more efficient to begin repairs on a part of the network that was lower priority. Repairs to wastewater pipe repairs were dependent on the availability of water supply in the vicinity of the pipe to be repaired and could not begin until the water supply was restored. This assumption was made based on Christchurch experience, where the wastewater pipes were to be flushed with water to clear the liquefied material so that breaks and leaks could be located. The pump stations were assumed to be operational at reduced capacity. In Christchurch, even the most severely damaged pump stations were returned to service within days of earthquakes. So, the minimum time to begin the repair work for a given part of the pipe network was equal to the restoration time for the water supply to that location. The repair time estimates for different parts of the network are listed in Table 10.

Computation of Outage Time of Wastewater Catchment Zones

Wastewater collection can be restored only when WWTP and the pump stations essential to lift the wastewater to the elevated level are functional. As discussed earlier, the treatment plant was assumed to be functioning at a reduced capacity. Out of 79 pump stations as shown in Table 10, 74 of them were likely to suffer 'moderate' damage (DS3) or less; and only 5 of them were noted with 'severe' damage (DS4). These 5 pump stations were not associated with significant catchment zones. In Christchurch, even the pump stations that suffered 'moderate' to 'severe' damage were restored to be functional to a reduced capacity [51]. Therefore, for this exercise, the pump stations were assumed to be restored well before the restoration of water supply to function at reduced capacity.

The wastewater network outage time was computed based on the approach adopted for water supply network. The number of damaged pipes were manually tabulated, and a specific number of crews were assigned. The repair rate for wastewater pipes was the same as it was considered for water pipes. Table 10 shows the priority and order of recovery for different components in the wastewater network. WWTP was given the highest priority to be recovered. It was assumed that 12 number of crews were available to begin the repair work after 6 weeks for water to be restored for the high priority recovery area. It may be noted that mains to PS 45, 46 and 47 needed to wait only for 2 weeks for water supply and theoretically wastewater repair should have begun in those areas even though they had low priority. However, it was assumed that the available crews in the first 2 weeks after the event would preferably be deployed to restore water supply network services. Figure 13 shows outage times for wastewater catchment zones.

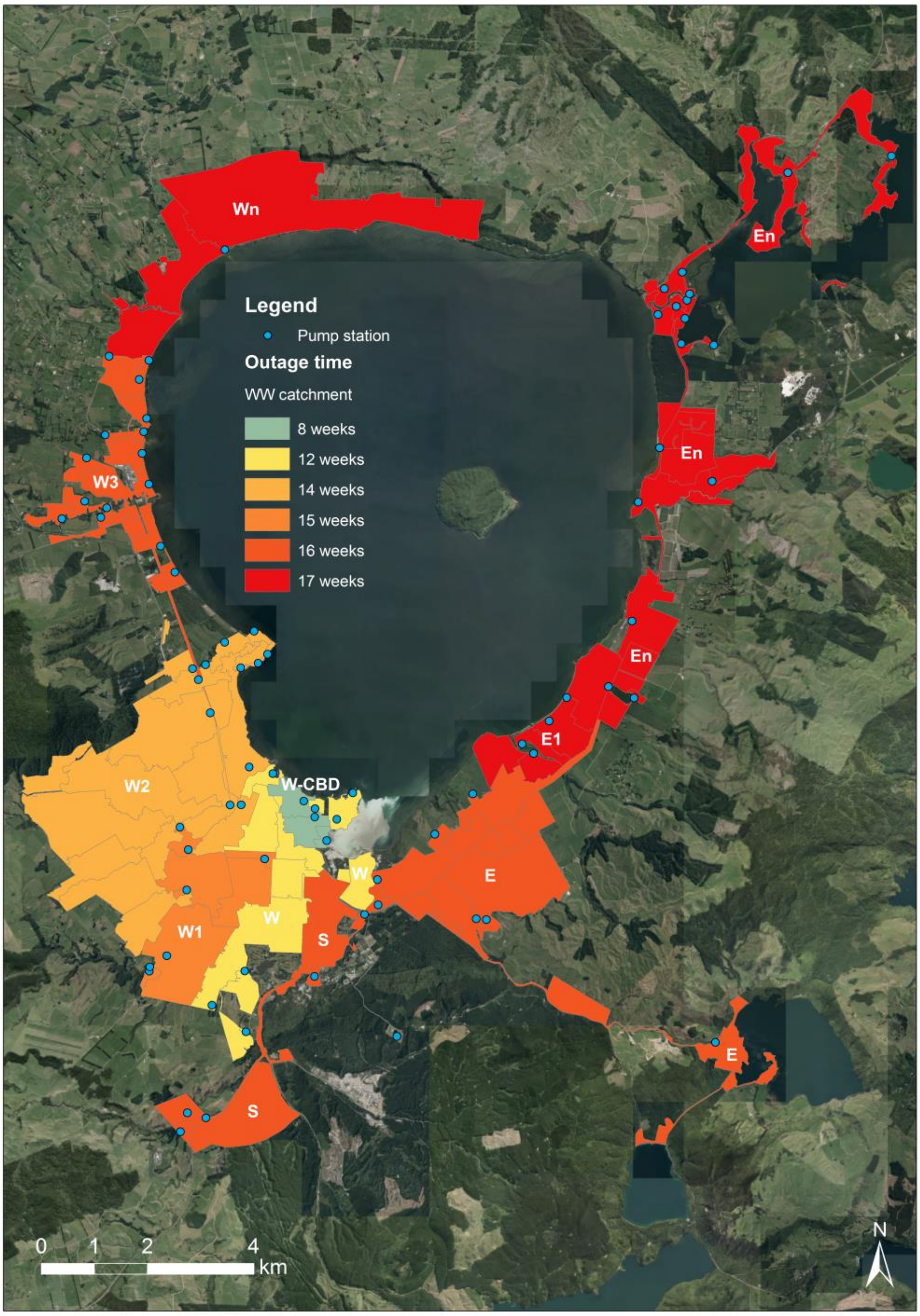

Figure 13: Outage map of wastewater catchments.

DISCUSSION

An earthquake risk assessment study depends on limited knowledge of the assets, their performance in the past events and of their future condition. The natural variability of earthquake-related processes means that there are many uncertainties in hazard and damage prediction procedures. The current study has considered the 84^{th}-percentile values of ground motion intensities for the analysis to provide conservative impact estimates. The fragility models used in this study are adopted from published literature and may not accurately represent the fragility of the asset; however, they are suitable for assessing the relative severity of damage to the network components. The distribution of pipe failures presented in this study shows one possible damage scenario. This scenario was chosen after performing multiple runs to achieve convergence in the total number of failures. However, because of uncertainties in the quality of design, the construction and the maintenance of the assets involved, and in the precise nature of the ground supporting them, the resulting damage scenario has relatively high levels of uncertainty.

The outage times presented in this study are based on a set of predefined values for the number of crews and repair rates available under the current conditions. This exercise helps to provide a sense of relative severity of outages among different supply zones and catchment zones. However, large variabilities are associated with these parameters in a real event and these parameters cannot easily be well constrained to optimise the outage time. Therefore, our current study did not model the effects of those variabilities on the outage time estimates.

The damage distribution and outage time are derived for Ngakuru Southwest fault earthquake scenario. Every attempt has been made to account for uncertainties in various stages of the risk assessment process adopted. However, it is worth appreciating that subjectivity and judgement were inevitably necessary given the scope of the study and variations in the assumptions could well generate different results.

The impact on the two water networks as presented in this paper only include those arising from direct damage to the point assets and the pipes caused by earthquake ground shaking and ground damage due to liquefaction and lateral spreading. Damage arising from other effects caused by landslides, aftershocks and fire following earthquake are not considered. The impact of landslides on the network performance was not modelled. Although landslide susceptibility has been mapped for the whole country, it is currently based only on the slope angle and simple geological characteristics. The true potential for slope failure depends on numerous factors including soil and geological conditions, vegetation, rainfall, and shaking level, among other factors. Sophisticated models can be developed using fundamental principles when all the necessary information is available for a given region [52]. These models are computationally intensive and require evidence-based data to generate reasonably reliable landslide scenarios. For the above reasons, landslide modelling and impact on the two networks was not considered.

In this study, it is assumed that the other dependent lifelines are functional and available for restoration of the two water networks. However, there could be an increase in the estimated outage times when accounting for the outage of interdependent lifelines [53].

CONCLUSIONS AND RECOMMENDATIONS

The present study exemplifies a science-based pragmatic approach to plan for resilience improvement of water infrastructure networks by generating results that are useful and usable by the end-user. Scenario-based risk assessment was conducted for two water networks for Rotorua Lakes Council under the potential rupture of Ngakuru Southwest fault to: (i) identify vulnerable parts of the network; and (ii) estimate the likely resulting outage time as a step towards RLC's infrastructure resilience planning.

The risk assessment approach adopted was effective and efficient to achieve the set objectives and did not warrant huge computational time and cost to generate results that are useful and usable. For example, the damage scenarios generated provide information related to the vulnerable parts of the network and their severity (damage states), at least in a relative sense. Similarly, the outage maps presented are a simple but effective means of communicating the impact of loss of services to the community and the stakeholders who are key financial decision makers. The study also extracted ground motion intensity values from the chosen active fault for this risk study (i.e. Ngakuru Southwest fault) at various critical facility sites which can be used for site-specific structural assessments for the identified critical assets.

In this work, restoration of the two water networks were modelled without considering their interdependencies on the availability of road access, electricity and fuel supply which could largely be influenced by the geography of the affected region and the resilience of the individual network. For example, the geography of Christchurch supports connectivity of various zones by alternate routes compared to the geography of Wellington which would be extremely isolated following a Wellington Fault event. Similarly, the robust electricity network in Christchurch showed very high resilience with very short recovery time after the Christchurch event. Modelling interdependencies can be dealt in different levels of complexity. In some cases, every network can be modelled for its damage and outage of services independently and the effects of interdependent network can be accounted in a systematic and logical manner. Even though this approach is not 'perfect', it still helps to appreciate the magnitude and order of interdependency effects on outage time. The advantage of such an approach is that not all interdependent infrastructure networks need to be analysed at the same time and the infrastructure providers can plan their risk assessment studies as per their priority and viability. This study can also be extended to test options for cost effective resilience improvements of the networks by comparing the costs of resilience improvements against the reduction in losses or outage times of the different options.

Some of the key highlights and success factors of this exercise include: (i) continual engagement with the end-user from the stage of conceptualisation of the problem to delivery; (ii) transparency of the proposed risk assessment methodology adopted; (iii) participatory approach with the council authorities (responsible for providing satisfactory levels of services to customers) in defining the event against which the resilience was to be assessed at least with the council authorities, if not community wide; (iv) presenting the deliverables that can be useful for the next step in the process of resilience planning; and (v) the willingness and enthusiasm shown by RLC in providing required information as feedback related to practical constraints. Thereby, this study demonstrates a pathway forward to plan for improving resilience of infrastructure networks.

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APPENDIX

Table A1: Damage state descriptions for pump stations (adapted from [35]).

Damage State	Description
None (DS1)	-
Slight/Minor (DS2)	Malfunction of plant for a short time (less than three days) due to loss of electric power and backup power if any, or slight damage to buildings.
Moderate (DS3)	Loss of electric power for about a week, considerable damage to mechanical and electrical equipment, or moderate damage to buildings.
Extensive (DS4)	Building being extensively damaged, or the pumps being badly damaged beyond repair.
Complete (DS5)	The building collapsing.

Table A2: Damage state descriptions for water intake structures (adapted from [35]).

Damage States	Description	Christchurch CC Damage Assessment Categories
None (DS1)	-	Good condition – no action required
Slight/Minor (DS2)	Malfunction of pump and motor for a short time (less than three days) due to loss of electric power and backup power if any, or light damage to buildings.	Damaged but repairable (e.g. spring head alignment lost)
Moderate (DS3)	Malfunction of pump and motor for about a week due to loss of electric power and backup power if any, considerable damage to mechanical and electrical equipment, or moderate damage to buildings.	Sandy – requires redevelopment OR Redevelopment and repairs required.
Extensive (DS4)	The building being extensively damaged or the pump and vertical shaft being badly distorted and non-functional.	Unusable – grout, seal and replace if necessary
Complete (DS5)	The building collapsing.	Unusable – grout, seal and replace if necessary

Table A3: Damage state descriptions for reservoirs (adapted from [35]).

Damage State	Description
None (DS1)	-
Slight/Minor (DS2)	The tank suffering minor damage without loss of its contents or functionality. Minor damage to the tank roof due to water sloshing, Minor cracks in concrete tanks, or localised wrinkles in steel tanks. Slight damage to inlet/outlet pipes
Moderate (DS3)	The tank being considerably damaged, but only minor loss of content. Elephant foot buckling for steel tanks without loss of content, or moderate cracking of concrete tanks with minor loss of content. Damage to inlet/outlet pipes
Extensive (DS4)	The tank being severely damaged and going out of service. Elephant foot buckling for steel tanks with loss of content, stretching of bars for wood tanks, or shearing of wall for concrete tanks.
Complete (DS5)	The tank collapsing and losing all its content.

Table A4: Damage state descriptions for wastewater pump stations (adapted from [35]).

Damage State	Description
None (DS1)	-
Slight/Minor (DS2)	Malfunction of pump station for a short time (less than three days) due to loss of electric power and backup power if any, or slight damage to sump and valve chamber.
Moderate (DS3)	Loss of electric power for about a week, considerable damage to mechanical and electrical equipment, or moderate damage to sump and valve chamber.
Extensive (DS4)	Sump and valve chamber being extensively damaged, or the pumps being badly damaged beyond repair.
Complete (DS5)	The sump and valve chamber collapsing.

Table A5: Damage state descriptions for manholes (adapted from [35]).

Damage State	Description
None (DS1)	-
Slight/Minor (DS2)	Serviceable. No repair required. Uplift up to 50 mm above ground level
Moderate (DS3)	10–20% connections damaged; 10–20% of manholes floating; 50-200 mm uplift
Extensive (DS4)	20–50% connections damaged; 20 to 50% of manholes floating; 200-500 mm uplift
Complete (DS5)	>50% connection damaged; >50% manholes in that area floating >500 mm uplift