The effect of localised factors on water pipe repair times post-earthquake

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ABSTRACT

In the Wellington Region, the capital of New Zealand, many lifelines are at risk, because they are in vulnerable narrow corridors close to active faults. In an earthquake, it is expected that these lifelines will be significantly damaged and unusable for extended periods of time. Because of this risk, many studies have been conducted to investigate the resulting downtimes. These studies, despite their usefulness, do not incorporate or make significant assumptions about localised factors. This paper summarises a Masters thesis that aimed to improve the current predictive models, by including these local, and contextual influences. Multiple stakeholders who manage and repair the lifelines were interviewed to identify these factors which were then included into one of the current predictive models, and the influence on repair times was recorded. It was discovered that localised impacts such as staff logistics, land sliding, the land gradient, interdependency, and access doubled previous predicted repair times.

Keywords
Lifelines, Earthquake, Localised factors, repair times

INTRODUCTION

Lifelines such as the electricity network, transportation system, communications matrix, and water supply are structures that provide essential services to the community (Ministry of Civil Defence and Emergency Management, n.d.; Nigg, 1995). Both Individuals and organisations rely on these systems to be able to survive and thrive (Little, 2002). Without a functioning supply, people are put at risk as they no longer have access to the critical services they rely on every day. Furthermore, businesses would not be able to function safely, or at all, depending on regional regulations (Department of Labour, 1995; United States Department of Labour, 1970). The access to potable water is of particular importance, as it is needed for drinking, cooking, sanitation, growing crops, cleaning, temperature, regulation and manufacturing, and is considered a basic human right, where at least 50 litres per person per day is expected (Gleick, 1996; United Nations General Assembly, 2010).

In the event of a disaster, this access to water and other critical lifelines may be removed for extended periods of time due to infrastructure damage and system failures (National Institute of Standards and Technology, 2016). For example, the wastewater network in Christchurch, the third largest city in New Zealand, took more than five years to fully restore after the 2010-2011 Canterbury Earthquake Sequence (CES) and the main transport route north of Kaikoura took more than a year to repair because of the 2016 Mw 7.8 Kaikoura Earthquake (Department of the Prime Minister and Cabinet and Christchurch City Council, 2016; New Zealand Transport Agency, 2018; Sherson, Nayyerloo, and Horspool, 2015). Many of the difficulties around these extensive repair times were a result of the local environment, where liquefaction and land sliding lead to increased damages and challenges in repair. For example, during the CES, widespread liquefaction was evident. This liquefaction caused significant structural damage as a result of uneven settlement and permanent ground deformation (Cubrinovski et al., 2014; O'Rourke et al., 2014). The wastewater pipes were especially impacted as the pipes became buoyant in the liquefied sediments and rose to the surface. This buoyancy changed multiple pipe gradients which produced blockages and flow reversal in the gravity fed system (Eidinger and Tang, 2012). The Mw 7.8 Kaikoura Earthquake, on the other hand, produced large landslides that ranged from 3000 to 112,000m3 along the main state highway. These landslides made repairs difficult, as the debris had to be removed before repairs could be begun (New Zealand Transport Agency, 2017).

The aim of this study is to improve the current repair time predictive models by incorporating the impact of these localised contextual factors. The water supply is specifically looked at in detail, as it is one of the more critical lifelines, being an immediate need for people and businesses (Gleick, 1996; United Nations General Assembly, 2010). New Zealand was picked for a base for the study as there are significant gaps in the literature, where most predictive models like (Cousins, 2013; Mowll, 2012; Nayyerloo and Cousins, 2014) focus only on the engineering and geological principals and make assumptions around local influences.

Wellington Region

New Zealand is home to many natural hazards, due to the active plate boundary that crosses through the centre of the South Island. This plate boundary drives the local topography and is responsible for nationwide mountain building, volcanism, and active seismicity. One of the most seismically active and vulnerable areas in New Zealand is the Wellington region, which is home to 500,000 people, and New Zealand's capital city (Statistics New Zealand, 2013). The Wellington Region is located at the southern tip of the North Island and contains three main population centres, Wellington City, Porirua, and Hutt Valley, all of which are spread along thin corridors between the Tararua Ranges, see Figure 1. Many believe that this region will be the next to be hit by a massive earthquake, because of the activity of local faults, and their history (Wright, 2016). One fault, the Wellington Fault, follows State Highway 2, crosses through the centre of the city, and has an 11% chance of rupturing with a moment magnitude (Mw) of 7.2-7.5 over the next 100 years (Cousins, 2013; Rhoades et al., 2011). A rupture with this size could produce movements along the fault of up to 5m horizontally and 1m vertically, which would significantly damage any nearby infrastructure (Mowll, 2012). As most of the lifelines, like the water supply and transportation network, closely follow this fault, substantial damages can, therefore, be expected, leaving people without necessary services for extended periods of time. Thus, an accurate understanding of the hazard must be first established so that precise plans can be made. This paper seeks to understand the magnitude of these local factors and unexpected events to improve current predictive models so that people in Wellington can be better prepared.

METHODOLOGY

Both broad and detailed approaches were used to gain an understanding of the impact of these local factors, incorporating these observations into regional system-wide calculations. Overall a mixed methods (MM) methodology is used to combine both broad and narrow approaches, integrating qualitative and quantitative information under a pragmatic paradigm, where information from the interviews (phase 1), affects the inputs into a quantitative predictive model (phase 2).

Interviews

The researcher sent out emails to various water pipe repair and management experts the author knew. These messages outlined the aims of the research and asked whether the recipient could participate in the interviews and if they knew of other experts that could be helpful and able to take part.

In total 20 experts from a range of different organizations were contacted, five of which were available for an hour-long phone interview. Overall, each interviewee was asked 29 pre-written questions on 15 different topics. During the interview, if more detail was needed the researcher used probing questions to develop a deeper understanding. Then, once each interview was completed, the responses to the questions were transcribed using a denatural approach where repetitions, pauses and filling statements like "um" or "ah" were removed (Oliver, Serovich, and Mason, 2005). These transcriptions were then coded, using an exploratory thematic approach in a qualitative analysis program, NVIVO, where like ideas and themes were identified and grouped together using filing statements, known as 'codes' or 'nodes' (Guest, MacQueen, and Namey, 2012). In total, 52 different nodes, were used to group responses, including location defining statements such as "Wellington" or "Christchurch"; topic codes such as "access" or "inspection"; and perspective determining nodes such as "problem" or "solution". For simplicity, multiple nodes were used to code the same text, using broad themes. For example, a statement around the access problems in Wellington, as a result of landslides, was coded as "Wellington", "Access-(road)", "landslide", and "Problem". Thus, resulting in a sentence linked to four different identifying codes.

After the transcripts were coded, the filed text was then summarised to 1) gain an overall picture of the responses, and 2) to highlight the different issues that had to be addressed. This summary was accomplished by summarising and then tabulating all coded statements and grouping them into different tables. The aim was to combine all views on the different issues to highlight the important factors that needed to be explored further and incorporated in the quantitative model, see Figure 2.

Figure 1 Wellington Region, showing the main urban centres. Image from (Google, 2017)

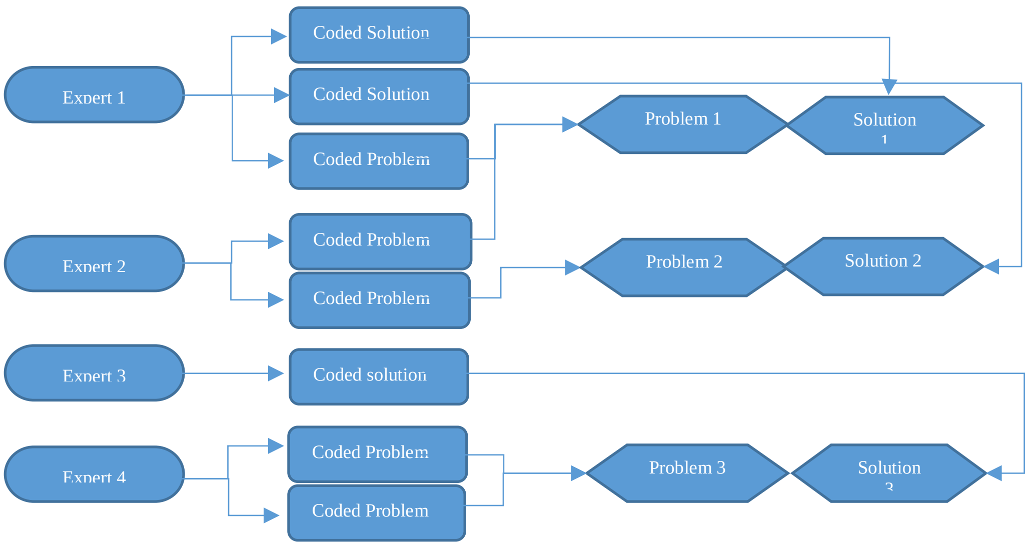

Figure 2 Summary and tabulation process, where multiple perspectives from the different experts are condensed down into specific categories. In some instances, the same statement may be placed in multiple different categories

However, before any of these factors could be further investigated quantitatively, controls for the damage and repair times had to be first be calculated so that the influence of these additional factors could be identified.

Base predictive model

The initial repair times were calculated using one of the current predictive models, specifically (Cousins, 2013; Nayyerloo and Cousins, 2014). This model was originally created to predict water pipe repair times from Kaitoke, one of Wellington Cities main water sources, to the various reservoirs around Wellington. Thus, before it could be used, the model had to be slightly altered to fit the scenario. These alterations included 1) changing the underlying visual basic (VBA) code to calculate repair times from four main water sources instead of just from Kaitoke. 2) Changing the code to calculate repair times to one endpoint instead of multiple reservoirs. And 3) adding redundancies in the damage calculations, and 3). For consistency, the bulk calculations were left alone as much as possible.

Alteration 1) simply involved adding extra assets into the calculation pool, and identifying the flow paths from each source. Alteration 2) involved removing reservoirs assets and any branch pipes that did not convey flows down to the Karori Reservoir, the endpoint. Finally, redundancies, (alteration 3) were then incorporated by factoring in sections with more than one travel pathway. These redundant sections included situations where there were multiple pipes that occurred in parallel, or as dendritic sections where several pipes converged from multiple different sources. For example, the Wainuiomata treatment plant has multiple collection sites each of which are not reliant on each other to function, where it is expected that only one pathway is needed in emergency situations. For both situations, it was assumed that all pipes would have to break for the particular segment be considered fully broken.

Redundancies were incorporated into the model by giving each pipe an additional value. This number represented how many pipes had to break for the section in question to fully fail. For example, two pipes side by side were given the number two, as both pipes would have to stop functioning to stem the flow of water. These numbers were then included into the damage prediction equations dividing the probability of failure by the total number of required failures Equation 1.

This main damage calculation follows the same principals used in (Cousins, 2013; Nayyerloo and Cousins, 2014), where pipe breakages were calculated by estimating each segments likelihood of failure using the equation below and using random numbers to determine if the pipe failed. For more detail around this equation see (Cousins, 2013; Nayyerloo and Cousins, 2014). In summary, if the random number falls within the predicted failure probability, then the pipe was considered to have failed.

(Equation 1)

$$Final\ Fail\ Probability = \frac{\left(\frac{\left(\left(1600 \times 10^{\left(\frac{(-40)}{MMI-0.6}\right)}\right) \times SM \times LIQ \times LS \times Segment\ length(m)\right)}{(Redundancy\ number)}\right)}{1000}$$

The first half of the equation relates directly to the seismic intensity, and the later to additional factors such as pipe attributes and liquefaction. Where MMI is the adjusted Modified Mercalli Index severity, see Eqation 2 and Table 1, SM the segment multipler or pipe attributes, see Table 2, and finally LS and LIQ refur to landslide and liquefaction hazard modifiers respectivly, see Table 3.

Adjusted MMIs are simply MMIs that include soil amplification using the equations below.

$$\text{For MMI's } > 7, AMP = 0.25 \times (X - 3)$$

$$MMI's\ 7 - 10, AMP = \left((-0.166667 \times MMI) + 1.666667\right) \times \left(\frac{x-3}{2}\right) \qquad \text{(Equation 2)}$$

$$MMI's > 10, AMP = 0$$

Where x stands for the soil class, detailed in Table 2, and AMP the amplifying factor added to the base MMI's.

Table 1 Soft Soil Amplification Factors

Soil Type	Base Number (X)
A Hard Rock	1
B Soft Rock	2
C Frim Soil	3
D Soft/Deep Soil	4
E Very Soft Soil	5

Table 2 Pipe attribute multipliers. Each of these multipliers adds towards the segment multiplier

Non -ductile materials	Old Couplings	Diameter < 600mm	Welded Steel Pipe
6	2	1.5	0.2

The liquefaction amplifiers (LIQ) were taken from an excel sheet containing regional cone penetration test (CPT) results created by GNS Science. The land sliding magnifiers (LS) were obtained directly from a landslide hazard map (Kingsbury, 1994). Overall the impact from each factor is represented in a hazard class, which alters the proability of failure indepednetly, see Equation 2.

Table 1 Added Liquefaction and Landslide Multipliers.

Hazard Class	Magnifier
None	1
low	2.5
Moderate	6.25
high	15.625

Repair times

As like damage predictions, the base repair times were calculated using the (Cousins, 2013; Nayyerloo and Cousins, 2014) model. In the Cousins model, each 'broken' pipe was given a standard repair time based on its diameter. Pipes with diameters larger than 600mm were estimated to take between two and three days to repair, and pipes smaller than 600mm were estimated to take only one day. Prospect times of 0.1 days per km of pipe in the network, were then added to these repair times, representing the time required to check the network for faults.

Any pipe that crossed a fault line was assumed to take extra time to repair depending on the fault, where a random number, between different maximums and minimums, for each fault, was used to provide some realistic randomness, see Table 4. Finally, the influence of response logistics and the required repair of source headworks were also included, see Table 5.

Overall, the total repair times were calculated by adding everything together, following the assumption that repairs cannot be made in parallel due to the fact that sufficient water pressure is needed to inspect for leaks, which cannot occur if there are holes upstream of the break.

Respondent 3 "And then we went around, and we turned on the first valve, and we repaired whatever the issues were in that outlet line, and once that was turned back on, we then went and turned on another valve, and we sort of worked our way out from the reservoirs".

Respondent 4 "when you have a lot of breaks, and you've got the pumps going, you have to have enough [water/pressure], or you can't have that many holes in the system, that it can't push up out of the road to show where the leaks are"

Table 2 Time required to fix fault crossings with one repair crew

	Min (days)	Max (days)
300mm fault bypass at Te Marua	5	5
Fault crossing at Silverstream	12	17
375 mm fault bypass at Karori	7	10
Fault crossing at Thorndon	15	20
Fault crossing at Korokoro	10	15

Table 3 Static additional factors used in Cousins (2012)

Source	Headworks	Securing situation	Assemble plant and materials	Inspection and planning
Hutt River (Kaitoke)	6	1	1	2
Wainuiomata	6	1	1	2
Waterloo	6	1	1	2
Gear Island	6	1	1	2

INTERVIEW RESULTS AND METHODS

The interviews revealed many different important factors to consider when repairing water pipes such as the impacts of politics, environmental impacts, the repair process, access, interdependency, geology and staff logistics. Unfortunately, due to time constraints, only a few could be addressed. Those chosen to be addressed were factors that did not have many solutions, were raised by multiple different respondents, or were easy to incorporate into the model.

The impacts addressed in the model are oddball or uncommon diameters, staff logistics, how the slope of the land impacts the inspection process, and access problems. Each of these issues are discussed below.

Oddball pipes

Multiple respondents raised the issue that pipes with odd sizes or diameters took longer to repair than standard pipe sizes due to no existent or low stock of replacement parts, see Table 6. In most situations where this occurred, the experts did reveal that the repairs could be done with multipurpose clamps. However, as discussed by respondent 1 these clamps, such as maxi clamps, are not fit for use on smaller pipes where they can be wound down too far and cause damage. Furthermore, many of the oddball smaller pipes had unusual layouts where that were placed underneath or around other lifelines and required speciality parts.

Respondent 1 "I don't like to use maxis, because you have to wind them down that far to get them to fit on properly, and normally when the pressure comes on they have the tenancy to twist on the main cause you have had to wind them down too far"

Therefore, to represent the impact of these oddball sizes on the repair times additional time was given to any pipe that was not a standard diameter, classified as a diameter that covered less than 1km of the network. Smaller pipes, smaller than 400mm were attributed a conservative additional three days repair time, assuming the local manufacturers would also have their own difficulties post-earthquake. Pipes with a diameter larger than or equal to 400mm, but less than 800mm were given 0.75 days per break, as temporary solutions such as clamps could be used, but may need to be altered slightly to fit the pipes. Finally, odd size pipes with a diameter greater than or equal to 800mm were given additional times of 0.5days per break, as temporary solutions such as welding plates on the side of the pipe could be implemented, and additional time may be needed to undergo unplanned alternative solutions.

Table 4 Oddball pipe interview summary table. The summarised problem statements are in black, solutions raised by the same or another respondent, are in red.

Odd Ball Sizes	
No easy to acquire replacements. Parts need to be specially made.	Parts can be created by any local engineer/manufacturer depending on equipment available. Prior plans to create these parts are already set up.
Maxis cause damage when wound down too far on smaller pipes, and thus should not be used	Also, common pipe diameters have pre-made available parts and proper clamps. Gibeault joints and maxis work on a broad range of materials. Unorthodox methods can be used temporarily, such as welding a plate over the break, or use Totara pegs, until special parts are made.

Staff logistics

Like oddball sizes, the logistics around managing and working with staff was also highlighted by the respondents as a vital factor to consider when repairing pipes. Multiple interviewees stated that working with other people, within and outside of an organisation, especially those with limited experience caused difficulties and slowed down repairs, see Table 7. For example, important assets like valves and shutoff valves can be challenging to find in the field, as council databases are often not fully accurate. Furthermore, essential information is frequently only kept as head knowledge, which is lost when staff leave an organisation. Finally, the respondents also revealed that there were difficulties in working with others from other organisations and regions during the response phase, post-disaster, as terminologies and standard processes of repair are different for each region. These differences often lead to confusion between different parties, and jobs being completed to different standards.

To address the in-house staff logistical impacts, or impacts from experience differences and knowledge losses, extra time ranging from 0 to 0.5 days was added to the repair time of all broken pipes. This addition simulates the difficulties of finding the exact location of assets, such as shutoff valves. A random number was then used to determine the exact increase, between 0 to 0.5 days, to add realistic randomness, replicating the issues the repair crew may face.

The out-of-house impacts, or the issues working with multiple stakeholders, were calculated by doubling base repair times for 10% of the pipe breaks. This adds an assumption that 1 in every 10 pipe repairs would have to be redone, following the comments by the respondents and patterns that arose in the aftermath of the 2010-2011 CES, where many residential repairs had to be completed many times due to poor communication and craftsmanship (Broadstock, 2016).

Table 5 Staff logistics interview summary table. The summarised problem statements are in black, solutions raised by the same or another respondent, are in red.

Staff	
Staff turnover leads to the loss of experience around efficient pipe repair and critical valve locations.	
Ineffective and sub-par databases. (Databases are unique to each region where they all use different methods of storing and analysing data) These databases especially become a problem when people from other areas join the response team and do things their way, producing discrepancies	Councils and other organisations are Becoming better with GIS and GPS systems
Database info often does not line up with reality	
Need better-pre-set plans to spring into action	Wellington has plans already set in place.
Logistics of moving people from other areas into the region in the aftermath to help. For example, it will be difficult to find beds, shelter and transport.	Campsites and naval ships often offer their services. These ships can also carry gear if needed
Each region has different terminologies between councils and regions	
Removal of staff from other commitments and jobs, to help repair phase	

Damage inspection

Another factor raised by the interviewees was the importance of water pressure when inspecting the pipes for damage. Many respondents stated that most inspections were conducted using surface observations, which can be influenced by the topography and subsurface hydrology. For example, hill slopes can cause water to flow downhill before surfacing, causing repair crews to dig in the wrong place. This confusion extends repair times as multiple holes have to be dug to locate the damage. For example, it took one expert five days to find a broken pipe in which countless holes were dug in the process, see Table 8. Alternative methods such as diviner rods, and loop locators, can be used to help in these scenarios. However, they are not always accurate and take time to employ.

Table 6 Damage inspection interview summary table. The summarised problem statements are in black, solutions raised by the same or another respondent, are in red.

Inspection Process	
Water can run downhill and rise to the surface away from the leaking pipes. Since leaks are often identified by looking at the surface, failures can be difficult to find. For example, one leak took five days to find, which lead to a higher cost and time wasted.	Loop locators and diviner rods can be used to find leaks. Hydrant boxes can show how far the water has travelled downhill (shows water level underground).
It is much harder to find leaks in non-pressurised pipes like wastewater as there is no bubbling or geysers etc. Earthquakes can create multiple holes which reduce the pressure. Need pressure to push water to surface for identification.	Previous experience with vulnerable regions can also increase inspection efficiency as the most likely areas of damage can be inspected first.
Need to pressurise sections to find leaks. Areas must, therefore, be shut off as too many holes make pressurisation impossible.	Predictive maps can be used before the event to show areas of likely damage.
House tobys are usually turned on, adding to more regions of pressure loss.	Finally, leaks can be found using telemetry systems that track pressure changes using GPS and GIS systems.
Liquefaction increased the difficulty of identifying leaks in Christchurch due to the amount of water on the ground surface. Thus, the inspection process had to wait for a day for the water to reside before turning the water supply back on for inspection. This liquefaction impact could occur in Wellington.	Often damages cause significant amounts of water to gush to the surface like geysers, thus finding leaks may be quite simple

Since the additional time required to inspect the pipes was based on the slope and water pressure, extra time was given to each broken pipe depending on the gradient of the land it lay in and the diameter of the pipe. The diameter was used alongside the slope as larger pipes carry more water, and are therefore more likely to create surface observations near the broken segment. Overall small pipes in steep slopes gained the greatest additional times, see Table 9.

Table 7 Additional times required to inspect the pipes. These final numbers were based on the respondent's stories, and the repair times stated.

Pipe type (ground surface gradient)	Min (days)	Max (days)
Main (steep slope)	1	2
Main (moderate slope)	0.5	1
Main (shallow slope)	0	0
Branch (steep slope)	1.5	3
Branch (moderate slope)	0.75	1.5
Branch (shallow slope)	0	0

Access

The final additional impacts explored were access problems. Multiple experts stated that as a result of a significant earthquake in Wellington, the main transport routes such as rail, roads, and the port would be closed due to shaking, landslides, and permanent ground deformations, see Table 10. Interestingly the overall impact of these access problems on repair times was debated. Some experts stated that there were no significant potential problems, while others saw serious issues. Those that saw only limited problems stated that at least one lane would be open in most circumstances, and hard to get to places could be reached by using equipment like diggers or bulldozers that can pull themselves up and over difficult terrain. In contrast, those respondents that saw significant hazards, stated that multiple areas would be far too difficult to reach until the potential damages and landslides were cleared or stabilised, especially when some of the possible landslides could be as large or bigger than those in the 2016 Kaikoura earthquakes which have taken at least a year to remove (New Zealand Transport Agency, 2018). Furthermore, it is believed that as a result of these potential damages, transporting the required equipment and resources in and out of Wellington would be very difficult, slowing down repairs (Ministry of Civil Defence and Emergency Management, 2010a). The exact effect of this difficulty is hard to determine since roll off roll on barges can be used and parts can be made locally.

Table 8 Access interview summary table. The summarised problem statements are in black, solutions raised by the same or another respondent, are in red.

Access	
Road damages make some locations completely inaccessible.	
28 slips occurred along roads in Kaikoura. The same thing can happen in Wellington. Getting rid of these 28 landslides was difficult as they could not simply be pushed into the sea, for safety reasons, etc. In Kaikoura, the banks of each landslide had to be shored up first before they could be removed or fixed. Furthermore, in Wellington, if there are properties above landslides, cautionary approaches would need to be taken.	Diggers and Bulldozers can tug each other up hills and across rough terrain. Paths can also be dug out, or diggers can pull themselves over hills by their bucket Rubber tires, and caterpillar tracks can also be used to make access easier. In residential areas, there is usually more than one way to go to get to damages. Finally, helicopters can be used to move supplies around.
There are multiple sites of possible slips in Wellington. For example, along State Highway 2 between Petone and Ngauranga Gorge, and along the road between Plimmerton and Paekakariki. Furthermore, the highway between Porirua and Plimmerton will also experience liquefaction.	Construction of Transmission Gully will reduce the effect of these landslides, as the road is only expected to be closed for three weeks, compared to 3 months for State Highway 1 and 2.
As a result of these landslides, regions could be closed off for up to a year. For example, the recent slip in the Manawatu Gorge took a year to clear.	Repairs should only take a couple of hours (3-4).
These landslides will stop large equipment and parts necessary to repair sections from reaching areas in need.	Lifeline groups already have collective plans and understandings.
Pipes too deep to easily access or hidden behind other pipes.	Most water supply pipes are relatively shallow as they do not rely on gravity to function.
Pipes can sometimes be in hard to get places, like under houses and schools, which is especially problematic if shut off valves are also located there	Entire problematic sections can be replaced by new pipes. These new pipes have the advantage of being made of better materials and more flexible joints.
Port is currently damaged, so not expected to be useful.	Roll on roll off barges can be used instead.
Rail is not an option either (see Kaikoura)	The airport can be used as a backup transport hub.
Some regions like Wainuiomata have only one route in an out. Thus people may become stranded.	Additionally, there is usually at least one lane available when repairing pipes, as the repair process does not take up the entire road.
Roads must be closed for pipe repair.	

What is agreed upon by the experts is the fact that landslides are inevitable in a large Wellington Earthquake event. These landslides may bury pipes under hundreds of thousands of cubic meters of debris, making it difficult to repair any broken pipes located directly underneath the deposits. To address these impacts specifically, pipes located in potential landslide runout zones, identified in Hancox and Perrin (2010), were given additional Id numbers. If a pipe with one of these Id numbers, fractured because of the earthquake, an additional standard of two weeks was added to the pipe's repair time. Two weeks was chosen as it is similar to the period needed to fix fault ruptures, which are often significantly damaged. Overall this number is very arbitrary, as there is no knowledge around exact times. However, these estimated impacts reveal the potential significance of how landslides affect final repair times. Once all the relevant factors raised in the interviews, like the influence of landslides, were added into the model, their specific influence on overall repair times was then calculated.

RESULTS AND DISCUSSION.

After running the altered predictive model for the first time, the total number of pipeline failures from an Mw 7.5 Wellington Fault Earthquake, control only, (without additional factors and redundancies) ranged from 10 to 51 pipe breaks depending on the source, see Table 11. Kaitoke experienced the lowest number of failures, despite having the greatest number of pipes exposed to earthquake conditions. Usually, it would be expected that the greater the exposure, the higher the damage, but because Kaitoke contains mostly resilient pipe materials and diameters, the likelihood and thus the number of failures is much lower, see Table 12.

When redundancies, or sections with multiple pipes, were included in the calculations the number of failures reduced by almost half for all sources except for Kaitoke, which experienced virtually no change, see Table 11. This stagnant change suggests that there are not many parallel or redundant pipes associated with the Upper Hutt Network. Overall the significant reduction, especially from Wainuiomata which experienced a decrease of more than 100% shows the importance of including redundancy, into damage prediction and repair time calculations as it can have a significant impact on the number of repairs, and thus the repair times.

Table 9 Final totals of pipe failures and repair times, including the influence of redundancy.

Source	Total length from source (Km)	Base inspection time (Days)	Number of failures	Base Repair time (Days)	Number of failures with redundancy	Base Repair time with redundancy (Days)
Hutt River (Kaitoke)	58.91	5.89	10.27	29.35	9.40	24.90
Wainuiomata	44.89	4.49	50.47	76.56	34.47	49.52
Waterloo	31.08	3.11	37.93	46.80	29.80	35.14
Gear Island	21.96	2.20	36.50	46.10	27.93	32.23

Table 10 Pipe attributes associated with each source. Cement pipes include brittle materials such as concrete and asbestos cement. Plastic pipes include materials such as polyvinyl chloride and polyethylene. Mains refer to pipes larger than and equal to 600mm in diameter. Branches are pipes smaller than 600mm. Old couplings are pipes with non-welded joints that were created before 1960

Source	% Cement	%Steel	%Iron	%Plastic	% Main	%Branch	%Old coupling
Kaitoke	0.46	99.53	0.00	0.00	97.92	2.08	29.21
Wainuiomata	2.97	84.09	11.74	1.20	64.14	35.86	41.65
Waterloo	0.00	98.27	0.00	1.73	51.46	48.54	35.21
Gear Island	0.00	98.09	0.00	1.91	54.53	45.47	38.18

Additional factors

With the addition interview factors, minus landslide impacts, repair times increased from 3 to 13 days depending on the source, see Table 13. The greatest increase, outside of land sliding impacts came staff logistics, adding an average of 7 days. The lowest increase came from oddball sizes which increased repair times by around a day. Land sliding at this point was left out of the final times, as there was not much evidence for the numbers given, due to the assumption of two-week repairs.

Table 11 Final repair times, showing the number of added time in days for each factor

Source	Repair + prospect times	Headworks	Securing situation	Assemble plant and materials	Inspection and planning	Fault repairs (with two repair crews)	Totals before adding Interview factors	Extra inspection	Oddball sizes	Find valve	Total (days)
Kaitoke	30.79	6	1	1	2	12.61	53.40	0.05	0.93	2.84	56.22
Wainuiomata	54.00	6	1	1	2	16.60	80.6	4.25	0.47	9.28	93.60
Waterloo	38.25	6	1	1	2	16.60	64.85	4.15	0.30	7.61	75.91
Gear Island	34.43	6	1	1	2	16.60	61.03	4.15	1.60	7.15	72.92

Despite the fact that the local impacts added an average of nine days to repair times, the final times produced are very similar to the previous models (Cousins, 2013; Mowll, 2012), where it is expected that the water supply from Kaitoke to Karori will be restored within 52 and 65 days respectively. This similarity questions to the impact of these local factors, as there is no evidence of significant changes. However, this simple comparison misses the important influence of alterations to the original model such as including redundancies and amplification factor changes, of which almost halved the number of failures as outlined in Table 11. The impacts of changing the amplification factors and adding redundancies can be seen in the reduced number of failures from Kaitoke, where previous models estimated 23 failures would occur along the Kaitoke line, more than twice the number predicted by the newly constructed model (Cousins, 2013). Therefore, despite similarities, it can be concluded that the local factors investigated do have a significant influence on final repair times, as not only were 3 to 13 days added, but the number of potential failures was cut in half. Unfortunately, better comparisons cannot be made between the new model and original models, as the previous models only focus on the Kaitoke source. However, It can be safely assumed that these factors do have a significant impact.

Landslide impacts

With the inclusion of landslides, final repair times increased by between 28 to 98 days depending on the source as shown in Table 14. In total between two and seven failures were located in potential landslide runout zones, of which would either have to be repaired by firstly removing the debris on top of the break, or by constructing temporary bypasses, like those used to cross the Brighton Bridge after the Christchurch Earthquakes (Eidinger and Tang, 2012). Interestingly all three of the Lower Hutt sources share the same repair time and number of failures. This similarity is a result of sharing the same pipes along State Highway 2, the region most vulnerable landslides and liquefaction, as shown in Figure 3.

In addition to the direct increase in repair times, landslides would prohibit and slow the influx of critically needed resources such as aid and replacement parts (Ministry of Civil Defence and Emergency Management, 2010a; Mowll, 2012). For example, land moving equipment such as the diggers used for digging down to the pipes may not be readily available after a large event, slowing down repairs. Alternative routes such as roll on roll off barges and helicopters can be used; however, these backup transport routes would be highly sought after and be limited in supply (Ministry of Civil Defence and Emergency Management, 2010b). Furthermore, they would require additional time to implement (Ministry of Civil Defence and Emergency Management, 2010a, 2010b). Thus, landslides can not only cause direct impacts to the final repair times but can cause secondary and tertiary impacts.

Table 12 Additional times needed to create an alternative route around broken pipes under landslides

Source	Total failures under a landslide	Additional Time (days)
Hutt River (Kaitoke)	2	28
Wainuiomata	7	98
Waterloo	7	98
Gear Island	7	98

Figure 3 Wellington water supply mains, with soil liquefaction potential. Stars represent water sources.

Possible methods to reduce the impacts in light of findings

Overall, the results of this study show that local impacts can have a significant effect on final repair times. Therefore, plans around these potential issues should be implemented. For example, the difficulties of working with inexperienced people and staff from different organisations increased repair times by an average of 7 days, as stated in Table 13. In an actual disaster, these difficulties could be much more extreme. For example, as a result of poor management, budget cuts and communication, many homes after the Christchurch Earthquakes had to be repaired multiple times due to poor and "shoddy" repairs, which drastically extended repair times and costs (Broadstock, 2016). If better management and communication are achieved, a more consistent approach could be reached, which would reduce the likelihood of poorly done jobs. This consistency requires regional or nationally known standards and terminologies so that repair crews from different companies and organisations can understand each other. Currently, most councils and regions have their own method of storing and managing data, with some using GIS databases, others through CAD programs, and some still use paper drawings (Table 7). If regional or national databases, such as the Canterbury Geotechnical Database, or software such as Risk Scape was used more regularly, communication and logistical problems could be reduced, as terminology and knowledge differences would no longer occur (Scott, Ballegooy, Stannard, Lacrosse, and Russell, 2015).

Enhancing the resilience of the transportation system will also allow for faster repairs as the pipes, required equipment, and needed resources will become easier to access after an earthquake event. Currently, work is being carried out in Wellington to improve nationwide access through the construction of an alternate route to State Highway 1 (SH1), called Transmission Gully (TG). This new road will make it easier to get into the centre of Wellington both during normal conditions and during disasters, as it is more resilient and less prone to landslides. Overall TG is expected to take only 30 days repair after an earthquake, taking 90 fewer days than SH1 (Brabhaharan, 2009; Mowll, 2012). However, despite TG's potential advancements to regional access, the alternative route does not improve access to the water pipe's themselves as the pipes still follow the SH1 and SH2 as shown in Figure 3. In the event of an earthquake, it can be expected that SH1 and SH2 will be closed off from landslides for extended periods of time. Thus, improvements, such as slope stabilisation should be conducted to reduce overall repair times and potential road damages. Furthermore, the pipes themselves can be improved. Better pipe materials lead to lower break rates, and thus faster restoration times (O'Rourke et al., 2014; Sherson et al., 2015)

The pipe material can have a significant impact on how the pipe behaves during a disaster. For example, ductile materials like polyethylene, break on average six times less than brittle materials (O'Rourke et al., 2014; Sherson et al., 2015). Thus, if the brittle pipes In Wellington were replaced with better materials, the potential damages would decrease. Furthermore, as larger pipes are more resilient, bigger pipes could also be used which would not only increase durability but would allow for more water to be transported through the pipes (Nayyerloo and Cousins, 2014). By allowing more water to flow, faults along the lines could become much easier to find, and clamps would be able to be used without worrying about winding them down too far as discussed in Table 6. Finally, by upgrading the pipes, oddball pipes could be removed, allowing for easier repairs, as spare parts and appropriate clamps would already exist. However, changing the pipes is not a simple undertaking, costing a significant amount of time and money to do so. For example, repairs to the water and wastewater after the Christchurch Earthquake cost 5% and 70% of the $2.2 budget for the rebuild respectively (Department of the Prime Minister and Cabinet and Christchurch City Council, 2016).

Finally, restoration times could be reduced by avoiding fault crossings altogether. This would be quite difficult as all Wellington sources gather water from sources on the opposite side of the Wellington Fault to Wellington City. Currently, there are plans for an inter-harbour pipe through the Wellington Harbour, which would bypass the faults and connect to the Lower Hutt sources (Wellington Water, 2015). Overall, the final solutions used will be determined by the local surrounding landscape and contextual influences.

Limitations and recommendations

Unfortunately, not all local factors raised in the interviews could be investigated. For example, the impact of politics, environmental concerns, and health and safety problems could not be addressed due to the time constraints and because of the complexities of modelling these factors. Those local impacts explored were only briefly investigated, focusing on the overall possible consequences, and general outcomes. For a more accurate model, these factors need to be investigated with more depth and care. Finally, this study only includes interdependency at a surface level. In order to fully understand the behaviour of each lifeline, an in-depth study of interdependency is required.

CONCLUSIONS

Lifelines like the water supply are critical for the survival of people, communities, and businesses where the loss of water can cause health problems and close businesses, causing long-term impacts. In the event of an earthquake the water supply, like many other lifelines is likely to be damaged and therefore be out of commission. The Wellington Region in New Zealand is particularly vulnerable because the bulk water pipes cross the Wellington Fault multiple times and reside in landslide-prone regions. Currently, the models that calculate the potential down times for Wellington, focus mostly on engineering principals and do not incorporate local or contextual factors. According to the multiple experts interviewed, various local factors can have a significant impact on repair times. For example, differences in staff experience and approaches to repair can cause inconsistencies and slow the repair processes. Furthermore, landslides can prohibit access to damaged pipes and needed equipment, dramatically slowing down repairs. When these local and contextual factors were included into current predictive models, the predicted repair times increased by between 3 and 13 days depending on the water source. When land sliding impacts were included, these final repair times increased by between 31 and 111 days depending on the source. Overall, local factors can have a significant impact on repair times and should be included into future predictive models and repair time considerations. However, further research is required to more accurately define these additions, where an in depth model sensitivity study is required to understand if these factors are worth modelling.

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