

Water supply network resilience in the Wellington Region

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ABSTRACT

Wellington sits across an active seismic fault line and depends on remote sources for its water supply. With widespread damage expected after a large earthquake, it may be months before a minimal water supply is restored to residents, and even longer before it reaches the tap.

This paper presents a recent study undertaken to identify network vulnerabilities and take water supply resilience to the next level. The study presented a possible timeline for repairs to the bulk network and restoration of supply to each suburb's reservoir. This highlighted the most critical areas where an alternative supply or storage was needed.

The study also considered how to get the water to the customers after the reticulation network had been damaged. The strategy considered by Wellington Water was to develop a seismically-resilient skeleton network connecting reservoirs and key distribution points. A notable innovation was the use of algorithms to determine optimal locations for public tap stands and identify the most cost-effective critical pipe network where strengthening upgrades needed to be focused.

The aspects of the project concerning its significance for the region, the overall resilience strategy and the pipeline resilience engineering were presented at the Institute of Public Works Engineering Australasia (IPWEA) and Water NZ conferences in 2017. While this paper touches on these subjects, its main focus is on the use of geospatial information for earthquake preparedness and resilience planning.

KEYWORDS

Water supply, seismic resilience, network recovery, geo-spatial optimization, shortest spanning tree.

INTRODUCTION

Wellington's water supply system is particularly vulnerable to a large earthquake, with significant damage expected to occur both on the bulk network and the distribution network. If it takes too long to restore essential services, many professional and public organisations may leave and potentially not return. This would cripple the region's economy and put pressure on other parts of the country.

Wellington Water has launched several initiatives to increase the resilience of the capital city. This paper presents the work done by the project team on two aspects of the overall resilience project.

First, the project team estimated the possible consequence of earthquake damage on the bulk network to frame the supply aspect of the regional resilience strategy. The second part of the work consisted of identifying critical distribution pipes that are essential to provide service to key customers and serve as a backbone to recovery.

PIPELINES AND FAULT LINES

Wellington Water manages the treatment and distribution of water in Hutt, Porirua, Upper Hutt and Wellington cities, with a total population of approximately 400,000. The three main sources are all located along, or east of, the Wellington Fault in

Hutt and Upper Hutt cities. The majority of the demand is located on the west side in Wellington and Porirua cities, with the Wellington CBD and regional hospital being the largest demand centres in the region. A bulk water network conveys potable water from the sources to over 100 storage tanks across the region. The bulk network is approximately 50km long between the furthest source and Wellington CBD and essentially comprises cement-lined steel pipes. The network can be simplistically described as two parallel pipelines: one starting in the North, one the East and both connecting in Wellington Central. There is only limited redundancy and interconnection between these pipelines. This bulk network inevitably crosses the Wellington fault line several times, as well as areas prone to liquefaction or lateral spread. Because Wellington Central is an important demand centre and is also located near the end of the network, it represents a critical point for the water supply system.

For the purpose of this study, the scenario adopted is a Wellington Fault earthquake resulting in 4-5 metre horizontal displacement and 1 metre vertical displacement. This was considered to be the worst natural disaster scenario that could hit the capital.

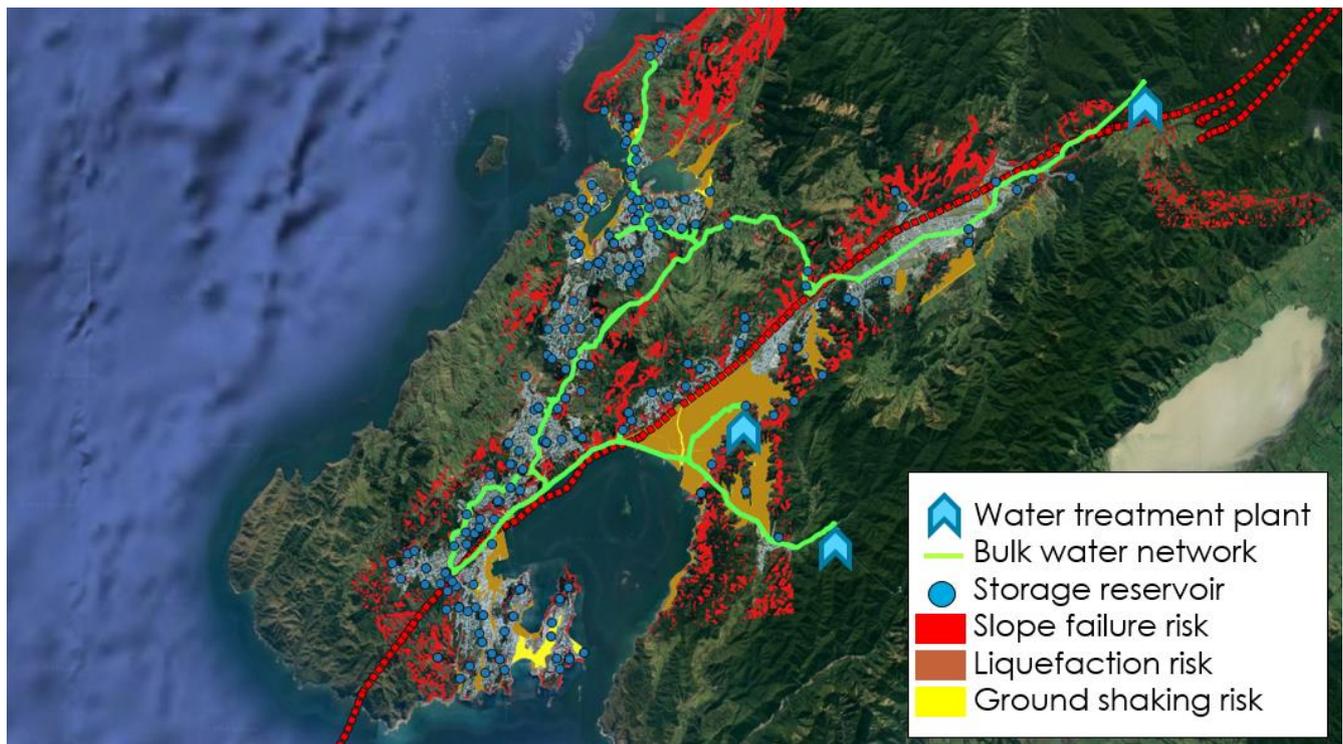


Figure 1. Bulk Water Network and Key Seismic Risks

BULK SUPPLY VULNERABILITY

The first main stage of the project consisted of estimating the time to restore the supply to the storage reservoirs. A series of workshops was organised with Wellington Water Operations staff and local pipeline contractors to:

- Identify likely damage sites.
- Estimate repair time.
- Identify risks and opportunities to the restoration timeline.

The damage to the bulk water network caused by a Wellington Fault earthquake was assumed to comprise:

- Ruptures of the pipeline at the fault crossings.
- Damage to the pipeline in the form of joints pull-out, pipe buckling or shearing resulting from ground movement.
- Damage to the pipeline in the form of joint failure or pipe shearing at locations where the pipe is anchored to a concrete structure such as a valve chamber or a pump station.

A total of 78 possible damage sites were identified. Some sites, such as fault crossings, were clearly localised. Others were only broadly identified: when a pipe is laid in a large liquefaction-prone area, a number of possible damage sites were proposed from previous work, with no indication of possible location (GNS, 2009).

Each damage site was discussed to determine the staff, time, plants and parts required for repair.

This led to the development of a possible restoration timeline aimed at minimising the population and critical users with no bulk water supply. Because of the linear nature of the Wellington regional network, there is not a lot of flexibility in the repair sequence. Known vulnerable locations may be assessed and repaired rapidly, but the long pipelines laid in the hills will inevitably take a long time to be brought back in service. It will be necessary to proceed by iterations to drain, repair, recharge, test the pipe and search for the next leak downstream.

The initial time estimate was that it would take 60 to 80 days to restore bulk water supply to the reservoirs in Wellington Central, and up to 100 days for some peripheral areas. This contrasts sharply with a reservoir's storage time of approximately 14 days, assuming survival levels of consumption and almost no reticulated supply.

This exercise also identified shortages of staff and contractors trained to repair large bulk water pipes as well as plant, fuel and, ironically, water for concrete support structures of certain sections of pipe.

BULK SUPPLY RESILIENCE

At the time of the study, Wellington Water was already planning several upgrades that would strengthen pipelines or facilitate network operation and isolation after the event. These upgrades were believed to reduce the restoration time to Wellington Central to 45 days. This is regarded as an optimistic estimate based on flawless organisation and easy access to manpower, sites and machinery.

Wellington Water is now considering a more ambitious, more resilient strategy of moving away from a linear system towards a circular system. The idea is that each of the four cities should have two points of supply and the ability to support the neighbouring networks. This proposed system would be expected to perform better after a seismic event and require less repairs before being operational again.

DISTRIBUTION POINTS

The second part of the work focused on distributing the water from storage reservoirs to the users. It is expected that, following a large earthquake, the auto-shut valves installed on the reservoir outlets will close, preventing the water from disappearing through the damaged distribution network. At this stage, people will have to rely on their personal reserves and limited community resources. Critical distribution pipes will be gradually opened and checked for leakage. These will constitute a skeleton network connecting reservoirs with critical users and public distribution points. Critical users are 395 in total and include elderly care facilities, civil defence centres, schools, lifeline and emergencies organisations, as well as medical facilities. Public distribution points will consist of tap-stands where people will be able to fill their own vessels, and possibly water bladders as emergency storage. As repair work progresses on the distribution network, all critical pipes will be brought back in service, followed by the remaining reticulation, gradually restoring supply to all customer connections.

Distribution points were positioned so that 90% of the residential properties are no further than 1,000m walking distance from a distribution point if the road is flat, 500m if the road is steep. Certain locations such as schools are obvious candidates for the establishment of a public distribution point. They generally have good car and pedestrian access, they have outside flat space, they are publicly owned and viewed as a community asset. Many schools also have their own water storage.

Other locations had to be identified, preferably located in areas where public can queue safely away from traffic and possible slope failures, and where cars and trucks can drive in and out practically. In many suburbs such locations simply do not exist, and compromises were made either on accessibility (properties are further than the target Level of Service) or on practicality (the distribution point site is narrow or difficult for cars to manoeuvre).

Each distribution point will require equipment and staff to set up and maintain. It was therefore important to minimise the number of distribution points while meeting the distance criteria. To quickly check the proportion of properties meeting the criteria, the project team developed a plugin to be used in the QGIS environment.

The plugin tool is based on a connected network of roads and walkways obtained from Open Street Map. This was imported as a graph object with nodes and edges (i.e. links). An elevation was estimated for all nodes based on 1m elevation contour

data obtained from LINZ. Between each node a virtual longitudinal profile was made to classify the proportion of the edge that fell into low-medium and high steepness categories. A penalty score was applied to each edge by multiplying its length by a steepness factor depending on its category. To identify the shortest steepness-weighted route between a given property and any distribution point, we used a travel distance optimizing algorithm based on Dijkstra's shortest paths algorithm. The coding was done with a combination of Python and the pgRouting libraries in a PostgreSQL database. This allowed us to interface directly with QGIS. The PostgreSQL database was hosted on Amazon Web Services, which allowed multiple users to work in parallel on the same data sets. QGIS was selected because it does not require buying licenses, which would have been impractical in the short time frame of the project.

The plugin analyses the road/walkway network and finds the shortest steepness-adjusted route between each property and all distribution points. It highlights and counts properties that meet the criteria. The operator could see quickly which areas were under- or over-served and adjust the location of the proposed distribution points accordingly. A total of 383 public distribution points were identified this way.

Some of these will comprise a single tap-stand, but others will be large-scale distribution centres, with over 100 people simultaneously present during day time. To maintain the waiting time below 30 minutes, calculations suggest that over 700 tap-stands will be required throughout the region.

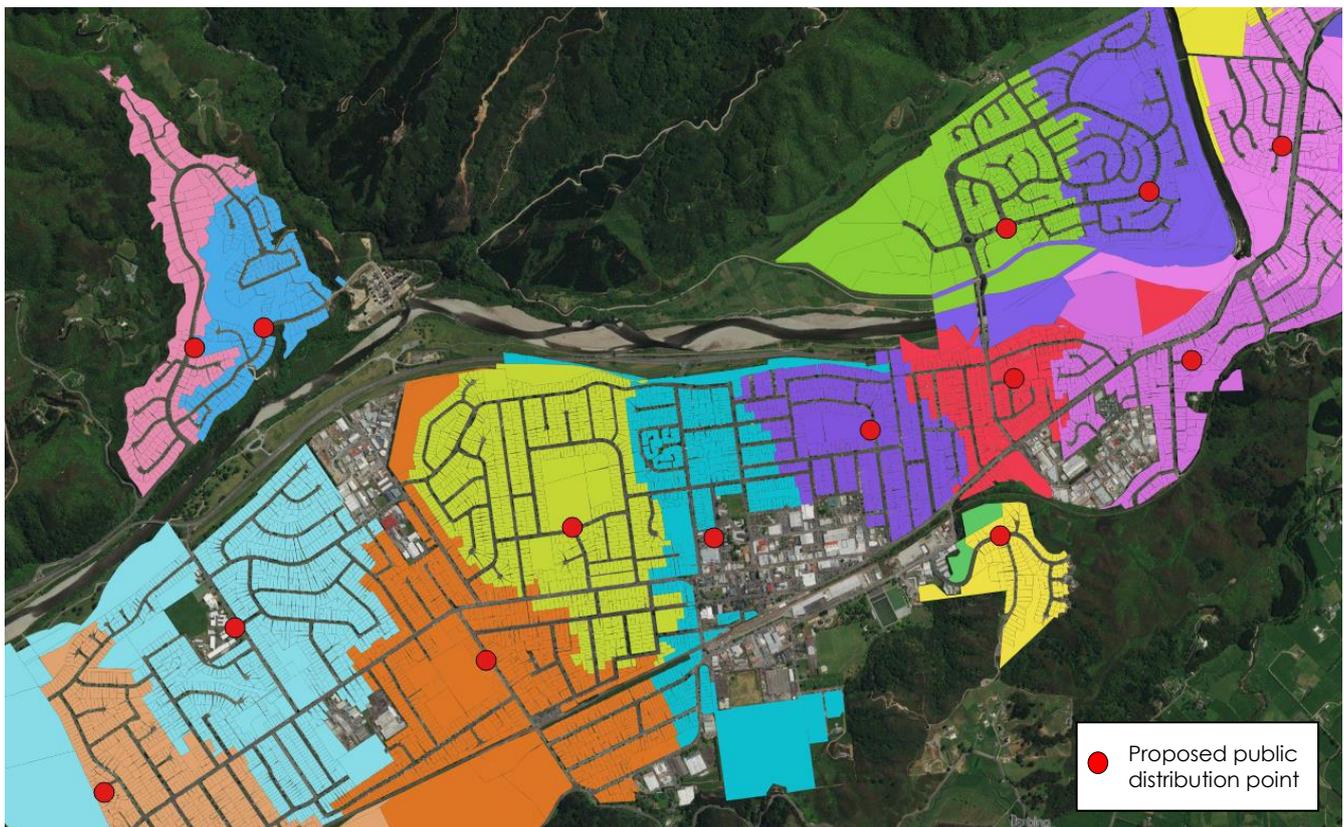


Figure 2. Clusters of Residential Properties by Closest Distribution Point Following the Road.

CONNECTING THE DOTS

The next challenge consisted of selecting certain pipes within the distribution network to connect all the critical users and distribution points to reservoirs; out of the many routes possible through a reticulated multi-looped network, which is the best one? The pipes selected in this process were called “critical pipes” in the context of this study, although this terminology has been historically used for other purposes.

There were several, sometimes conflicting, principles guiding the selection of the critical pipes. The most important one was that they should have the best chance of remaining functional following a large earthquake. As an initial filter, pipes were categorised as either resilient or non-resilient, essentially based on material and ground hazards captured in GIS. Pipe failure

modes are numerous and complex, and ground conditions are never known with precision, especially when assessing possible seismic damage. The categorisation is therefore far from perfect, but can serve to guide the selection of high value pipes in the existing network.

Larger pipes were preferred to smaller pipes as they have more capacity, they are more resilient to earthquakes and they tend to be already treated as “critical”.

Pipe age was also considered; if the choice was between two non-resilient pipes, the one closer to replacement age should be preferred, and upgraded.

The process to select the critical pipes was two-fold. A first selection was undertaken by a custom-made geo-spatial program. The second step consisted of engineers reviewing and correcting the network generated by the computer.

A second plugin was developed within the QGIS environment to determine the best route to connect reservoirs with critical users and distribution points. However, the goal of the program was not only to reduce the distance of the critical network, but to reduce the distance with penalty/reward allocated based on resilience, diameter and age. This second tool shares a lot of similarities with the first one. It is based on the connected pipe network rather than a road/walkway network. The same libraries were used to calculate a series of minimum spanning trees following the shortest penalty-adjusted pipe routes between the sources (generally reservoirs) and the end points (public distribution points, critical users or secondary reservoirs).

The process integrated all the principles and rules to provide a theoretically ideal, high-value, low-cost critical network. As a result, the critical pipe routes generally avoid liquefaction-prone areas and often include large diameter PE or ductile iron pipelines.

Because it was not linked to hydraulic models, the computer-generated network had no notion of hydraulics or ground elevation and did not hesitate crossing zone boundaries or going up hills where it should not. Our team of engineers reviewed each selected network to ensure that it was hydraulically sensible. Where this was not the case, the plugin allowed the operator to apply local penalties/rewards to guide the algorithm in the next iteration into going through certain gateways or avoiding certain areas. In this way, engineering judgement was applied to the program outcome in a documented, repeatable way.

We also trialled a fully-automated process combining both steps: distribution points would be generated, and a critical network would be identified; then an optimizer would change the distribution point locations and review the critical network. The optimization algorithm was developed in the Julia language. The outcome was a series of distribution points meeting the coverage criterion and requiring a critical network with an optimal score. Unfortunately, the program lacked the common sense understanding of what constitutes a suitable place for a large number of people to travel to and congregate safely. The fully-automated process was not used for the project output.

The outcome of the two-step process was further reviewed with Wellington Water operators to ensure that it was operationally straightforward and easy to isolate from the rest of the distribution. Beyond the minimal network required to connect all the dots, pipes were categorised as critical because they allow water transfer between a zone with a relative excess of storage to a zone with a relative shortfall. Finally, certain pipes were selected because they can provide redundancy in supply at a low cost.



Figure 3. Critical Pipe Network

Approximately 350km of pipe was categorised as critical, including 220km considered non-resilient and likely to require an upgrade.

The general assumption is that the critical pipes, by their nature or through future strengthening, would sustain the effect of an earthquake better than the rest of the distribution. It is therefore important to be able to isolate them from the rest of the supposedly non-resilient network.

Approximately 5,000 valves would need to be closed throughout the region to achieve this, including 1,200 proposed valves.

BUILDING RESILIENCE

Since two-thirds of the pipes constituting the critical network are considered non-resilient, the question naturally emerged of how to build a seismically resilient pipe.

In the context of this study, “seismically resilient pipeline” refers to a section of pipe that can be reasonably expected to remain in operation, without significant deformation or leakage, following a significant earthquake.

As the location, magnitude and effects of earthquakes are inherently unpredictable, it is not possible to propose prescriptive instructions to design and build a pipeline that would be guaranteed to survive a given seismic event. It is, however, possible to design and build pipelines according to best practice for seismic resilience. It is recognised that “best practice” will vary depending on local ground conditions and the importance of the pipe. For example, pipe bedding requirements are higher in liquefiable ground than in rocky soil. Similarly, a strategic arterial pipe may warrant more geotechnical investigations than a small reticulation pipe.

Conference proceedings, industry information and journal articles were reviewed to recommend improvements to the current Regional Standard for Water Services and Regional Specification for Water Services. The review focused on the structural resilience of the pipeline rather than the configuration of the network.

Overall, the existing guidance documents were found to be satisfactory and reflected industry's best practice. The major recommended changes to the existing documents were clarification around the use of materials and more robust quality assurance processes. This latter point is very important: the best rules are worth nothing if they are not followed throughout the entire supply chain.

THE "CRITICAL" IN CRITICAL PIPES

The principle behind the critical network is that it should form a relatively reliable backbone for the supply of water to key demand points. It should sustain a seismic event without disastrous damage, or be easily repairable. It should be easy to isolate from the rest of the distribution, test and connect to critical users and distribution points.

The first outcome of these requirements was that 220km of critical non-resilient pipes are likely to require upgrading. These pipes were flagged in Wellington Water's asset management system, and their critical non-resilient nature may make them early candidates for renewal, along with other criteria normally used by Wellington Water.

The second outcome was that critical pipes should be free of customer connections. If the pipe moves laterally following an earthquake, most customer connections will shear or pull-out, resulting in leaks. This will require the installation of rider mains on both sides of the street where this is not already the case for all 350km of critical pipe, along with new isolation valves.

Hydrant connections and isolation valves will need to be engineered and managed so that the critical network can be operated when needed.

Finally, it was recognised that, in some areas, no amount of engineering can guarantee pipe survival. This is particularly the case in liquefaction prone-areas. To cater for these, Wellington Water plans to have a stock of flexible lay-flat hose pipes to be used above ground, to connect hydrants or tap-stands if and where needed.

SAFETY FIRST

This project was an opportunity to improve the way health and safety is approached in planning studies. Following the principle that it is never too early to consider safety, a preliminary risk register was prepared for:

- The construction of seismically resilient pipelines for the critical networks.
- The isolation and operation of the critical networks.
- The operation of public distribution points.

This exercise consisted of documenting possible hazards that can be identified at the high level of the study: the main sources of information being aerial pictures, Street View imagery and asset data. Besides general pipe construction hazards, sites that would involve working near asbestos pipes or on steep and narrow streets were identified and recorded.

These were compiled in a preliminary risk register that should be passed on to the next stage of design or implementation.

THE SCALE OF OUR WORKS

A significant amount of work is involved in strengthening the network, extending rider mains, installing valves, procuring repair and emergency equipment and improving the organisational preparedness, just for the operation of the critical distribution networks.

The study included a cost estimate for the pipeline component of the critical networks, excluding ancillaries and bulk network activities.

This was an opportunity to improve the way cost estimates are formulated for large projects for Wellington Water. Uncertainties, risks and opportunities were documented and captured in a Monte Carlo analysis. This provided a statistical distribution of possible out-turn costs to the project and a 95th percentile estimate. This identified the main risks and

opportunities that had a greater potential to influence the total out-turn cost of the project. These were found to be the procurement model and the design requirements specific to seismic resilience.

Advanced procurement models can drive efficiencies through reducing tendering costs, creating centres of excellence and innovative methods.

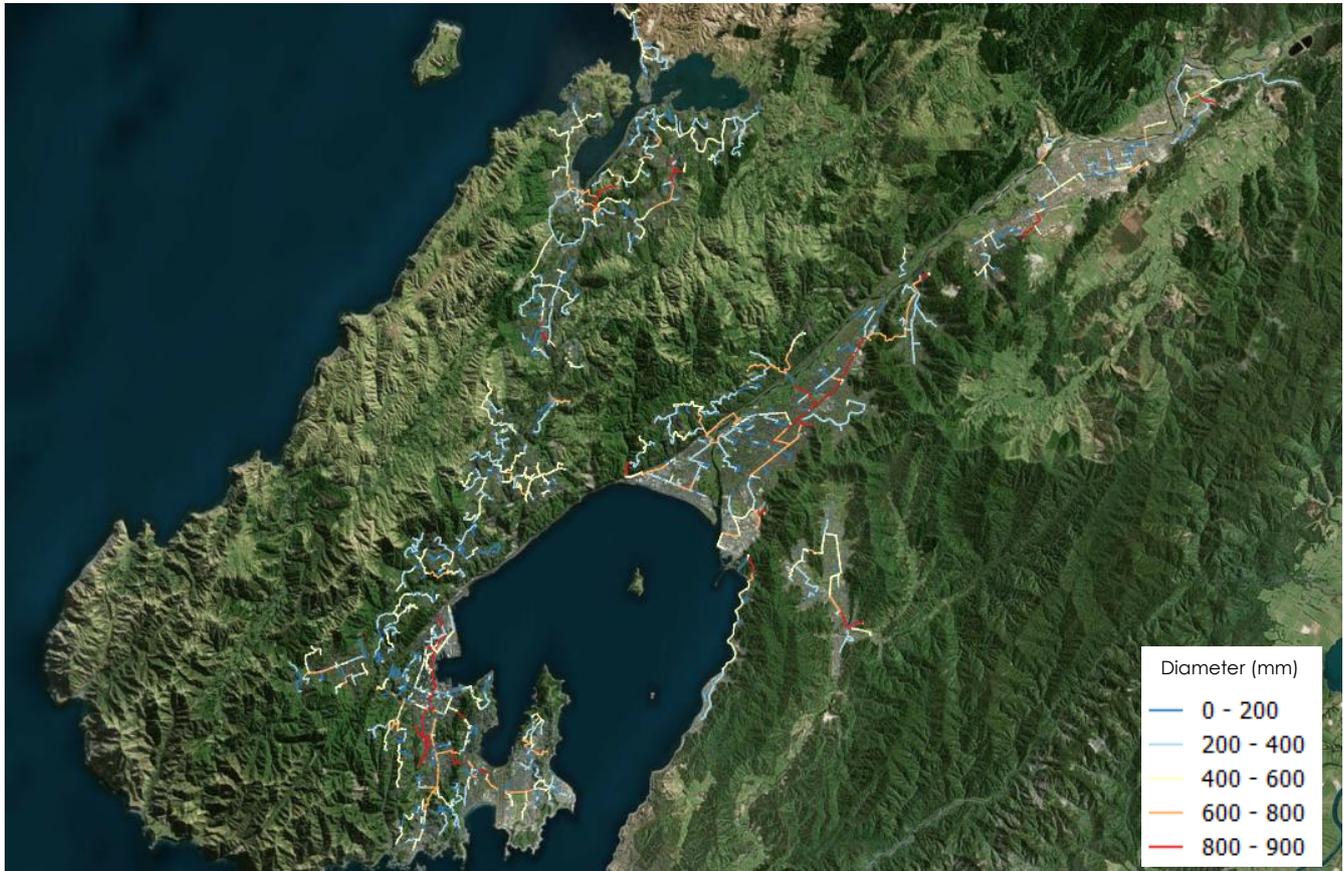


Figure 4. Critical Pipe Network for the Wellington Region

THE BROADER CONTEXT

Wellington Water is discussing with local Councils to agree on a shared goal to work towards a situation where water supply to households and businesses would be restored from about 30 days (rather than over 70 days).

With a shared goal established, the focus can shift to how to achieve that goal, and how quickly. To clarify and support the investments required, Wellington Water is using Treasury's Better Business Case approach. The outcome of these deliberations has been reflected in each of the local authorities' Long Term Plans, which were submitted for public consultation mid-2017.

The region's overall resilience also depends on other critical infrastructure, including roading, electricity and telecommunications. Wellington Water is working with these other providers of critical infrastructure to ensure that individual plans for improving the respective networks' resilience are strategically integrated and will maximise efficiencies. Through such an integrated approach, regional stakeholders may speak as a unified single voice with central government about its contribution to building regional resilience to mitigate risks to GDP from loss of productivity following a major earthquake.

CONCLUSION

The Wellington region's preparedness in the event of a large earthquake will determine how it sustains the event, how it recovers and how much emergency support will be needed from the rest of the country. Restoring essential services rapidly is a key step towards minimising the impact of such an event. Wellington Water is building a business case to support an investment and action plan to that effect. In the process, innovative and best-in-class practices are being implemented, improving the quality of the local water industry as a whole.