Potential Benefits of Implementing Water Network Resilience Projects in Wellington Region of New Zealand

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Abstract

Seismicity in New Zealand varies regionally from moderate to very high on a world scale. The country has witnessed several major earthquakes in the last decade (e.g. 2010-2011 Canterbury Earthquake Sequence, 2016 Kaikōura earthquake) that have tested the resilience of its built environment and communities. Damage to infrastructure networks during such events and the resulting disruption to services that significantly impacted businesses and communities have demonstrated the need to accelerate building resilient infrastructures in the country.

One of the regions in New Zealand that is highly vulnerable to a major natural hazard event is Wellington. With the regions' population continually expanding and placing increased demands on its ageing infrastructures, and with many of its assets close to or intersecting fault lines, a large earthquake in the region (such as that due to rupture of Wellington Fault) can be highly disruptive resulting in serious social and economic consequences. This paper will discuss modelling work undertaken by GNS Science on the regions' water and wastewater networks, carried out as part of a project aimed at demonstrating the economic benefits of implementing an accelerated and sequenced programme of infrastructure investment. Potential physical damage to the networks and the resulting likely service outages due to a large earthquake will be discussed for two cases: (a) base case considering the networks in as-is condition; (b) second case considering enhanced resilience of the networks (i.e. if the proposed resilience projects are implemented). For each case above, the impact of service outage of other networks (e.g. roads) on the water network outages will also be presented.

Keywords: resilience; water and wastewater networks; outage; recovery; interdependency; earthquake

1. Introduction

New Zealand is a predominantly urban country, with almost 74% of the population living in seventeen main urban areas (i.e. population 30,000 or greater, [1]). Of country's total population of about 4.2 million, 55% are spread in the four largest cities - Auckland, Christchurch, Wellington, and Hamilton. The country as such is extremely prone to many natural hazards, and in the last decade it has witnessed several devastating earthquakes that have tested the resilience of its built environment and communities [2]. Damage to infrastructure networks (e.g. roads, water networks etc.) during such events, and subsequent service disruptions have significantly impacted the businesses and communities that rely on the lifelines. One of the regions in New Zealand that is highly vulnerable to a major natural disaster is Wellington. Approximately 11% of NZ population live in this region, with over 90% of this population residing in five cities in the region (Fig. 1), including the country's capital, Wellington. A large earthquake in this region, such as from rupture of the Wellington Fault (see Fig. 1) that passes through heart of Wellington, can result in serious repercussions at regional and potentially to the country as well (e.g. significant economic loss - as this region contributes approximately 14% of New Zealand's GDP).

This paper will discuss a sub-set of a modelling work (Fig. 2) carried as part of Wellington Lifelines Group Programme Business Case (WeLG PBC, [3]) aimed at demonstrating potential economic benefits that can be gained by implementing an accelerated and phased programme of infrastructure resilience projects in the five cities of the region. Damage modelling on ten different lifelines/utilities (e.g. transportation [4] fuel etc.) were conducted; however, the focus of this paper will be on two key infrastructure networks i.e. water and wastewater, with the aim of demonstrating effectiveness of water resilience projects in restricting physical damage to the networks and to reduce impact on the services these infrastructures provide.

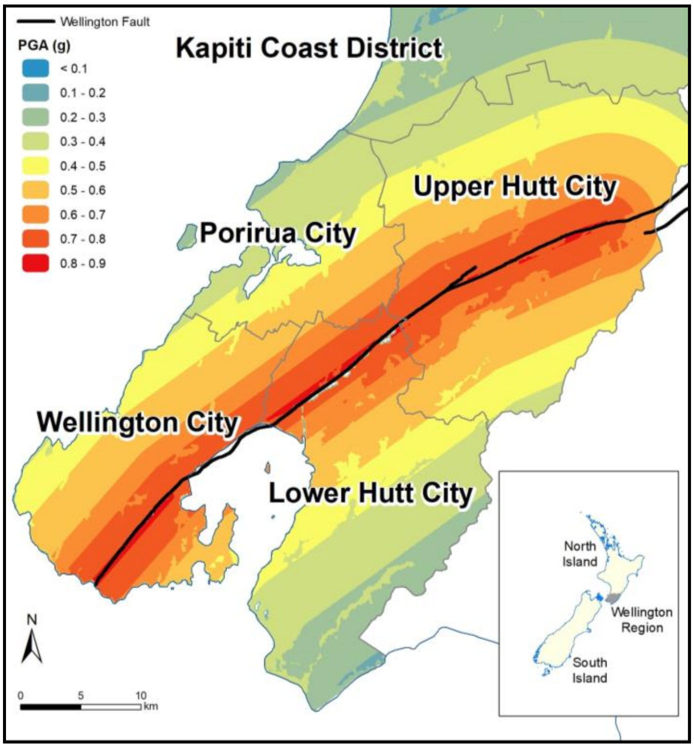

Fig. 1 – Modelled peak ground accelerations (from a Wellington Fault earthquake scenario) in five cities of Wellington Region

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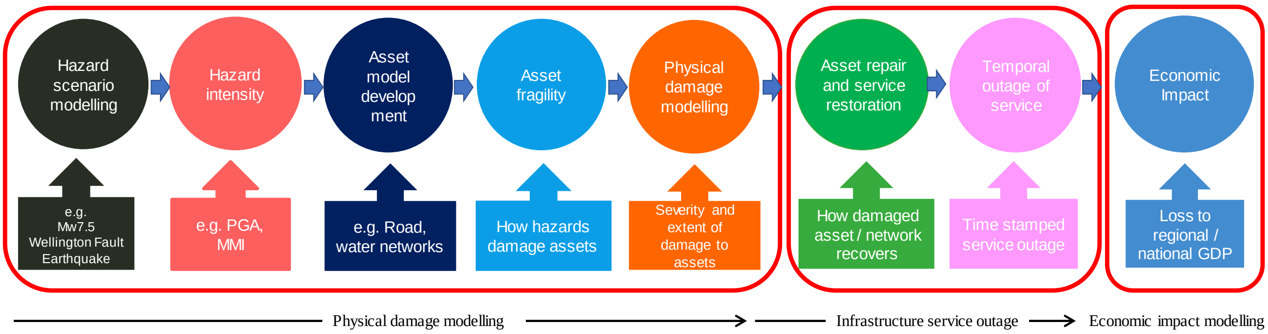

Fig. 2 – Impact modelling workflow

2. Hazard Scenario

Three natural hazard scenarios in the region were initially considered for impact modelling (Fig. 2). A high-level qualitative assessment of the potential impacts from each scenario was carried through Business Behaviours workshops [5] with the stakeholders. This was followed by discussions with the Project Steering Group before selecting a Wellington Fault earthquake scenario (Table 1) for this work for many reasons (e.g. it is well researched and commonly used as a probable maximum loss scenario for insurance risk assessments (e.g. [6]), it has a probability of occurrence of 10% in the next 100 years and is also a principal contributor to the 1 in 500-year earthquake hazard which is used to define the seismic loading levels for NZ building code for general multi-story commercial and residential buildings).

Table 1 – Hazards considered for damage modelling

Hazard	Description
Fault rupture	Fault rupture is defined as a deformation zone around the fault trace. Mapped trace of the Wellington-Hutt Valley segment of the Wellington Fault (e.g. [7]) was used including a buffer for both expected ground deformation around the fault trace and uncertainty of location.
Ground shaking from earthquake	Fault source model of the Wellington-Hutt Valley Fault (as defined in the NZ National Seismic Hazard Model [8]) was used and ground shaking across the region was estimated using ground motion prediction equation of Bradley [9]. To accommodate MMI based fragility models, ground motion-to-intensity conversion equation of Worden et. al. [10] was used.
Liquefaction and lateral spreading	The latest liquefaction susceptibility map of the Wellington region [11] was used. Here, liquefaction susceptibility is a 5-class dataset with values of none/negligible, low, moderate, high, and very high. A map of Liquefaction Severity Number (LSN) was also used where the fragility models required this input.
Landslides from ground shaking	Slopes in the study area have been mapped and assigned a probability of failure (and size of failure) given a level of PGA. These are then modelled stochastically based on the input PGA map (Fig. 1). Realisations of landslide distributions were modelled using GNS-NZTA Road Risk Evaluation Tool [12].
Co-seismic subsidence caused by fault movement	Subsidence is defined here as the estimated mean subsidence of land caused by the rupture of Wellington-Hutt Valley segment of the Wellington Fault. Subsidence caused by fault movements can result in some areas being inundated by seawater. The model used for this project is based on work that is derived from a range of geological datasets [13] and only includes the Hutt Valley as there has been little work to date on possible subsidence in other parts of Wellington from a Wellington Fault earthquake.

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3. Asset Model

Three water services (water, wastewater, storm water) to Wellington, Lower Hutt, Upper Hutt and Porirua (covers about 90% population in the study area) is provided by Wellington Water Limited (WW). They are a shared service, council-controlled organization that is jointly owned by the four city councils and Greater Wellington Regional Council. WW provided GIS files containing data on the assets (Fig. 3 shows key assets) in these four cities, and data related to the assets in the Kapiti area was sourced from Kapiti Coast District Council (KCDC). Where there were any gaps in the data provided, engineering judgement and/or proxy attributes were applied so that appropriate fragility models could be assigned to the assets for damage modelling (Fig. 2). A summary of the assets modelled is shown in Table 2. Here, the values inside the brackets represent the assets in the Kapiti area, and the values outside the bracket represent the assets combined from the remaining four cities in the study area.

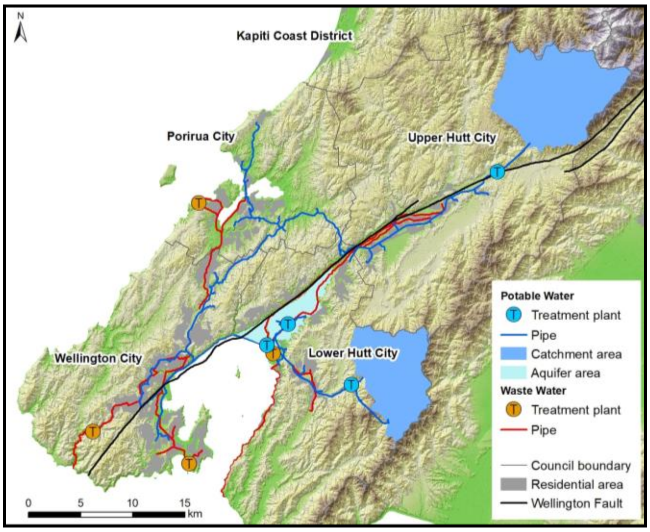

Fig. 3 – Water and wastewater networks in four cities of Wellington Region.

Table 2 – Water and wastewater assets in the study area (values within brackets represent assets in Kapiti)

Network/service	Asset					
	Catchments (nos.)	**Wells (nos.)**	**Reservoirs (nos.)**	**Treatment Plants (nos.)**	**Pumping Stations (nos.)**	**Pipelines (km)**
Water*	3 (1)	11 (13)	148 (21)	4 (4)	87 (16)	2447 (451)
Wastewater	-	-	-	4 (2)	224 (154)	2367 (331)

* includes untreated water and treated water (i.e. potable). Storm water network is excluded here.

4. Damage and Service Outage Modelling

The water and wastewater networks were spatially overlaid on the ground motion map generated (Fig. 1) to obtain the shaking level estimate at each asset location. Here, for point assets (e.g. treatment plants, reservoirs) the centroid of the asset footprint was considered to represent their location. For linear elements (e.g. pipes), they were segmented into approximately 50m lengths or shorter, and the centroid of the segment was taken to represent its location. The asset layers were also overlaid on the geological hazard maps (e.g. liquefaction susceptibility map) to enable the assets to be related to the potential geological hazard features.

Potential physical damage to the two networks when exposed to the Wellington Fault earthquake scenario, and the resulting likely service outages, were modelled following the workflow shown in Fig. 2 for two cases (discussed below).

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4.1 Base case

In this case the earthquake is assumed to strike the assets in their current "as-is" state. To model the potential physical damage to the assets, a fragility model was assigned to each exposed asset as per Table 3.

Damage modelling results from preliminary assessment were presented to WW and KCDC for calibration of the modelling process and to verify on any assumptions made. The analysis was then re-run (after incorporating any changes to the model) to produce the damage maps for water and wastewater networks, shown respectively in Fig. 4 and Fig. 5.

Table 3 – Fragility models used for modelling damage to water and wastewater assets

Asset		**Fragility model**		
Type	**Key attributes**	**Ground shaking**	**Liquefaction & lateral spreading**	**Other perils**
Pipelines: *Water*: Transmission pipes (TP) – bulk from source/mains-to-reservoir; Distribution pipes (DP) – mains, submains, reticulation *Wastewater*: Mains (inceptors); Laterals or service pipes (collection sewers)	Location, diameter, material, age, joint type	TP: [15] DP: [16] Inceptors: [15] Collection sewers: [16]	TP: [15] DP: [16] Inceptors: [15] Collection sewers: [16]	If the asset is located inside (or intersecting the hazard footprint area) a critical damage state (highest damage state) is assigned to the asset. If the asset is not intersecting or inside the hazard footprint then the asset was assumed to be not affected (i.e. a "no damage state" was assigned)
Treatment Plants and Pump Stations (also called lift stations in wastewater network)	Location, capacity, building material, foundation type, seismic restraining (anchored or unanchored components)	[14]	[17]	
Reservoirs*	Location, capacity, age, material type, seismic restraining	[14]	Not considered (assumed to be on non-liquefiable ground)	
Wells*	Location, condition, and depth	[18]	[18]	

* applicable to water network only

The results from the damage modelling formed the key basis for estimating the service outage times. A series of workshops were conducted with WW and KCDC staff and repair strategies/sequences were explored considering operational hierarchy in the networks, inter and intra dependencies of the network components, priority/critical customer needs, proximity to the sources, ease of access to each supply zone, availability of repair equipment/machineries, replacement materials etc. Two levels of service were considered for water service – untreated (e.g. used for firefighting purposes) and treated (potable). Similarly, wastewater services were staged into two service levels - collection and treatment. As can be expected, the treatment plants need to be functional for treated services to resume. Any delays to restore the plants will have an impact on delivering the treated services.

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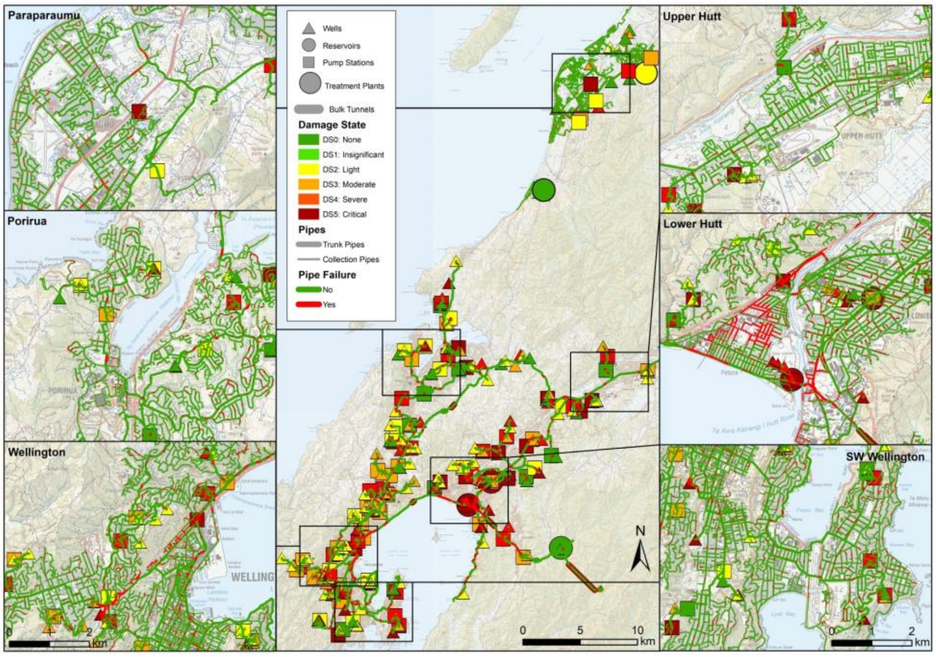

Fig. 4 – Potential damage to water network (base case) under the Wellington Fault earthquake scenario

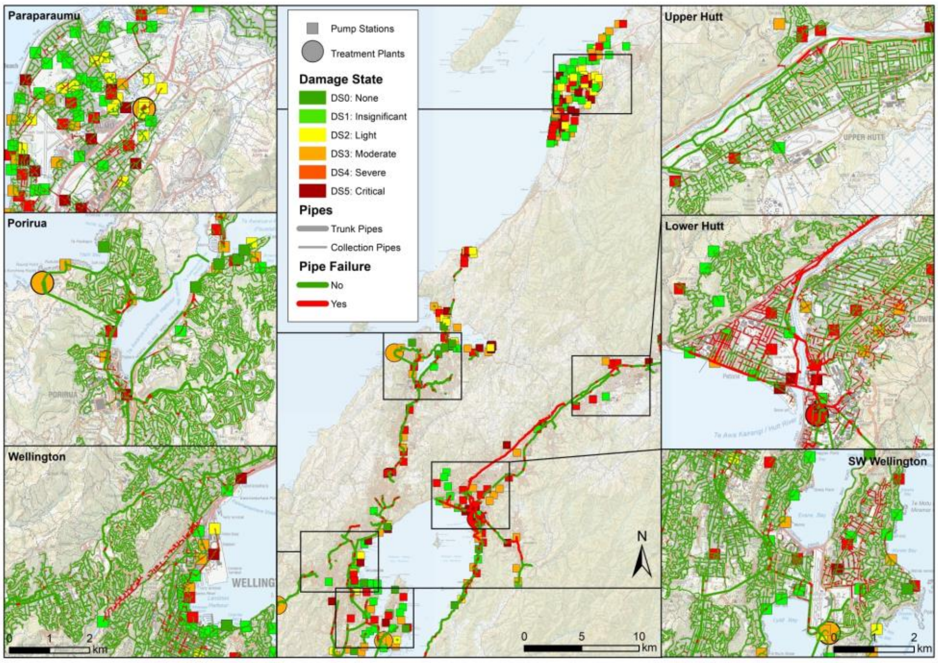

Fig. 5 – Potential damage to wastewater network (base case) under the Wellington Fault earthquake scenario

Infrastructure networks are often dependent on each other for successful delivery of their services. A key feature of the PBC was to make allowance for this in the modelling. Road access and electricity/fuel is required to undertake repairs on the damaged water networks. It was assumed that repair work on the water assets in a road zone [4] will not commence until road access to the zone is available. Fuel supply to the affected areas is expected to be available when roads are reopened for emergency vehicles, and when fuel is available electricity (if required) can be generated locally using mobile generators etc. Therefore, the fuel outage times were used to offset the water outage times. When water service is restored, repairs on damaged

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wastewater network is expected to make progress as water is required to keep the network flowing (i.e. water outage times were used to offset wastewater service restoration times).

While estimating the repair times more focus was put on working out the time and resources that may be required to repair damages on the pipe networks. It was assessed that generally damage to most of the point assets (e.g. pump stations) could be repaired within the time required to fix (includes damage identification, site preparation etc.) damaged pipes, or they may be bypassed to restore a basic level of service until repairs are fully completed. Certain key point assets such as the treatment plants may take longer (compared to repair times for the pipes connecting to the plant) to have their damages repaired. Also, additional time may be required to order and source from overseas any special machinery parts/equipment required for operation of the plant. As such it was estimated that up to six months may be required to remedy any damages to a water treatment plant and make it operational.

Pipeline failure results from the modelling work were tabulated for each pre-defined coverage zone (e.g. 10 zones in total for WW water service coverage) to help estimate the repair times. Repair crews were assigned to the zones based on their likely availability over time and other factors (e.g. priority of service to critical customers etc.). Restoration per zone was defined as 80% of properties within the zone having service to at least the property boundary (which excludes laterals). For treated water (i.e. potable), the repair times of treatment plants were added to the base restoration times. Damage to transmission pipes (e.g. bulk water pipes) will be attended to first before repairing the distribution pipes (e.g. mains, submains). This linear repair process will be followed because water pressure is required for testing the distribution pipes (and retesting after repairs) to identify the damage locations. It was assumed that no repair crew and supporting staff will be available for the first seven days following the earthquake. This is to allow for the time that they may require to attend to their own personal response/needs following the event, as well as to source any additional resources (e.g. skilled workers, equipment etc.) that may be required from outside of the directly impacted area. In fact, all households in the region are expected to manage their water demands themselves for at least seven days following a major earthquake [19]. From week two onwards, work on the damaged transmission pipes is expected to commence. For this, a staged availability of repair crew was assumed (e.g. only one crew available in the second week, followed by two crews in the third week, with a maximum of up to 10 crews from week six onwards). An average of 3.5 days was assumed to be required for a well-equipped crew to repair each bulk water failure site (that may have closely-spaced multiple pipe failures). Thirty repair crews (constant until completion) were assumed to be available from week seven onwards to start working on the damaged distribution pipes. Here, to repair smaller pipes (of diameter less than 100mm), shorter repair times were assumed (three leaks or breaks on the pipes fixed by a repair crew in two days), and for pipes of diameter equal to or greater than 100mm it was assumed that a repair crew will require one day to fix a pipe leak and two days to fix a broken pipe. It was estimated that at least eight months will be required to complete repair works on all the damaged water assets and deliver the water services to pre-earthquake service levels. Outage times estimated for potable water service to the study area are shown in Fig. 6.

Restoration times for wastewater collection from the suburbs in the study area were estimated considering the following: (a) availability of at least one water course nearby to which the wastewater can be discharged to; (b) availability of storm water channels or pipes nearby to enable the discharge; (c) the extent and severity of damage (from the modelling work) to the network components so appropriate repair strategy could be framed. Sewer assets in suburbs of Petone, Miramar, and Wellington CBD are expected to be mainly damaged due to land damage in strong shaking, resulting in long outage times. The wastewater trunk main passes through centre of flat area of Lower Hutt (Fig. 3). This means, on the west of the trunk main the wastewater flows from west to east. Subsidence due to Wellington Fault rupture will likely reverse the gradient of the pipes in this area, thereby requiring significant effort and time to fix the damages and bring back the service. Based on the modelled damages to the assets, and the repair strategies applied, significant delays are expected (at least 3 years, largely due to long repair times to fix damages to treatment plants) to restore all wastewater services to pre-earthquake service levels.

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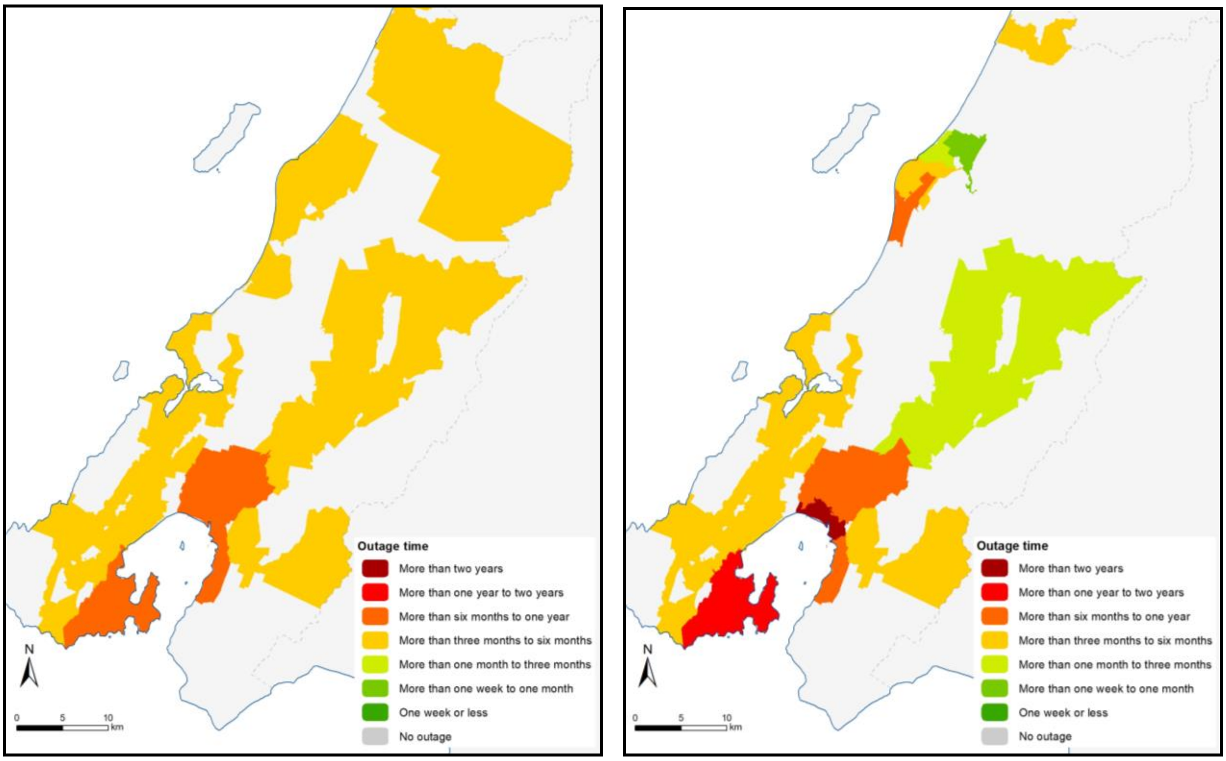

Fig. 6 – Service outage times estimated: potable water (left) and wastewater collection (right) – Base Case

4.2 Improved Resilience Case

In this case the earthquake is assumed to strike the improved networks (i.e. with resilience investments made). As part of the PBC, series of workshops were held with all the participating lifeline organisations (17 in total) and government representatives to collectively identify problems to be addressed, discuss the potential benefits that can be gained by improving infrastructure resilience, and to define investment objectives. As many as 140 resilience improvement options (covering all the lifelines in the scope) were initially put forward, which after critical assessment the short-listed projects were put into two groups (lower and higher investment level programmes). For some of the lifelines, such as for the water and wastewater networks, the two programmes had identical set of projects. A further assessment was made, and the two investment programmes were refined and reduced to one programme. This preferred programme comprises a total of twenty-five projects across the fuel, transport, electricity, telecommunications, water and gas networks. While short-listing the projects due consideration was given to infrastructure interdependencies to maximise the benefits they may all bring together, and the projects have been sequenced to be phase-delivered over a twenty-year period.

Table 4 details the list of water and wastewater initiatives that originally featured in the two investment level programmes. Indicative project costs and the proposed project phase for construction (under the preferred programme) is also shown in Table 4. As can be seen, there were originally ten, and two, projects respectively related to water and wastewater networks. However, both the proposed wastewater initiatives, plus one project related to the water network were eventually excluded (highlighted in Table 4) from the two investment level programmes. These three projects were assessed to provide only short-to-medium term benefits and not contribute much to potential combined economic benefits from all the 25 projects (the main objective of the PBC). Several initiatives have been put in place/or underway to help communities with their water needs for some period following a major earthquake (see [19] for some examples).

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Damage modelling was conducted for the improved resilience case assuming the proposed projects are implemented before a major earthquake occurs. The same assessment methodology as in Fig. 2 was followed to simulate the potential impacts from the same earthquake scenario that was considered for the base case. No explicit modelling was done in some of the cases as the performance of the assets were qualitatively assessed (e.g. new constructions are expected to be designed to current seismic standards so were assumed to perform well in a major earthquake). However, for some initiatives (e.g. replacing brittle pipes with ductile pipes), the fragility functions were re-assigned to reflect the strengthening to the assets, and modelling carried. As can be expected, the modelling results showed reduced damage to the improved network compared to the base case. The damage maps generated for this enhanced resilience case was referred to during the workshops with WW and KCDC staff and similar process as followed for the base case was applied to estimate the revised service outage times (Fig. 8). Note that although there are no wastewater intervention projects included in the preferred programme (Table 4), wastewater service is dependent on availability of water service and therefore changes to the water outages will impact wastewater collection service (Fig. 8). There is however no change to outage times for treated wastewater service due to long repair times estimated to fix damages at the treatment plants.

Table 4 – Proposed resilience investment projects for water and wastewater networks

Project	Description
Cross Harbour Pipeline Phase 1: 0-7 years Cost est.: $103m	Installation of a 12.7km underwater pipeline (likely electro fused 500mm HDPE) carrying water from the Hutt Valley across Wellington Harbour to avoid crossing the Wellington Fault.
Prince of Wales and Bell Road Reservoir Upgrade Phase 1: 0-7 years Cost est.: $45m	Replacing the vulnerable Bell Road Reservoir (over 100 years old) with a new 10ML reservoir, plus a 35ML reservoir at the Prince of Wales (Omaroro) site to support flows from the proposed cross-harbour pipeline
Silverstream Bridge Pipeline Replacement Project Phase 1: 0-7 years Cost est.: $18m	This project (Fig. 7a) will involve replacing pipeline from Te Marua to Ngauranga where it crosses the Silverstream Road bridge and the Wellington Fault. Where the pipe crosses the Hutt River it will be elevated on piers with large ball joints on each side of the fault permitting around 5m of horizontal movement. Existing pipe that branches off supplying Kingsley Pumping Station and a steel rising main from Kingsley Valley will also be replaced.
General water supply toughening acceleration Work phased evenly across the 20-year programme Cost est.: $315m	Upgrading a critical network of pipes to ductile pipes (predominantly mains and mains-to-reservoirs of about 152km in total length)
Carmichael to Johnsonville and Karori Pipeline Phase 2: 8-14 years Cost est.: $190m	This option forms part of an existing project designed to establish a new bulk main from Porirua to Carmichael over the longer term and get the existing bulk main off Moonshine Valley/fault line (Fig. 7b). It will involve installation of new CLS welded pipelines, better damage resistant flexible pipe joints, construction of a new pump station etc.
Porirua Branch Replacement (Fig. 7c)*, and* *Emergency Water Treatment Facility* Phase 2: 8-14 years Cost est.: $30m	Replacing existing vulnerable pipeline with a CLS fully-welded watermain from Moonshine Valley to Cleat Street, and then by a 345mm welded steel pipe to State Highway 1 (includes a 300mm bridge crossing with isolation valves). Also, a 345mm butt-welded steel pipeline will be constructed along Mana. Provision of a containerised emergency water treatment facility that can treat 10-15ML of water a day.

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Porirua Low Level Zone Reservoirs Phase 2: 8-14 years Cost est.: $21m	Providing an additional 9ML reservoir near existing Porirua Low Level 1 and 2 reservoirs, and 3ML (additional) reservoir at Takapuwahia. The reservoirs will be fed by the upgraded Porirua Branch main.
Waterloo Water Treatment Plant liquefaction mitigation Phase 2: 8-14 years Cost est.: $2m	Undertaking ground improvement measures at the southern end of the Waterloo Water Treatment Plant. Any additional structural support required at the site will also be provided so that the treatment plant remains operation (or with minimal disruption).
Waterloo Pump Station extension and new pipeline from Waterloo to Haywards Phase 3: 15-20 years Cost est.: $97m	Installation of a new pump system adjacent to Waterloo Water Treatment Plant, and provision of a CLS fully welded watermain from Waterloo Pump Station to Haywards Valve, including a new flexible pipeline crossing the Wellington Fault.
*Emergency water infrastructure in communities (cost est.: $30m)**	This initiative (already committed project) involves providing emergency water infrastructure (e.g. on-site reservoir/community water stations, transportable water bladders etc.).
*Ablution facilities across schools (cost est.: $20m)**	A community facility in which pit latrines (or similar) will be provided at schools that are likely to be used as emergency assistance centres following a major disaster. This will help minimise short-to-medium term sanitary service disruption to communities. It will also enable the schools to reopen as quickly as possible after the event.
*Provision of buckets for a two-bucket home toilet system**	This initiative involves providing communities with a two-bucket system for separating solid and liquid human waste and on-site storage.

* projects subsequently excluded from the core programme following discussion with the Steering Group as they relate principally to recovery stage.

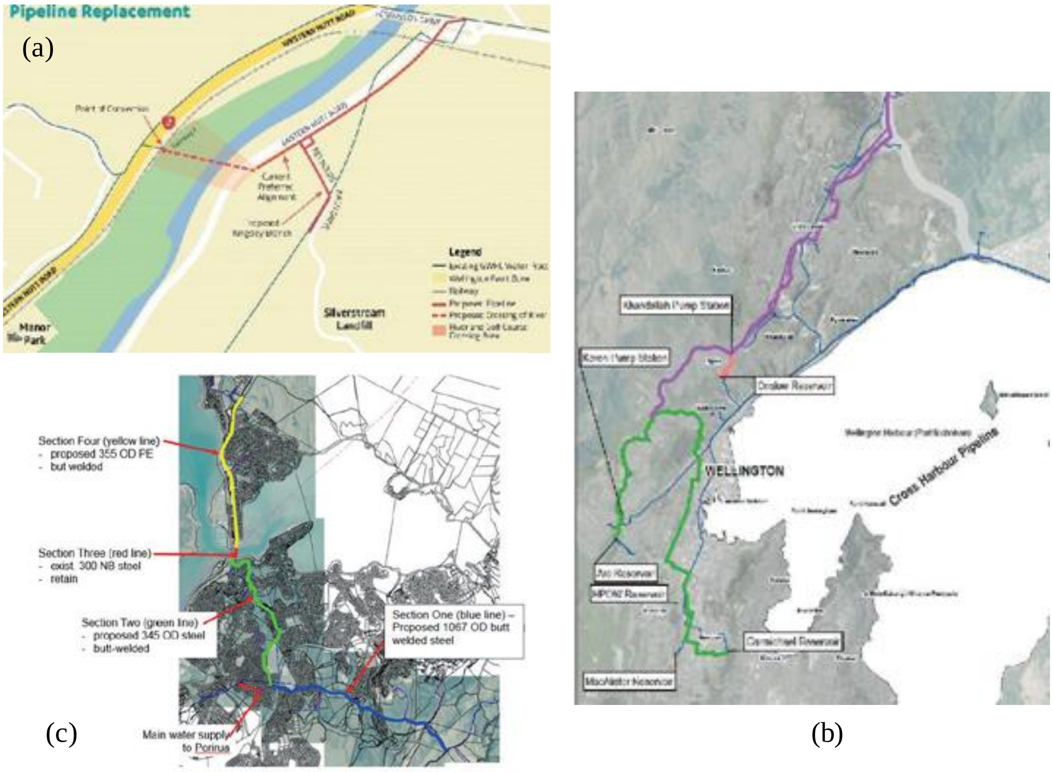

Fig. 7 – Snapshots detailing some of the water projects in Table 4

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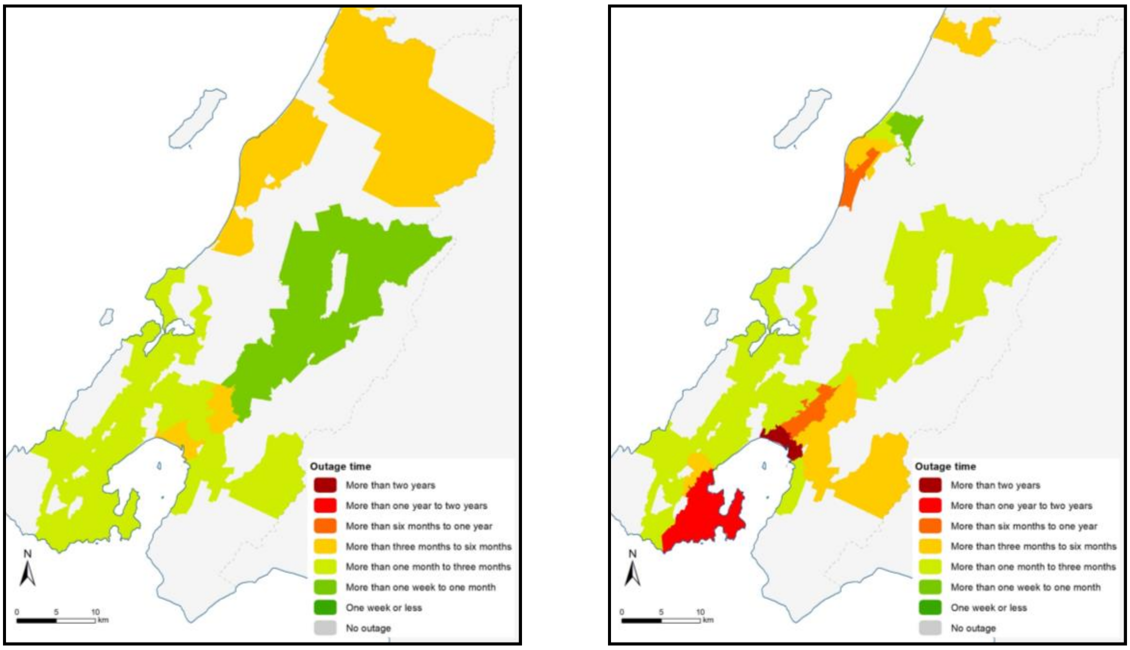

Fig. 8 – Service outage times estimated: potable water (left) and wastewater collection (right) – Improved Resilience Case

5. Conclusions

This paper discussed a modelling work on Wellington Regions' water and wastewater networks, carried as part of a Programme Business Case for Wellington Lifelines Group aimed at demonstrating the economic benefits of implementing an accelerated and phased programme of resilience enhancement projects. Potential physical damage to the networks in its current state, and the resulting likely service outages, due to a Wellington Fault earthquake was first discussed. An overview of the proposed projects to enhance the resilience was then presented. It was shown that by implementing the projects before a major earthquake in the region the damage to the networks can be restricted, and as a result the services to the customers can be restored to pre-earthquake levels much quicker than if the proposed projects are not actioned. The importance of infrastructure interdependencies was given due consideration; both during short-listing the projects as well as when estimating the service restoration times. The time-stamped service outage maps generated from this work were a key input to economic modelling and they have been used to estimate the reduction in economic loss to the region (and the country) if the proposed infrastructure investments are made.

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