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**The impact of contextual factors on the
predicted bulk water pipe repair times in
Wellington City**

A thesis presented in partial fulfilment of the
requirements for the degree of Master In Emergency
Management

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Abstract

Lifelines, like the water supply, are essential for the survival of people, communities, and businesses. In the event of a significant natural disaster, like an earthquake, it can be expected that these regional lifelines will be severely damaged. Wellington, the capital of New Zealand, contains many lifelines that are highly vulnerable to failure. The water supply is especially susceptible, as it crosses the Wellington Fault multiple times and carries water through landslide prone corridors. Because of the risk, and potential impact on people, several predictive models have been created to calculate the likely downtimes so individuals and organisations can prepare for the loss. Many of these predictive models are comprehensive in what they calculate. However, they require improvement as they do not include local and contextual factors or the influence of other lifelines. For example, they do not include the impact of staff logistics, assume access to required equipment is a given, and ignore interdependencies between lifelines, such as the loss of access to repair sites because of damage to the transportation network.

This research aims to improve these current models by investigating the magnitude of these site-specific and interdependency factors. Following a sequential mixed methods approach and using a pragmatic viewpoint, experts directly involved in the repair and maintenance of lifelines were selected for interviews. In total 20 professionals were contacted using a snowball and convenience sampling technique. Out of these 20, five were available for in-depth semi-structured phone interviews. From these interviews, anything stated to affect the repair times was highlighted, the most prominent of which were incorporated into current predictive models and their influence on repair times calculated. In total 12 different issues were discussed, 4 of which were examined further. These factors were: staff logistical problems; the slope of the land affecting damage inspection processes; the impact of uncommon pipe diameters on the repair process; and access problems. Once identified, these factors were incorporated into current predictive models, and the impact on repair times calculated. By including these contextual influences, it was found that they increased repair times by between 3 and 13 days depending on the water source and 31 and 111 days when incorporating the influence of landslides. Thus, proving contextual influences have a significant impact on repair times. Overall this study 1) revealed the importance of including contextual factors into predictive calculations and 2) created more accurate downtime predictions for the water supply in Wellington City, allowing for people, organisations, and planners to better prepare for the potential risk.

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Chapter: 1 Introduction

This chapter begins by briefly discussing the importance of understanding how natural disasters can impact people, businesses, and the community. In this exploration, the research gap is described, and the need for improved predictive models is discussed. Once a brief overview is given, the scope of the investigation, study objectives, and research questions are then addressed. Finally, the chapter introduces the structure of the thesis and summarises the purpose and construction of each chapter.

Natural disasters can cause significant damage, set nations back, dramatically alter the environment, and cause thousands of deaths. For example, (1) the eruption of Mount Vesuvius in 79AD, killed 4000 people and permanently destroyed both Pompeii and Herculaneum (Francis & Oppenheimer, 2004; Hyndman & Hyndman, 2016). (2) The 2004 Sumatran Tsunami killed around 300,000 people and left 5 million homeless, many of which had no way of recovering from their losses (Coenraads, 2009; Hyndman & Hyndman, 2016). (3) The Nepal Earthquake in 2015 damaged 900,000 homes and temples, killing 8969 people (Chaulagain, Rodrigues, Jara, Spacone, & Varum, 2013; Pokharel & Goldsworthy, 2015), and (4) Hurricane Katrina caused US\$80 million in damages, left many with nothing to return to, and lead to millions distrusting those involved in the response (Coenraads, 2009; Cole et al., 2015). Although there are significant consequences from disasters, their severity can be reduced if people are prepared. For example, (1) many of the deaths from the Mount Vesuvius eruption could have been avoided if people had known about the dangers of volcanic eruptions (Francis & Oppenheimer, 2004). (2) The impacts and deaths from the Sumatran Tsunami could have been significantly reduced if there were warning systems, education around what to do in a tsunami threat, and evacuation structures (Coenraads, 2009). (3) Many of the damaged homes in Nepal could have been avoided if the buildings were built to code (Dixit, 2008; Pokharel & Goldsworthy, 2015), and finally (4) many of the costs and losses from Hurricane Katrina could have been avoided if there was adequate maintenance of the levees that protect the city and proper coordination between the organisations involved in the response (Cole et al., 2015; Hyndman & Hyndman, 2016). Thus, properly preparing for and knowing the potential risks is essential, as effective plans can reduce the impact of a future event.

1.1 Understanding of Disaster Risks

There are many ways to understand the possible risks disasters pose. The five more common methods are: studying past events, estimating the likelihood of future events, creating predictive models, carrying out damage consequence analyses, and conducting tabletop scenarios.

Studying previous events involves investigating the disaster's impact by looking at what occurred; how it happened; and what people did in response (Coenraads, 2009; Hyndman & Hyndman, 2016). Through investigating past disasters and their very real impact on people, the knowledge of what could happen in the future is obtained, as the implications from the past can be implemented into current and future situations. Overall if there is no knowledge of previous events and their impact, preparation could not occur as the risks would be not be known (Francis & Oppenheimer, 2004; Hyndman & Hyndman, 2016).

Likelihood estimations take the study of previous events one step further. Instead of just estimating what could happen by looking the past disasters, a quantifiable value of the probability of occurrence is produced (Coppola, 2015). For example, the return period of different magnitude earthquakes can be calculated from historical data and the local geology to allow for a better understanding of the probable future events (Pondard, 2012). These return periods allow organisations to understand how likely different magnitude events are to occur, allowing them to make specific plans. Another example is the calculation and use of a risk statement, such as a "50-year flood", which is used to define the magnitude of a flood that has a 1 in 50 chance of occurring each year (Coppola, 2015). Overall, through likelihood estimations, planners can prioritise what to prepare for.

Predictive models such as Nayerloo and Cousins (2014); Penjamani, Chandran, and Srinivas (2011); Sherson, Nayerloo, and Horspool (2015) involve calculating the potential impact from possible disasters by measuring the effects of previous events. Models are slightly different to case studies or likelihood calculations as they have a narrow focus, concentrate mainly on the quantifiable impacts, and look at the mathematical relationships between the variables. Constructing predictive models involves multiple steps. First Information from previous events, such as infrastructure damage, event magnitude, geology, event frequency, likelihood, and building attributes are collected. Then the relationship between different variables

is explored, and a regression line produced (O'Rourke et al., 2014; Sherson et al., 2015). For example, a common equation created is the link between ground displacement, and building damage state (Rota, Penna, & Magenes, 2010). With the newly constructed curve or equation, the model can then be used to predict possible future damage based on known potential magnitudes. For example, if the relationship between shaking intensity and damage state is known, the degree of damage can be estimated from a possible shaking magnitude (O'Rourke et al., 2014).

Damage consequence analyses (DCA) involve calculating the potential impact from a disaster by estimating the likely losses from an event. The process is similar to predictive models, but the focus is on the costs and consequences of the event rather than the likely damage (Puissant, Van Den Eeckhaut, Malet, & Maquaire, 2014). Generally, there are two methods of conducting a DCA, an abbreviated DCA and a full DCA. The abbreviated DCA estimates the consequences of the event by using historical event impacts to predict the possible damage to current and updated infrastructure, similar to the first method (Coppola, 2015). The full DCA is much more comprehensive, where the cost of losing structures, contents, and operations are included in the calculations. Overall the total cost of losing a certain asset to the community is calculated. This quantitative information is then combined with likelihood information and qualitized by separating the values into a range of qualitative consequence descriptions. These descriptions are then used to evaluate the potential risk of the disaster where different events are compared and contrasted (Coppola, 2015).

Tabletop scenarios or drills are another method that can be used to determine the impact of future events and involve unleashing a fake disaster with a certain magnitude in a specific region, to train responders and emergency care providers (Chi, Chao, Chuang, Tsai, & Tsai, 2001; Edzen, 2014). There are commonly two methods of conducting tabletop scenarios. One involves a group discussion where representatives from each provider gather in a stress-free environment to discuss how they would accomplish tasks and solve any problems that arise. The second involves time constraints and uses of equipment, where organisations deploy responders and test coordination (Edzen, 2014). Instead of focusing on one attribute, which most predictive models do, tabletop scenarios concentrate on an entire region and multiple services at the same time, like a DCA. However unlike a

DCA, the plans around how to respond to the disaster are then virtually implemented, and the coordination of different groups practised, the outcomes of which provide an excellent example of the possible situations and scenarios that can happen (Edzen, 2014).

Tabletop scenarios, DCA's, predictive models, likelihood calculations, and case studies provide valuable insights into the likely impact of various events, helping people and organisations prepare. However, despite their usefulness, these methods are limited to the information entered and therefore are not foolproof. This can lead to people being misinformed when poor information is incorporated. This misinformation can become hazardous when individuals or organisations become complacent, assuming there is no need to prepare for a potential disaster as they believe the protective and planning systems set in place will not fail (Ericksen, 1986). For example, before Hurricane Katrina hit, most people and planners were under the impression that the levees would not be overtopped, and thus were not prepared to deal with the widespread flooding that occurred when the levees were breached (Cole et al., 2015; Litman, 2006; Robillard, 2009).

1.2 Research Context

The various infrastructure that provide essential services to the community are defined 'Lifelines' due to their importance for individuals, communities, businesses and the economy (Ministry of Civil Defence & Emergency Management, n.d.; Nigg, 1995). The transportation network and electricity supply are great examples as they help people; goods; and services to get from one place to another, and power equipment; tools, services; and technology (National Institute of Standards and Technology, 2016a). Without either, people would not be able to get to work, goods and services could not be transported, and equipment would not be able to function (Rinaldi, Peerenboom, & Kelly, 2001).

One of the most vital lifelines is the water supply. Clean water is a requirement for life, as it is needed for consumption, hygiene, and sanitation (Gleick, 1996). According to Gleick (1996) at least 50 litres of water per person, per day, is needed for long-term living, and is considered a basic human right. In developed countries like New Zealand, a majority of individuals expect and rely on potable water to be piped directly to their house (National Institute of Standards and Technology, 2016b). Without this service, knowledge of, or the ability to obtain potable water,

people may develop health problems from using contaminated water or from having limited access to a source. (Lam, Pace, Campanella, LeSage, & Arenas, 2009; World Health Organisation, 2009). Furthermore, many businesses rely on direct piped connections. For example, water is vital for processes such as manufacturing, growing crops, cleaning, and cooling. Without easily available water, businesses would struggle as they would not be able to operate properly (Lam et al., 2009). Furthermore, without water businesses cannot legally function as various Health and Safety Acts state that businesses must supply their workers, clients, and customers with basic amenities (Health and Safety at Work Act, 2015; Occupational Safety and Health Act: No. 1915.88, 1970).

Disasters like earthquakes can severely damage lifelines, leaving them non-functional for extended periods of time (Cousins, 2013). For example, the Northridge earthquake caused 1400 failures along the water pipes in Los Angeles in 1994; the 1995 Hyogoken earthquake broke 1610 distribution mains; and 8556 repairs were required in Christchurch after the 2010-2011 Canterbury Earthquake Sequence (O'Rourke, 1996; Sherson et al., 2015). Therefore, it is important to plan for potential losses. One way to prepare is to identify the potential weak points so that plans can be made to address or quickly repair them.

1.3 Scope of the Research

New Zealand is one of the most seismically active countries in the world sitting upon the boundary between the Indo-Australian and Pacific plates. As a result of this collision and the complex mechanics of the Alpine Fault, many fault lines have been created that actively move and generate earthquakes (Cooper, 2008). One of the most vulnerable regions to natural disasters in New Zealand is the Wellington Region, which is home to the nation's capital and around 500,000 people (Statistics New Zealand, 2013). Wellington is particularly vulnerable as its water supply is transported through landslide prone corridors that are near to, and cross the Wellington Fault. In a large earthquake event, significant damage to the pipes can therefore be expected, where thousands of people will be cut off from potable water for months (Mowll, 2012). Due to these risks, Wellington was selected as the focus of the study, where bulk water pipe repair times will be investigated. Overall this study will look at the various impacts to the water supply repair process, aiming to understand how long it will take to fix the pipes. As a specific understanding around how a particular infrastructure will behave during an earthquake is

required, the predictive model approach, for understanding the impact of a potential disaster, will be used. Overall a current well-validated model, the Cousins model from the Cousins (2013) report, will be used as a base for the calculations.

1.4 The Cousins Model

The Cousins Model in the Cousins (2013) report, is a predictive model that calculates the extent of the water shortages after a Wellington Earthquake. The water supply downtimes are produced by adding together the time required to repair each broken pipe from the water source to each Wellington Reservoir, taking into account the time required for planning, staff needs and fault crossing repairs. This model was chosen, as it is the only Wellington predictive model that mathematically calculates downtimes directly from pipe information and local geology. Most of the other predictive models only estimate the repair times, where there are no calculation methods; or only provide damage estimations with no reference to repair times such as O'Rourke et al. (2014); Sherson et al. (2015); Zare (2012). Overall the Cousins Model provides the strongest foundation to undergo the research. More information on this model can be found in section (2.7).

1.5 Current New Zealand Damage and Downtime Predictive Models and Their Limitations

Unfortunately, many of the current predictive models like the Cousins Model in New Zealand require improvement, as they focus only on one area of expertise, ignore the interrelationships between lifelines, do not incorporate key contextual factors, and make too many assumptions around possible disaster impacts. For example, studies such as Cousins (2013); Cubrinovski et al. (2015); Goded et al. (2016); Kongar, Rossetto, and Giovinazzi (2014); O'Rourke et al. (2014); Sherson et al. (2015); Zare (2012) focus on a single structure type and ignore the influence of other lifelines and contextual factors. The New Zealand studies that do account for the impact of multiple lifelines, or interdependencies; only briefly look at the interrelationships between lifelines (Mowll, 2012); are too basic to be used at a large scale Buxton (2013); Buxton and Pringle (2014); do not incorporate site-specific factors, such as access problems from landslides; or miss important physical considerations such as the impact of water pressure on liquefaction severity. Thus, there is room for improvement. However, despite the many gaps, the models should not be considered useless, as they are comprehensive in what they do. What

is required are better models that fully address the likely impact of disasters like the models from the National Institute of Standards and Technology (2016a, 2016b) reports, in a New Zealand context.

1.6 Overarching Research Aim

Having considered the described research background above, and the gap in the literature, this research aims to improve the New Zealand repair-time predictive models by determining how much these site-specific factors and interdependencies affect the bulk water pipe repair process.

1.7 Research Questions and Objectives

To fulfil this aim, the research will seek an answer to the following questions:

- 1) What are the important context-specific factors that need to be considered when repairing the bulk water pipe network in Wellington?
- 2) How much of an impact do these factors have on the overall repair times for the bulk water pipes?

This research intends to answer the above questions by successfully achieving the following objectives:

- 1) Identify the essential elements, tools, and equipment needed to carry-out a water pipe repair, by exploring the repair process.
- 2) Identify the various site-specific and lifeline interdependency factors that need to be considered when repairing a pipe.
- 3) Gain an understanding of the situation after a Wellington Fault earthquake, focusing on the extent of damage to the various lifelines.
- 4) Alter and improve the existing base predictive model so that it fits the scenario better to allow for contextual factors to be tested.
- 5) Compare the time required to restore water to Wellington City from the different water collection points.

Overall, objectives one, two, and three will answer the first research question and objectives four and five, the second.

1.8 Organisation of the Thesis

The following segment describes the roadmap of the thesis, where the purpose of each chapter and its structure is addressed.

1.8.1 Chapter 2: Literature Review.

Purpose: to explore the wider literature and identify a research gap that needs further investigation.

Structure: The chapter starts by exploring the need for lifelines and the importance of understanding their vulnerability. Literature that addresses the research questions is then unpacked. This exploration begins with discussing the interdependency between the lifelines, which is followed by an investigation of the importance of understanding the impact of site-specific factors. After discussing contextual influences, the literature is narrowed down into a regional context, where the geology and hazards of the Wellington Region are discussed. Finally, the current damage and repair-time models are examined, where the strengths and weaknesses of each are addressed.

1.8.2 Chapter 3: Methodology

Purpose: To investigate the possible methods available, and narrow down on one approach that addresses all research objectives.

Structure: Firstly, the different paradigms and how they relate to the research objectives are discussed. Secondly, the various methodologies that work within the selected research paradigm are explored. Thirdly the different methods that can address the research questions are investigated, where the qualitative and quantitative methods are examined separately. In the methods section the diverse sampling, data collection, and analysis methods appropriate for use are discussed, where the reasons for the final choices are mentioned.

1.8.3 Chapter 4: Data Analysis

Purpose: To explain the research process, and what was done to obtain the final results.

Structure: The chapter is split in two where the various qualitative and quantitative methods are described separately, following a sequential mixed methods structure. The chosen qualitative methods are discussed first where the sampling procedures,

collection approaches and data analysis processes are described. Then the various quantitative data collection procedures are unpacked. Once the collection methods are described, the chosen data analysis methods are explored, where the different alterations to the Cousins (2013) models are described. Then the integration process between the qualitative and quantitative methods is explained and the methods of how the site-specific factors and interdependencies are incorporated into the model are discussed.

1.8.4 Chapter 5: Results

Purpose: To identify the magnitude of the different factors explored and calculate the final repair times.

Structure: The chapter begins by investigating the overall attributes of the collected data, where the interview statistics, are summarised and described. Once an overview is established, the responses from the interviews and their impact on the repair times is explored, where qualitative and quantitative elements are discussed together. For each important factor highlighted in the interviews an estimated additional repair time is produced. These additional times are then combined to produce the final repair time from each source.

1.8.5 Chapter 6: Discussion and Conclusions

Purpose: To explain the final results and their relevance while comparing the outcomes with the wider literature.

Structure: The chapter opens by discussing the role each lifeline has in relation to the functionality of the water supply. Following this discussion, the meaning behind the results is explained, and the main impacts are explored. Then, the research gap is redescribed, and the final times are compared to the original model and wider literature. In this comparison, the reasons for the various alterations and additions are discussed. After this explanation, the impacts from the various contextual factors explored are unpacked in more detail. With the impacts of the contextual factors determined, the possible management decisions that need to be conducted in light of findings are discussed, where the different ways of mitigating the likely damage to the pipes, and lowering of their repair times are investigated. Finally, the limitations and recommendations are discussed, where the conclusions of the study are stated.

1.9 Summary

This chapter briefly explains the context of the study and the various topics that are explored. The need for accurate modelling is touched on, aligning the need with disaster preparation requirements. It was determined that in-depth data on the region is required to accurately plan for a catastrophe as unexpected localised impacts can drastically alter how an event occurs. Unfortunately, many of the predictive models from New Zealand need improvement as they make too many assumptions, miss local influences, and ignore interdependency. In this gap, the aim of the study is explained, where the scope of the research, its context, objectives and research questions are discussed. Finally, a roadmap of the thesis is given, explaining the purpose of each chapter and how the thesis is structured.

Chapter: 2 Literature Review

This chapter begins by exploring the need for various lifelines, looking at how people, communities, and businesses rely on them to survive. Multiple examples are explored to understand this relationship better. Once an understanding is achieved, literature that addresses the research questions is then discussed, looking at 1) interdependencies between lifelines, 2) the possible impact a local earthquake can have on the different lifelines, and 3) the strength and weaknesses of the current damage prediction and restoration models. Each topic is explored in detail through the investigation of various research studies. This research involves examining what was done in each study; describing the scope; outlining the aims and conclusions; discussing the strengths and weaknesses, and highlighting the limitations and assumptions used. The goal is to understand the literature environment, the location of gaps, and where improvements can be made.

2.1 Background on Lifelines

Lifelines such as electricity, transportation, communication, and water supply are necessary for daily life. For example, water is needed for hygiene, sanitation, cooking, and consumption; all of which are considered human rights. It is estimated that a standard of at least 50 litres per person per day, is needed for survival, where anything below this number leads to health problems and death, especially if limited access occurs over extended periods of time (Gleick, 1996). In developed countries, houses are connected directly to a water source through a series of pipes and pumps and thus use substantially more water, using up to 400 Litres per person per day (Gleick, 1996). This high consumption is considered a right, where people expect and rely on 24/7 access to potable water (Attari, 2014). Many processes are required to produce this direct water service, all of which are often forgotten. The following sections describe these processes and the contextual background where the needs of individuals and businesses are addressed.

Each lifeline system consists of a significant amount of infrastructure, processes, and management staff, which work together to produce the required service (National Institute of Standards and Technology, 2016b). The electricity system, for example, relies on multiple generation, distribution, and management networks, all of which involve long, complex chains of infrastructure to work (Energy Exchange, n.d.). This complex chain begins with power generation, which involves

finding efficient and sustainable methods to produce energy, either relying on fossil fuels, or natural systems such as wind, hydro, or solar power. During the generation phase, hundreds of systems are required to safely extract the energy with the least amount of adverse effect on the environment and community (Breeze, 2014). Once extracted, the energy is transformed into electricity and then transported at high voltages, to reduce energy loss through heat, to different transforming stations around the country. After transportation, the voltage is then lowered through various transforming stations, and then distributed to the end users (Energy Exchange, n.d.). Each point in this supply chain relies on each other to function properly and effectively, where a failure in one sector can cause problems throughout the entire process. Thus each step is monitored and managed by different companies and corporations (Energy Exchange, n.d.). Furthermore, as many other systems rely on the electricity to operate, simple failures in the power supply chain can cause widespread impacts. For, example, a loss of electricity can stop traffic lights, which cause congestion, making workers late to work, which then disrupts businesses operations (Rinaldi et al., 2001). Losses such as these often occur as a result of lifeline damage, as the damage prevents the systems from functioning correctly.

2.1.1 Lifeline Damage

Unfortunately, in disasters such as earthquakes, lifelines are often damaged, leaving many people and businesses stranded. For example, the Marmara Earthquake in 1999 caused blackouts throughout Western Turkey for several days because of failures to 7% of transformers, 30% of underground electrical cables, and 6% of large transmission towers. Water was also unavailable for an extended period due to damage to the pipe network (Unen, Karaman, Sahin, & Elnashai, 2010). Additionally, the Tohoku Earthquake and Tsunami in 2011 caused havoc throughout Japan, cutting off 2.3 million homes across 187 towns, from water. This loss of water was caused by damage to several kilometres of distribution pipes and multiple treatment plants (Kazama & Noda, 2012). Closer to the coast, infrastructure damage was more extensive, where roads and railway lines were unusable, making the transport of needed resources, such as food and petrol, difficult. For up to two weeks after the quake, helicopters were the only form of transportation along these coastal routes (Mimura, Yasuhara, Kawagoe, Yokoki, & Kazama, 2011).

Another example of damage to lifelines creating problems was the 1999 Chi-Chi earthquake in Taiwan. Lifeline failures included damage to water intake systems, an 18000-ton storage pool, primary water supply bridges, purification plants, distribution pipelines, and wells, leaving multiple municipalities without any water. Furthermore, shaking, liquefaction, and lateral spreading in the Northridge earthquake in 1994, produced more than 1400 breaks on the water pipes, and multiple failures to gas lines (Trifunac & Todorovska, 1997). Additionally, in 2005 Hurricane Katrina in caused substantial damage to cities throughout Louisiana and Mississippi. As a result of failures to protective levees, 80% of New Orleans was covered with water, making the use of roads practically impossible (Belanger, 2013). Due to widespread flooding, emergency services had difficulties reaching those in need. In addition, many of the pre-assumed communication mediums were out of commission, prohibiting effective and efficient coordination of the multiple organisations involved in the response (Cole et al., 2015; Levitt & Whitaker, 2009). Overall the loss of both road access and communication, lead to a much more severe and catastrophic disaster, forever known as one of the worst social disasters in the developed world (Cole et al., 2015). Finally, as a result of the extensive damage to the wastewater pipes in the 2010-2011 Canterbury Earthquake Sequence, tens of thousands of people in Christchurch were not able to use their own facilities for at least eight months (Eidinger & Tang, 2012). Overall, these instances are only a few of the countless examples, where lifeline damage caused significant problems.

2.1.2 Impact on People

Extensive damage to lifelines, like the previous examples, can cause significant impacts on individuals, as seen in the aftermath of disasters such as Hurricane Katrina. Every lifeline is essential for the survival and well-being of people. For example, communication, as described briefly in the previous section, is needed for relief coordination, and for the individuals to reach family members, understand what is going on, and where to go to get help. Poor communication and pre-planning for disasters can increase the impact of these natural hazards (Marra, 1998). For example, insufficient coordination and communication around the 2010 Tsunami in Chile, lead to a poorly initiated evacuation and emergency response. This poor response was one of the many factors that resulted in the death of around 500 people (BBC News, 2015). Five years later a similar event occurred in Chile, but

due to improvements in many areas including communications, the evacuations were much more successful, and the death rate was far lower (BBC News, 2015; Franklin, 2015). Water is another necessity for life. Without potable water, people start to become dehydrated and in extreme circumstances, die (Gleick, 1996). Sickness can occur if sanitation is not maintained, especially if there are difficulties with the wastewater network. For example, due to damages along the sewage pipes in the Christchurch earthquakes, raw sewage was spewed directly onto properties and into local rivers for months, producing contamination problems and unusable waterways (Eidinger & Tang, 2012).

2.1.3 Impact on Businesses

In addition to the adverse effects on the individual, the loss of lifelines can be very significant to local businesses. Many companies, particularly small, single location organisations, struggle after disaster events as they are unable to open until lifelines are restored (Lam et al., 2009). This struggle occurs because by law businesses must be able to provide basic amenities to their staff and their customers (Health and Safety at Work Act, 2015; Occupational Safety and Health Act: No. 1915.88, 1970). Furthermore, lifelines must be restored for the business processes to operate in the first place. For example, power must be restored to be able to run basic equipment and safety gear. Additionally, for a strong customer base, the site must be easily accessed. If road conditions and transport links are unusable, then the business is likely to fail (Lam et al., 2009; Orhan, 2014).

In the aftermath of the Christchurch Earthquakes, many businesses struggled, due to road closures. For example, 6000 businesses were unreachable in the months following the quakes, due to the central business district (CBD) cordons (Chang et al., 2014). Furthermore, many businesses lost customers once the CBD cordon had been removed, as localised barriers around damaged buildings that disrupted transport routes and walkways remained. Thus, to survive, many businesses relocated to areas outside of the CBD (Chang et al., 2014). However, this relocation did not come without its problems. For example, the CBD cordon only allowed limited access for owners to do things such as building inspections, removal of important documents, and turning off water valves. No stock or large items could be extracted until the cordon was removed. Additionally, those that moved found it tougher to operate, as new locations were too far from the original customer base, had smaller customer pools, had less storage space, and had fewer available

staff (Kemp, Chan, & Grimm, 2013). Some businesses did thrive in their new locations. However the vast majority struggled, and if given the option wanted to shift back to more central locations (Kemp et al., 2013).

One of the biggest influences on businesses after an earthquake or natural disaster is the shift in the market (Alesch, Holly, Mittler, & Nagy, 2001). These shifts occur because of infrastructure damage, losses or gains in competition, alterations of the surrounding environment, and changes to people's individual needs. For example, after an earthquake, the demand for scientists, builders and tradespeople may increase, while the demand for administrative, educational, or health care roles may reduce (Lam et al., 2009). As Alesch et al. (2001) state, businesses that do not adapt to these new changes fail, as the new change becomes the next norm.

Overall, the longer the company remains closed, the more likely it is to fail, especially when the business is small and in a single location (Waugh, R Brian Smith). This failure can be very detrimental to the local community as potential employment, useful local products, needed services, and culture are lost. In extreme examples, the loss of these smaller businesses can lead to a loss of critical mass necessary to sustain urban environments, as businesses are never replaced (Waugh, R Brian Smith). It is clear that businesses are important for the local community and economy, relying on all four mentioned lifelines to operate. Each of these lifelines can be damaged in a natural disaster, thus can have a significant impact on the functionality of businesses. This relationship can also include the lifelines themselves through interdependency, where the damage of one influences the other (Rinaldi et al., 2001).

2.2 Interdependency Between Lifelines

As touched on briefly, no lifeline acts in isolation. For example, to fix water pipes, both road access and electricity is required, where power is necessary to run the pumps that pressurise the water for supply and inspection, and road access is essential to reach and transport the needed resources to broken sections (National Institute of Standards and Technology, 2016a). This relationship does not flow in one direction, in fact, each lifeline relies on each other. For example, electricity is also required to power road lights, traffic lights, and petrol stations. The power network also relies on these petrol stations to fuel repair and maintenance works, producing a circular relationship, or interdependency. This interdependency

between lifelines can lead to failures that span across a large area, where locations nowhere near original event are affected by cascading failures (O'Rourke, 2007). The paper by Rinaldi et al. (2001) attempts to understand these complex relationships by investigating how the interdependency between lifelines functions in general. The investigation revealed four different types of interdependency, 1) physical interdependency, such as the reliance of lifelines on each other for function, 2) cyber interdependency, which is the need for information flow, or automated communication, 3) geographic interdependency, where the lifelines are dependent on each other due to proximity, and 4) logical interdependency, where there are non-tangible links such as, economic, political, or societal connections. Rinaldi et al. (2001), then further discusses the different dimensions of lifeline interdependency, shown in Figure (2.1).

To understand and apply these different dimensions, an agent-based complex adaptive system approach (CAS) is used. Agent-based CAS, treats different parts of the lifelines as agents who can communicate, integrate with each other and carry memories, acting as a system that can adapt, rather than just a static group of objects (Business Dictionary, n.d.). CAS approaches are instrumental in understanding how lifelines interact with each other and provide great insight around how the systems act. However, due to the countless inputs that occur in real life situations, they cannot correctly represent reality.

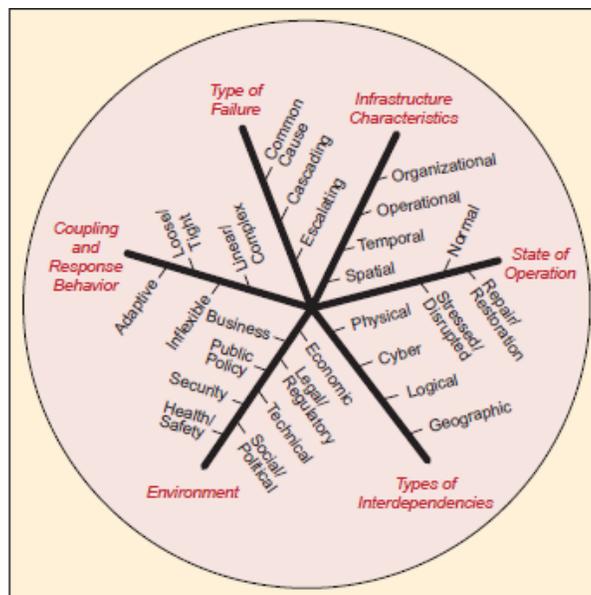


Figure 2.1 The six dimensions of lifeline interdependency. Image copied from Rinaldi et al., (2001) pp 12 with permission from IEEE, Copyright © 2001 IEEE.

Many of these numerous inputs are discussed by Duenas-Osorio (2005) and include social, economic, technological, and political factors. The aim of the study by Duenas-Osorio (2005) was to understand the flow of information from one network to another to create a mathematical model that can be used for loss estimation. Relationships between different sectors are explored statistically, focusing on how information travels from one area to another. Different structures were created to represent the flow of information, such as the simple grid, made of evenly spaced connectors and nodes; small clusters, representing the movement of information through social media or the internet; and a dendritic pattern, with a primary route and multiple branches. Secondary and tertiary, effects are also included in the mathematical analysis. For example, Duenas-Osorio (2005) discussed the impact that earthquakes have on the road networks, which affects the transportation of oil, which slows down and delays flights, affecting how many businesses function. Different mathematical relationships between infrastructure were explored using different vertex removal techniques to replicate damage moving through each system. It was found that different lifelines fit different vertex removal equations better. For example, some, like the water supply, have delayed cascading failures, while others are more immediate. Overall the study gives a very comprehensive view of the interdependencies between lifelines, and how they affect the downtimes after an earthquake.

What is missing from Duenas-Osorio (2005) and many other studies that address interdependency, are location specific factors. These site-specific factors can have a huge impact on the way systems behave. For example, water pipe damage in Christchurch was much more significant than expected due to the severe liquefaction (Cubrinovski, Hughes, & O'Rourke, 2014; Eidingner & Tang, 2012). Furthermore, location-specific influences can slow down inspection and repair processes. A good example of this effect is how liquefied sediments blocked the wastewater pipes after the 2010-2011 Christchurch earthquakes. These blockages, made the inspection process much harder, as the debris had to be removed before cameras could inspect the pipes, significantly slowing the entire inspection process (SCIRT, 2011). Additionally, Duenas-Osorio (2005) attempts to understand both the tangible and intangible impacts from a purely mathematical perspective, assuming everything, such as social factors, can be explained simply through mathematics,

missing the critical complexities of social inputs that a qualitative analysis would provide.

Understanding lifeline behaviour is especially challenging when including site-specific factors, as each region is unique in layout and geology, making universal trends practically impossible. Thus, local case studies like Lee, Kelly, and Poland (2014), are critical for understanding lifeline behaviour. Lee et al. (2014)'s report focuses on lifeline resilience and interdependencies around San Francisco, from the perspective of ten different stakeholders that work with lifelines on a daily basis. Each stakeholder provided insight around the everyday hassles and problems of maintaining each network, giving unique perspectives that are immeasurably useful in understanding the complex relationships between lifelines. In addition to these views, a short geological and geomorphic study was completed around San Francisco, creating risk maps that highlight the most at-risk areas. As a result of the investigation, it was found many critical vulnerabilities needed to be addressed in and around San Francisco. For example, it was expected that after an earthquake, the streets would become difficult to navigate, preventing access to essential water and gas valves, making repair and resource loss management difficult. Furthermore, gas line failures would create fire risks, and breaks to the water supply network would inhibit firefighting abilities, leaving the city vulnerable to fire. Therefore, multiple different mitigation measures that focused on the coordination and planning between the various stakeholders were suggested. For example, the creation and use of a table-top exercise. Unfortunately, the report fails to back up many of its claims with data. Instead, it bases most of its conclusions on expert opinions. Thus, it is hard to quantify the significance of each factor raised on lifeline performance. However, the overall picture produced by this report is very useful in understanding the relationships between different lifelines in San Francisco and provides an understanding that can be loosely applied elsewhere.

2.3 How Local Contextual Factors Affect the Accuracy of Predictive Models

Most of the studies in this section provide a comprehensive understanding around lifeline interdependency. Both Duenas-Osorio (2005); Rinaldi et al. (2001) provide well thought out perspectives on interdependency in general. However, both ignore local site-specific factors that can have significant effects on how lifelines behave, and thus the potential damage state in an earthquake. Lee et al. (2014)

address these site-specific factors by combining local expertise with geological maps. However, in doing so, Lee et al.(2014) miss the crucial mathematical element of damage prediction, only giving postulated damage estimates. Finding a balance is therefore important. One report, the National Institute of Standards and Technology (2016a, 2016b) report, does manage to find this balance. However, since site-specific factors can have a significant impact on how lifelines behave in a disaster, and because each district contains different contextual factors that need to be accounted for, this report constructed in the United States, cannot be used in a New Zealand context.

The National Institute of Standards and Technology (2016a, 2016b) reports are very comprehensive, where not only the potential damage to the lifelines is explored, but also the impact to the community as a result. Many different avenues are investigated where the lifelines are broken down into their working parts, and the relationship between these parts and other lifelines are examined. The impact of interdependency is also explored, where the effects of other lifelines on the repair and restoration times are discussed. In addition, the various roles of different organisations and their influence on the recovery and response estimates are investigated. Finally, information on how the local community fits into the response and repair phases are explored, where the impact on the local community is described. In general, the reports provide a very comprehensive understanding around the possible implications of a disaster.

2.3.1 How the Locational Setting Affects the Calculations.

Unfortunately, because of the previously mentioned localised contextual factors, these reports cannot work effectively outside of their intended context. For example, the impacts to the community and infrastructure would be different in other countries, like Chile, Indonesia, Nepal, or New Zealand, as they have different environments and vulnerabilities. For example, New Zealand is a small island nation that resides on top of a plate boundary, resulting in rapid mountain building, earthquakes, and volcanic activity (Cooper, 2008). It is home to around 4.5 million people, of which less than 1% live under the international poverty line (UNICEF, 2013c). Nepal is a landlocked country located next to a plate boundary which is responsible for the Himalayas, the tallest mountain range in the world (Marshak, 2008). It is home to 24 million people, 24% of which live under the international poverty line (UNICEF, 2013b). Chile is a long and thin coastal country that resides in

one of the most seismically active areas in the world. Over the last 110 years the region has experienced ten destructive Mw 8-8.5, and three very damaging >8.5 Mw events (Melgar et al., 2016). It is home to around 18 million people, 1.4% of which live below the international poverty line (UNICEF, 2013a). All three of these countries have experienced significant earthquakes in the last few years, each of which lead to very different results. The 2012 Mw 6.3 Christchurch earthquake in New Zealand caused 181 deaths and NZ\$20 billion of damage. The 2015 Mw 7.8 Gorkha Earthquake in Nepal lead to 8,510 deaths and US\$10 billion which is more than half their the annual GDP. Finally the 2015 Illapel earthquake in Chile caused 13 fatalities, and a predicted US\$50 million of damage (Cubrinovski et al., 2015; Goda et al., 2015; South, 2016; Vervaeck & Daniell, 2015). Therefore, understanding and working with calculations that take into account the local context is important when predicting the impact of a future event.

Unfortunately, despite the risk of natural hazards in New Zealand, there are not many New Zealand studies or models that look in-depth into local impacts, and interdependencies like the National Institute of Standards and Technology (2016a, 2016b) reports. There are however regional reports, such as Auckland Engineering Lifelines Group (2014) & Mowll (2012) reports that address the potential damage to the various lifelines from a geological and engineering perspective, and countless studies that focus on single lifelines such as Cousins (2013); Cubrinovski et al. (2015); O'Rourke et al. (2014); Sherson et al. (2015); Zare (2012). However, there are almost no studies that look in depth at both site-specific influences and interdependence. Those that do are either still in development, or are very simple and focus on small noncomplex regions.

2.4 Models that Incorporate Lifeline Interdependency in a New Zealand Context

Presently GNS Science and the National Institute of Weather and Atmospheric Sciences (NIWA) have been working on a piece of software called RiskScope. The purpose of RiskScope is to be a useful tool in predicting damage and managing information, as well as a valuable tool for mapping the losses of multiple different assets and lifelines at the same time (GNS Science & NIWA, n.d.). This project has been in construction for many years and is continually being worked on and improved. In tandem with this project is the extensive research on the interdependency between lifelines in a New Zealand local context, with the aim of

creating multiple models that can accurately predict damage and down times for lifelines that depend on each other. These new models are currently a proof of concept but will improve with time and further research. One of these models is Buxton and Pringle (2014)'s CAS study, which tests the accuracy of a new CAS model in mapping the interrelationships between pipes, cables, transmission stations, and pumps. In the study, four different damage scenarios are run, each with a different degree and location of damage. Each scenario is run through 11 time cycles, where the function status of the lifelines is observed. It was found that the CAS approach works well for understanding how multiple networks respond to disaster events in small scale. This model works well because it produces expected and realistic results, such as the water supply being dependent on upstream pipes and key crossover points such as pumps. However, the CAS approach is difficult to apply in more complex and realistic situations that involve vast networks, as adding more agents increases computation times exponentially (Buxton & Pringle, 2014). Furthermore, the CAS approach is limited to modelling the interdependency in only one format, missing the important factors from other perspectives, such as geographical or cyber interdependency (Rinaldi et al., 2001). Also, the current CAS model does not include secondary impacts such as road closures preventing water pipe repairs by stopping external aid from reaching damaged sections. The primary focus of the interdependency in this report is one direction, in which water is reliant on electricity. There is no mention of any flow in the opposite direction, such as the dependence of power supply on water. Therefore the model has not adequately addressed interdependency, as interdependence is multi-directional (Rinaldi et al., 2001). This backwards flow of water to electricity is discussed in a sister paper by Buxton (2013) where the Bayesian Belief Network model (BBN) is used to explore interdependence. However, this article also misses secondary aspects, only focusing on direct relationships between lifelines. Despite their shortfalls, CAS models do provide a useful understanding around how systems interact with each other, and may eventually improve as technology and computational power allow the inclusion of more complex interactions. Overall the various models in New Zealand need improvement. One area that particularly needs resilience models is Wellington, due to its vulnerability and lifeline placement.

2.5 Wellington Situation

The Wellington Region is located at the southern tip of the North Island in New Zealand and is composed mainly of greywacke that has been uplifted by multiple faults driven by the adjacent subduction zone between the Pacific and Australian plates. (Begg & Johnston, 2000). Five of these faults, the Wellington, Wairarapa, Ohariu, Wairau, and Shepards Gully Fault, are active and pose a threat to the region (Fig 2.2) (GNS Science, n.d.-b).



Figure 2.2 Major faults in the Wellington Region. Copied from GNS Science (n.d.) with permission from GNS Science.

Of the five faults, a rupture along the Wellington Fault would have the highest impact to Wellington due to its proximity to urban centres and possible magnitudes. In a realistic worst case scenario, a Mw7.2-7.5 earthquake would hit the heart of Wellington City (GNS Science, n.d.-a; Rhoades et al., 2011). As a result, widespread damage throughout Wellington, costing NZ\$20 billion, would be expected, where significant damage to infrastructure and the various lifelines would isolate Wellington City from the rest of the country for at least four months, and cut water supply off for at least two to three months (Mowll, 2012; Stewart, 2012). The majority of damage would be caused by fault offsets, liquefaction and accompanying landslides (Mowll, 2012). Thus, significant damage can be expected,

as the Wellington fault crosses through the centre of Wellington, along State Highway 2, and through the Hutt Valley (Fig 2.2). Overall the Wellington region would experience high degrees of shaking, up to 10 on the Modified Mercalli scale, which is associated with widespread land sliding, liquefaction, and building collapses (Dowrick, 1996; Nayerloo & Cousins, 2014).

One of the difficulties in the aftermath of a Wellington event would be the restoration of water supply to Wellington City. Wellington City receives water from four different sources, Wainuiomata, Kaitoke, Waterloo, and Gear Island, all of which transport water across long distances and through landslide prone corridors (Fig 2.3). The Wainuiomata system collects water from the Wainuiomata and Orongorongo Rivers, where it is then treated and piped to Hutt Valley and Wellington City, supplying around 20% of the entire region (Wellington Water, n.d.). The Te Marua Treatment Plant in Kaitoke collects and treats water from the Hutt River, supplying Porirua, Upper Hutt, and Wellington City with water, reaching about 40% of the Wellington Region (Wellington Water, n.d.). Finally, both Waterloo and Gear Island draw water from the Waiwhetu Aquifer in Lower Hutt where water is drawn from multiple different wells. Generally, only Waterloo is active, as Gear Island is only turned on in emergencies or when the Waterloo station is shut down for maintenance (Nayerloo & Cousins, 2014). Overall the wellfields supply water to about 40% of the region (Nayerloo & Cousins, 2014).

Unfortunately, the pipes used for transporting the water from each source cross the Wellington fault at least two times before reaching Wellington City (Fig 2.2 & 2.3). Thus, because a Mw7.5 earthquake is expected to produce at least 5m horizontal and 1m vertical offsets along the fault, each water source is expected to fail (Mowll, 2012). Furthermore, as the pipes lie in landslide-prone regions, the pipes could be unreachable for an extended period of time. The recent 2016 Mw7.8 Earthquake in Kaikoura is a good example of these potential impacts, where the main route north of the Kaikoura has been, and is still cut-off by multiple large landslides, ranging in size from 3000m³ to 110,000m³ (New Zealand Transport Agency, 2017). Landslides of a similar magnitude can be expected to occur along State Highway 1 and 2, the only road routes in and out of Wellington, where it is assumed that both highways will be unusable after a massive earthquake (Fig 2.4) (Mowll, 2012).



Figure 2.3 The Wellington City bulk water pipe network, with the four water sources and final destination, the Karori Reservoir, represented by stars. The predicted liquefaction severity hazard, extracted from the Excel Spreadsheet (Section 4.2.2), is used to show which pipes are included into the model.

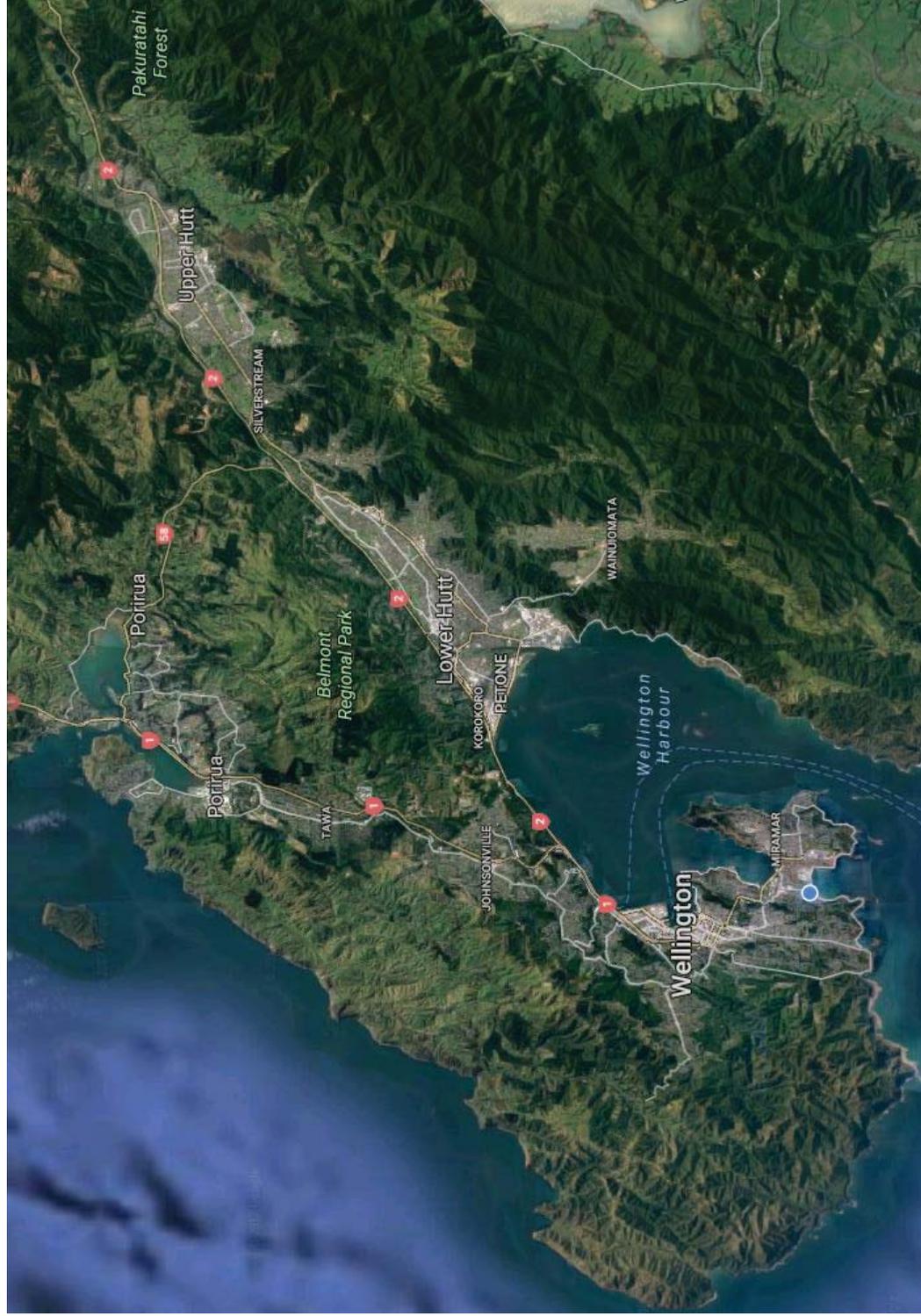


Figure 2.4 Map of the Wellington urban centres. State Highways represented by red labels and yellow lines. Map from Google (2017).

2.5.1 Landslide Hazards

To understand these risks in more detail, Hancox and Perrin (2010), investigated all potential landslide sites along State Highway 1 and 2 and determined the possible direct impact of each on the water supply. Multiple landslide sites were identified through aerial photography and expert opinion, focusing attention on previously prone sections. The possible direct effects from each potential site were explored, focusing on two main scenarios: 1) dropouts, where the supporting rock is removed from below the pipe, and 2) direct damage to the pipe from falling debris. In total, 9 out of 36 different potential landslide sites investigated, involved possible direct damage to the water supply, where two locations were identified to be prone to falling debris, and seven to dropouts.

Unfortunately, not all potential landslide sites were discussed in depth, as the focus of the report was on the larger and more impactful ground deformations. Furthermore, it is assumed that the non-exposed pipes would not be directly impacted by a landslide. Instead, it is assumed that the pipes would be simply buried by more debris, and therefore would not need any remedial or mitigation measures. This conclusion may be correct as unexposed pipes are not likely to be damaged by the landslide directly. However, it misses the potential problems burial creates. For example, large slips can 1) completely cover pipe earthquake damage, 2) close transport routes that are required to access the pipes, 3) make access to critical shut-off valves, or pump stations difficult, slowing or halting the inspection process, and, 4) temporarily stop the movement of outside aid and equipment into Wellington (Mowll, 2012; Zhao, Cousins, Lukovic, & Smith, 2008). These processes are not directly related to the damage of the pipes themselves but do substantially alter how the damage is fixed. Thus, although there may be no direct impact from the landslides themselves, these secondary and tertiary effects should be included in the decision of whether mitigation is needed. In addition, to produce accurate prediction models, the potential damage to other lifelines such as the transport network must also be included.

2.5.2 The Impact of Damage to Other Lifelines

To understand the impact of water pipe damage in Wellington, the potential failure of other lifelines and their impact on the functionality of the water supply pipes must be fully understood. This understanding involves investigating how much of

an effect each lifeline has on the water pipe repair process. Since the water supply pipes closely follow the main transport routes and depend on the carriage routes to access the pipes, the transport routes can be considered necessary. However, despite their importance, there are only a few road damage prediction models available throughout literature. Penjamani et al. (2011) is one of these and attempts to bridge this gap by creating a new road damage measure termed the 'Road Damage Scale' (RDS). RDS aims to replace the MMI scale, as MMI does not accurately model road damage sufficiently, especially when using instrumental MMI. This lack of accuracy is because, 1) road damage is highly determined by surface geological influences such as landslides, liquefaction and lateral spreading, and 2) because the MMI scale was created for modelling point sources such as buildings, not continuous networks like roads (Penjamani et al., 2011; USGS, 1989). To create the RDS model, a selection of 35 damaged road segments, from 21 different earthquakes events were studied in depth, and a 5-tier damage scale was constructed to represent the range of observed damages. This observational damage model was then linked with epicentre distance (ED) event magnitude. In the construction of the model, 18 different equations were considered, that looked at various combinations of magnitude, ED and observational damage. Only four of the best-fit equations were further considered. All four equations represent the earthquake damage well, with acceptable R-squared values of above 0.7. However, these equations do miss localised impacts that can significantly increase damage, as both land sliding and liquefaction effects were not included in the model. Instead only the magnitude and epicentre distance are required to determine RDS. Thus the model would not work in regions that are prone to landslides and liquefaction, like Wellington, where some roads may become redundant due to local landslide (Hancox & Perrin, 2010; Mowll, 2012). Furthermore, there are many assumptions made in the study around how data is grouped, that may not be correct. Overall, however, the model provides a good understanding of road damage outside of localised effects.

In contrast to the transportation network, only a brief amount of research was conducted for electricity, telecommunications, and wastewater, as each fall outside of the scope, because of time constraints, and because they are not essential for repairing the water supply. For example, both wastewater and stormwater pipes, although necessary for sanitary and flood control reasons respectively, are not

critical to the short-term restoration process of the water supply, shown by the fact water pipes are usually repaired before the wastewater pipes in earthquake events (Sherson et al., 2015). Additional damage from co-location can also occur, but a functional wastewater system is not required to restore water supply to customers (National Institute of Standards and Technology, 2016a). The electricity supply is different as it is necessary for restoring water, as both the water treatment plants and pumps require power to operate. However, due to fast restoration times and commonly available generators, the need for electricity is no longer significant in the short term (Massie & Watson, 2011). Finally, due to the numerous telecommunications mediums, it is expected that communication will still be possible after the event, and thus not an essential requirement for the restoration of the water supply network which as discussed is very important for individuals and businesses and is vulnerable in Wellington due to its location along vulnerable corridors.

2.6 Factors that Determine Pipe Damage

As literature discusses, lifelines like the water supply are prone to being damaged in an earthquake, specifically from larger permanent ground deformations that occur in severely hit, or easily susceptible regions. According to O'Rourke et al. (2014); Sherson et al. (2015) water pipes that are affected by liquefaction and lateral spreading are between 3 and 30 times more likely to be damaged than those not affected by liquefaction. This increase is a result of the large vertical and horizontal displacements that occur when the ground liquefies. These displacements produce significant tensional and extensional forces that focus on weak joints, causing pullouts and breakages (Cubrinovski et al., 2011). A good example of this increase in damage is the spread of pipe breakages in the 6.3 Mw February Earthquake in Christchurch, where pipe damage was much less severe in the southern suburbs than in the Residential Red Zone, despite being closer to the epicentre (Sherson et al., 2015). Overall, the pipes that were mostly affected by this increase were those that were not able to flex and cope with the permanent ground deformations.

2.6.1 Pipe Attributes

Non-ductile materials like galvanised iron and asbestos cement commonly have break rates that range from two to more than ten times the break rate of their more

ductile equivalents, as they are brittle and can't flex (Sherson et al., 2015). Diameter is another factor that affects pipe resilience, where pipes with smaller diameters are more susceptible to both shaking and liquefaction. Furthermore, the age of the pipe affects the strength of the pipe where corrosion and weak regions may start to develop, leading to higher break rates (Nayyerloo & Cousins, 2014; O'Rourke et al., 2014; Sherson et al., 2015). Additionally, the joint type can completely change how a pipe behaves, where strong materials like steel, outside of extreme ground conditions, can have break rates that are as high as 0.1 breaks per km (Nayyerloo & Cousins, 2014). However, despite the impact of joint type on the resilience of the pipe network, many studies have not incorporated it, unlike material type, age or diameter.

Throughout the literature, the joint type is either classified in only a few broad categories or is left out entirely. This treatment of the joint type is a problem as around 50% of all failures occur at the join (Cubrinovski et al., 2011). Often joint type is left out because it is very rarely included in local stakeholder or Council databases, making it difficult to make accurate conclusions about the damage. For example, when compiling damage data from Christchurch in Sherson (2015), the joint type had to be assumed based on material type and what joints were commonly used by that material. By not understanding the influence of different joint types, the information extracted from Christchurch could be strongly skewed. For example, many of the Asbestos Cement pipes that failed in Christchurch could have failed as a result of weak joints rather than the material itself (O'Rourke et al., 2014).

2.6.2 Further Difficulties and Complexities Learnt from the Christchurch Earthquakes

In addition to the challenges in not knowing the joint types and not being able to model their impact, Christchurch experienced significantly more severe liquefaction than originally anticipated for the various local soil types (Cubrinovski et al., 2014). As S. Cox (Personal communication, February 23, 2015) explains this exaggerated liquefaction is an outcome of the behaviour of the various shallow artesian aquifers that lie under the city. During and after the earthquakes, the artesian aquifers lost water to the surface, because the liquefied sediments could no longer contain the water pressure. As a result, the pressurised water rose to the

surface, eroding the nearby soil and silty sediments, creating sand boils at the surface, and empty pockets underground which lead to uneven settlement (S. Cox, Personal communication, February 23, 2015)

Further complexities around modelling damage from the Christchurch Earthquake Sequence arose from the fact that multiple large earthquake events occurred close together. These were the February, June, and December 2011 events. Because of their proximity, identifying which earthquake caused what damage was difficult, especially for the non-pressurised wastewater and stormwater pipes as they were not fully inspected for February damage before the June earthquake occurred (O'Rourke et al., 2014). Both Sherson et al. (2015) and (O'Rourke et al., 2014) attempted to solve these inaccuracies by combining the Christchurch results with other studies from around the globe. However, most of these additional data points from outside of New Zealand were from pipes that were made from different materials, lay in various types of soils, had different joint types, functioned at unlike pressures, and were either not influenced by; or experienced liquefaction differently. Sherson et al. (2015) show this difficulty, through the inclusion of only a small section of international data.

2.6.3 Current New Zealand-Specific Damage Fragility Curves for the Water Pipes

The model constructed in Sherson et al. (2015) is a predictive fragility curve that maps pipe damage against shaking intensity. Its primary purpose was to be used as a prediction tool for mapping pipe damage in significant New Zealand earthquake events. The model was created by combining damage information from the Christchurch earthquakes with data from earthquakes around the globe. Data was collected by segmenting the council's pipe network into 20m sections for ease of calculation, which was then spatially joined with shaking intensity and liquefaction maps using GIS software. Contractors notes along with the council's repair schedule were then used to determine when the pipes were fixed, and which earthquake caused the damage. Each data point on the graph represents a different pipe class, based on material type; diameter; liquefaction severity; earthquake event, where the number of breaks per kilometre (break rate) was mapped against shaking intensity in Modified Mercalli Index (MMI). From these points, a nonlinear powered relationship for each pipe class was determined. Unfortunately, due to the limited

crossover of international and Christchurch pipe classes, there were not many pipe classes that obtained regression lines. Of those that received a regression line, most had very low R-squared values, with only 3 of the eight having values higher than 0.7. The (Sherson, 2015) & Sherson et al. (2015) reports, explain that these poor relationships are a result of 1) the uniqueness of the Christchurch Earthquakes, where damage was much higher than expected and thus did not combine well with the international plots. Moreover, 2) because instrumental MMI was used instead of actual MMI, which did not register the influence of liquefaction, creating flat relationships between break rate and MMI. Interestingly O'Rourke et al. (2014) produced much better R-squared values with the same information. However, these regression lines either did not incorporate any data outside of Christchurch or only included a small amount of data. For example, Fig 5 (pp 11), only added three plots from Christchurch to a large pool of international data, and Fig 5 (pp 11) only included one plot from the Northridge earthquake to the Christchurch data. Thus, a significant portion of information was missed. Overall both studies provide an excellent understanding of how water pipes can be damaged by an earthquake, due to the depth of investigation and the questions they ask. Also, many of the limitations and difficulties that arose add insight into numerous factors that need to be considered when mapping damage, such as localised geological effects. However, the models only look at the physical damage of one lifeline, missing the importance of including other lifelines into the calculations, like many of the other local predictive models.

2.7 The Cousins Model

One of the more prominent New Zealand damage predictive models, used for predicting damages in cities such as Wellington, is the Cousins Model, created for predicting building damage from earthquakes (Cousins, 2004). Although created for buildings initially, the Cousins Model can be slightly altered to predict damage to underground water pipes. The paper by Nayerloo and Cousins (2014) unpacks this alternate use, where the model is compared with other fragility curves, such as the ALA model in (American Lifelines Alliance, 2001). It was found that the Cousins Model works well in a New Zealand context, where it precisely calculates pipe damage based on MMI, producing more accurate results than other models like the ALA model, which are built for different contexts. Once the model is established, the potential impacts from a Wellington Fault earthquake are discussed, where the

repair times to each reservoir are explored. Overall, the paper aims to calculate the magnitude and length of post-earthquake water shortages by combining repair times with the volume of stored potable water.

Emergency water supply is the focus of the paper, where shortfalls are calculated in multiple different ways. The paper begins by discussing the Wellington setting, including the various fault lines, possible placements for alternative water sources, vulnerable assets, and possible earthquake scenarios. Once the setting is established, the amount of water available after an earthquake is calculated, by measuring the volume of water stored in hot water cylinders, reservoirs and personal emergency supplies. Water shortages are then estimated by calculating how long it takes for each reservoir to empty from daily use. Two different consumption rates, 6L and 20L per person per day, and three reservoir volume retention percentages are used to understand the various situations that can occur (Fig 2.5). Overall it was predicted that most people would be without water within 20 to 80 days depending on the consumption rate and the volume of water retained in each reservoir.

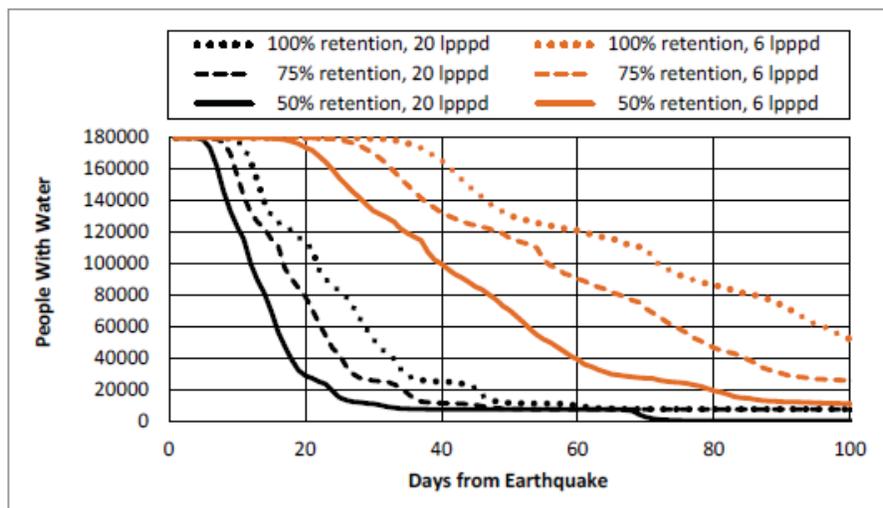


Figure 2.5 Stored water depletion rates after a strong earthquake in Wellington. Figure copied from Cousins (2013, p. 19) with permission from GNS Science.

Once the shortfalls are estimated, the potential damage to the pipes is then calculated using the equation below

$$RR = K1 \times K2 \times K3 \times K4 \times K5 \times A \times 10^{\left(\frac{B}{MMI-C}\right)}$$

Eq 2.1. Equation copied from (Cousins, 2013, p. 104) with permission from GNS Science.

Where RR stands for repair rate, K1 to K5 the pipe material, joint type; pipe diameter; and geological hazards, MMI the amplified Dowrick and Rhoades MMI, and A; B; and C fitted constants (Table 2.1).

Most often K1 to K5 have the value “1”. Alternate numbers are only used when the pipes are made of brittle materials like cast iron, are old, have small diameters, lie in liquefied soils, or are located in landslide-prone regions (Table 2.1). For example, the repair rate for a cast iron pipe with old joints in moderately susceptible soil to liquefaction is calculated by the following equation.

$$RR = 2 \times 2 \times 1 \times 1 \times 3 \times A \times 10^{\left(\frac{B}{MMI-C}\right)} \quad \text{Eq 2.2}$$

Table 2.1 The different multipliers used to alter damage calculations. Table copied from Cousins (2013, p. 99) with permission from GNS Science.

| Factor | Name | Conditions | Value |
|--------|----------------------------|----------------------------------|-------|
| K1 | Pipe Material Factor | Cast-Iron | 2 |
| K2 | Coupling Age Factor | Couplings more than 50 years old | 2 |
| K3 | Size Factor | Diameter < 400 mm | 4 |
| K4 | Landslide Hazard Factor | Moderate | 3 |
| | | High | 9 |
| | | Very High | 27 |
| K5 | Liquefaction Hazard Factor | Moderate | 3 |
| | | High | 9 |
| | | Very High | 27 |

Dowrick and Rhoades MMIs are calculated through an attenuation model which estimates the probable shaking intensity from a fault rupture based on the fault's type, hypocenter depth, orientation, epicentre location, and mechanism (Dowrick & Rhoades, 2005). Alterations are then made to these initial intensities due to soft soil amplification which increased or decreased the observed MMI based on the soil type (Fig 2.6)

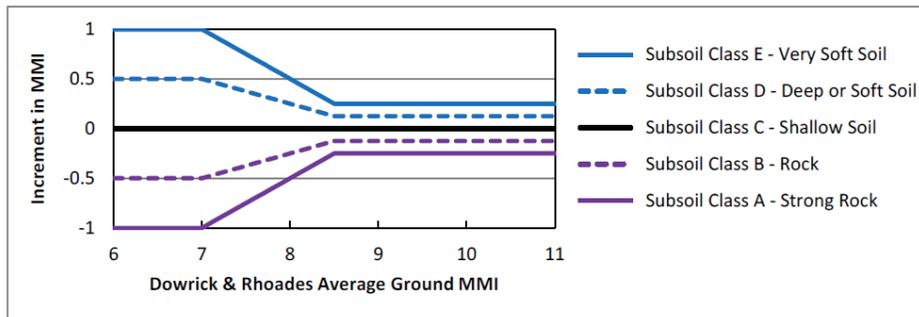


Figure 2.6 Increments applied to the MMI based on soil type. Figure from Cousins (2013, p. 72). Copied with permission from GNS Science.

Once the repair rate is calculated, it is converted into a probability of failure by multiplying by the length of the pipe and dividing it by 1000 to convert the final value into kilometres. Each pipe is then given a random number between 0 and 1. If this random number falls inside the probability, then the pipe is considered to have failed.

Repair times to each reservoir are then estimated by calculating how long it takes to fix each broken pipe that connects the reservoir to the water source. This calculation involves giving each broken pipe a standard time between the maximum and minimum 'pipe repair times' in Table (2.2). Extra time is then added to this base time to take into account the additional time required for the pipe repair crews to secure family and personal situations, planning of the repair endeavour, assembling the necessary materials, prospecting for leaks, and repairing fault crossings. Overall the repair times are calculated by reading off Table (2.2) and adding relevant factors together, considering that multiple repair crews can be used. For example, the Kaitoke workstream 1 and 2 can be done separately, and many faults could be repaired simultaneously as the damage locations are already known without the need for water pressure. Overall, it was concluded that after an earthquake each reservoir would be disconnected from the bulk water supply for 20 to 105 days depending on the region (Cousins, 2013).

Table 2.2 Repair times required for different repair processes. The table is copied from Cousins (2013, p. 103) and Numbers are from McCarthy (2009). The table is used with permission from GNS Science.

| Activity | Item | Estimated Time MIN (days) | Estimated Time MAX (days) |
|--|----------------------------------|------------------------------|------------------------------|
| Kaitoke Work-stream 1 Repair fault break | Secure personal situation | 1 | 1 |
| | Inspection and Planning | 2 | 2 |
| | Assemble plant & materials | 1 | 1 |
| | 300 mm fault bypass at Te Marua | 5 | 5 |
| | Fault crossing at Silverstream | 12 | 17 |
| Kaitoke Work-stream 2 Repair other damage | Secure personal situation | 1 | 1 |
| | Inspection and Planning | 2 | 2 |
| | Repair major damage to headworks | 6 | 6 |
| Whakatikei Other damage | Secure personal situation | 1 | 1 |
| | Inspection and Planning | 2 | 2 |
| | Assemble Plant & Materials | 1 | 1 |
| Pipe Repair Times | Repair to trunk main (> 400 mm) | 2 | 3 |
| | Repair to branch main (< 400 mm) | 1 | 1 |
| Prospect for leaks | Te Marua to Silverstream | 2 | 2 |
| | Silverstream to Judgeford | 1 | 1 |
| | Whakatikei to Judgeford | 1 | 1 |
| Prospect for leaks | Judgeford to Reservoirs | Allow 0.1 day per km of pipe | |

Unfortunately to calculate restoration times many assumptions had to be made. Firstly, it was assumed that each pipe failure would require the same amount of time to repair, where the only distinction was between mains and sub-mains. In addition, no thought was placed on contextual factors such as staff logistics, access, or the time needed for constructing replacement parts. Different extents of damage were considered based on pipe attributes; however, this distinction was not applied to repair times. Additionally, all pipe damage was assumed to be easily identifiable, where a standard damage inspection time was given for all pipes. Access to broken pipes was also assumed, where there was no investigation of possible problems from road closures or access problems from mass wasting processes. Finally, there was no discussion around lifeline interdependency such as the water supply's reliance on electricity. Therefore, downtimes could be very different. Overall, however, despite these assumptions, the paper does provide a very comprehensive discussion on the availability of water in Wellington after an earthquake.

2.8 The Wellington-Lifelines-Group Model

Most studies that research lifeline interdependency at a significant depth do not include the influence of important local influences. For example, they do not incorporate the availability of different resources or repair crews; the impact of different lifeline material types, or physical vulnerabilities; geology; the expectations of the stakeholders involved; secondary or tertiary impacts; and how vulnerable the lifelines are to disasters other than earthquakes. Therefore, there is a desperate need for studies that address these factors. The report by Mowll (2012) discusses some of these issues by combining and summarising work from multiple projects around lifeline damage and repair times in Wellington. The report begins by addressing the potential earthquake threats in Wellington, by factoring in the possible damage from shaking, fault crossings, landslides, and liquefaction. A worst-case scenario perspective of damage to these lifelines is then taken, where it is assumed that some lifelines will always be at risk due to the topography, despite seismic resilience engineering. For example, it is expected that there will be no road access in and out of Wellington for up to 120 days as a result of landslides along state highway 1 and 2. Each lifeline including water, electricity, telecommunications, and gas, is discussed individually, summarising layouts, various vulnerabilities, and direct impacts to the community from a service failure. Final restoration times for different suburbs around Wellington are then calculated for each lifeline and range from 20 to 65 days. The paper then explores different redundancy plans to solve these issues, such as the use of local quarry equipment for the restoration of roads up Ngauranga Gorge, and the use of the airport as a base of operations for the import of food and needed resources. Overall the report is a very comprehensive look at the likely need during and after a natural disaster such as an earthquake, giving a very stable platform on which to base the research for this thesis.

The study by Mowll (2012) does address some of these local influences, but makes many assumptions and misses many things that need consideration. For example, it is assumed that there will be at least one useable lane along transport routes to access water pipes and cables after a significant earthquake event in Wellington. Furthermore, Mowll (2012) assumes that the materials needed to repair each lifeline will be available immediately locally, and then externally within 10- 20 days. In addition, Mowll believes that civil machinery will also be available locally.

However, this ease of access may not occur after a significant earthquake event, as it is highly likely that large landslides, of a similar size those in Kaikoura, will block all routes in and out of Wellington. Therefore blocking access to the bulk water pipes (Hancox & Perrin, 2010; New Zealand Transport Agency, 2017).

2.9 Summary

Water supply pipes are essential for the well-being of individuals, businesses, and the community. People require access to potable water for drinking; cooking; cleaning; and growing crops, and businesses need a direct connection to be able to survive, as they cannot legally or practically function without it. Unfortunately, pipe damage is quite common in natural disasters like earthquakes, and often takes months to repair. In a future Wellington Fault event, it can be expected that the water supply will be not functional for an extended period due to their vulnerability, proximity to fault lines, and residence in landslide-prone corridors. Currently, many of the models that look at the overall repair times in Wellington do not incorporate contextual factors and are rudimentary in their calculations, taking a broad perspective towards the interrelationships between lifelines. For example, most studies do not include the influence of landslides on repair times and road access. Furthermore, a majority of the studies miss the importance of incorporating social aspects like staff logistics. These contextual factors could significantly inflate overall repair times, increasing the time people, communities and businesses are without water. Therefore, to better prepare for, and reduce the impact on individuals, a thorough understanding of these possible contextual impacts is required. Thus, predictive models that incorporate these interdependencies and in-depth site-specific factors are needed.

Chapter: 3 Methodology

The following methodology chapter discusses the possible methods available and explains which methodologies are chosen and why. Firstly, the various research paradigms are investigated, looking at the positives and negatives of each approach, where the overall best-fit perspective is determined. Then the chapter investigates the various suitable methodological viewpoints available within the chosen paradigm. Once the most appropriate research structure is selected, the different methods that can answer the research questions are discussed, where the best and most suitable procedures are selected. Finally, various analysis methods are discussed, where the final chosen approaches are explained in detail.

3.1 Research Paradigm

Firstly, to determine the overarching research approach, a paradigm or research perspective must be selected. According to Wahyuni (2012), there are four main research paradigms: positivism, post-positivism, constructivism, and pragmatism. Each of these paradigms defines truth, and the ways of understanding truth, differently.

3.1.1 Positivism

Positivism sees truth and knowledge as external and objective, being something that can be understood and quantified. Within this perspective, objectivity is necessary, where truth must be determined outside of the researcher's influence (Guba & Lincoln, 1994). To accomplish this objectivity, repetition and large sample sizes are used to filter out biases and outliers, where the most valid conclusions are those that can be repeated by different researchers who get the same results (Creswell, 2014). Through positivism, broad patterns can be identified and easily validated. However, by focusing on general trends, the meaning behind the data and relevant localised information critical for understanding processes like pipe restoration, is missed (Krauss, 2005; Wahyuni, 2012). Therefore, positivism is not a good fit for the study as the research aim is to improve the Cousins Model by exploring these contextual factors and values.

3.1.2 Constructivism

Unlike positivism, constructivism includes local elements and values. A constructivist perspective sees truth as experiential or subjective, where truth is

determined by the context and meaning of what is occurring (Krauss, 2005). From this point of view, no absolute objective truth exists. Instead, 'truth' is relative and different for each individual. Like positivism, some specific methodologies and methods must be used to interpret the environment. For example, most methods focus on people's perceptions and experiences (Patton, 2002). Often researchers embrace the experimental context, inserting themselves into the field to understand the setting. Biases are therefore welcomed and acknowledged instead of avoided (Creswell, 2014). The advantage of a constructivist approach is that detailed information about the context and why things occur can be known (Patton, 2002). This context can be very beneficial, and can often reveal relationships and phenomenon that would otherwise not be known. However, by taking a constructivist approach, no generalisations and trends can be made, as it is seen as inappropriate to apply findings from one context to another (Patton, 2002). This inability to be able to generalise becomes a significant problem when working with large-scale networks such as lifelines which expand for hundreds of kilometres, as it becomes impractical and confusing to look at each section of the system individually. Therefore, constructivism is also not considered as a good fit for the study.

3.1.3 Postpositivism

Post-positivism is a modified view of positivism, where social conditioning is added to the thought process. Unlike positivism, complete objectivity is seen as impossible, and the absolute objective truth is understood through imperfect social lenses (Wahyuni, 2012). Post-positivism agrees with the thought that researchers are biased and will bring their assumptions (Phillips & Burbules, 2000). The disadvantage of post-positivism is that it is still rooted in a positivist perspective, in which absolute objective truth exists, and that only observable data can make valid conclusions (Wahyuni, 2012). As this study aims to investigate localised factors that may not be tangible, post-positivism may not be an appropriate paradigm to take. Furthermore, since post-positivism is still connected to positivism, it cannot effectively bridge the paradigm gap, and bring in two contradicting schools of thought effectively (Wahyuni, 2012).

3.1.4 Pragmatism

Pragmatism, on the other hand, falls directly between positivism and constructivism, taking aspects from each perspective depending on what is the most practical approach available. In a pragmatic paradigm, the truth is based on practicality, rather than by absolutes or individual views. (Mastin, 2008). Truth also does not need certainty or complete understanding, as the closest most practical knowledge is sufficient (Mastin, 2008; McDermid, n.d.). Pragmatism allows for the full use of both positivist and constructivist perspectives, as it is not just an alteration of either paradigm. Furthermore, as truth does not need certainty, conclusions can be made from limited knowledge (Mackenzie & Knipe, 2006). This ability to make conclusions from incomplete information is critical when studying interdependencies between lifelines, as lifeline interdependency can be quite complex to comprehend. This complexity arises because interdependency looks at the interrelationships between two or more already intricate, and vast systems, that by themselves can be difficult to model accurately (Rinaldi et al., 2001; Sherson et al., 2015). Therefore, since the objectives of the study require the incorporation of both perspectives while investigating casual relationships, it can be argued that a more pragmatic view is the best-suited research paradigm. Within this practical approach, different methodologies or research structures that answer the various research questions can then be selected.

3.2 Methodology

Methodology defines the focus, principals, and logic of the research approach, outlining the types of methods used and the data collected (Kothari, 2004). Since a pragmatic viewpoint believes that the most practical method is the best approach, almost any methodology can, therefore, be considered if it effectively answers the research questions (Patton, 2002). For example, with the pragmatic view, contrasting methodologies such as grounded theory, experimental research, and ethnography can all be used individually or in combination, as long as they effectively answer the research questions. Grounded theory is an exploratory approach to research, where natural and emergent patterns define the focus instead of the researcher's preconceived ideas or hypotheses (Willig, 2013). Experimental research, on the other hand, relies on these preconceived ideas, where the investigator aims to prove or disprove hypotheses. In experimental studies, the testing environment is carefully controlled the to identify the behaviour

of specific variables (Kirk, 2009). Ethnography is the study of people and culture, where researchers immerse themselves into the environment to observe the relationships between different phenomena (Creswell, 2014).

Each methodology described above takes a specific approach to the research, collecting and analysing qualitative or quantitative data from a positivist or constructivist perspective. For example, experimental research falls into the positivist paradigm, and ethnography is usually associated with the constructivist viewpoint (Creswell, 2014; Patton, 2002). Most methodologies used throughout literature follow this either-or approach, structuring the research from either a positivist or constructivist perspective. Very few methodologies bridge this paradigm gap, where both perspectives are addressed. Since the aim of the research involves understanding water-pipe repair times from both an empirical and non-empirical standpoint where the influence of people and stakeholders are also included, a methodology that incorporates both qualitative and quantitative paradigms must, therefore, be used.

3.2.1 Mixed Methods

One methodology that ignores the research dichotomy is mixed methods. A mixed methods (MM) approach combines both positivist and constructivist perspectives in a single study, to obtain a broad and narrow understanding (Creswell, 2014). Methods from either view can be conducted in isolation or parallel. For example, a randomised controlled trial can be used in tandem with interviews, surveys can be combined with focus groups, or interviews can be utilised with computer-simulated models. By combining two or more different methods, a better and more holistic understanding is achieved (Bazeley, 1999; Bryman, 2007). Furthermore, MM fits well with a pragmatic perspective as pragmatism also ignores the paradigm dichotomy conflict, bringing together the strengths of both qualitative and quantitative approaches (Patton, 2002).

Unfortunately, MM is quite difficult to define as there is a range of different viewpoints throughout literature with no universal agreement (Johnson, Onwuegbuzie, & Turner, 2007). Furthermore, there are no agreed-upon data analysis methods that can be used, since paradoxical data is combined. To get around these two problems, one definition, Teddlie and Tashakkori's (2006) sequential mixed methods design, will be used for the research (Figure 3.1). Teddlie

and Tashakkori's (2006) definition was chosen as it conducts the qualitative and quantitative methods separately at different times. By carrying out the methods separately, the most practical method for the research can be selected. Furthermore, since the methods are separate, the analysis of the data is much simpler.

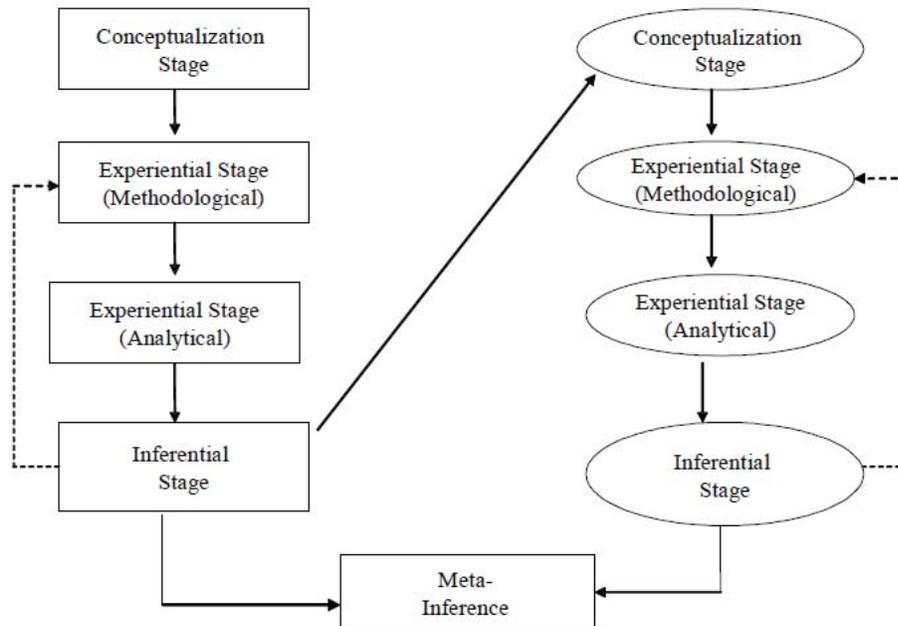


Figure 3.1 Teddlie & Tashakkori's (2006, p. 22) sequential mixed methods structure, showing two integration phases. The first is where one study informs the conceptualisation phase of the other and the second is at the end, during the meta-inference phase. Copied with permission from the Mid-South Educational Research Association.

Each method is then combined through integration. This integration occurs both when one study informs the design of the second, and throughout the discussion where two different research approaches are combined (Teddlie & Tashakkori, 2006). Integration is necessary as it distinguishes between simple studies with a couple of various methods, like a modified survey, and mixed methods studies, which combine two contradictory paradigms (Morse & Niehaus, 2009; Teddlie & Tashakkori, 2006). Overall by using mixed methods as the methodology for this study, different methods that are the most practical for the research can be implemented, giving a more holistic viewpoint that not only fits the pragmatic perspective but more accurately answers the various research questions.

3.3 Methods

The overall aim of the research is to improve current water supply downtime predictions by including the impact of contextual factors in repair time calculations. To accomplish this goal, and to answer the research questions, quantitative information must be integrated with qualitative data. This integration is essential as qualitative information is needed to understand localised contextual factors, and quantitative data is required to be able to calculate water pipe damage patterns and regional water supply downtimes. Neither information type nor method can adequately answer the research questions individually. Therefore, both qualitative methods and quantitative methods will be used in the study. Overall for ease of understanding, and because the methods will be done at different times, the details around the qualitative and quantitative data collection and analysis methods will be discussed separately in the following subsections.

3.3.1 Qualitative Data Collection and Sampling Methods

There are many different methods commonly used in qualitative research. For example, simple observations, focus groups, interviews, and action research are all frequently used throughout literature (Patton, 2002; Tracy, 2012). Observational research involves either etic or emic enquiry where the investigator collects information that they see and experience. Focus groups collect responses from individuals in a group discussion setting. Interviews collect perspectives and responses from individuals separately. Lastly, action research is a dynamic problem-solving method which includes the participants into the research process (Patton, 2002). Each method described can be used to collect valuable information. However, only focus groups and interviews can be used to answer the various research questions as they can easily obtain specific expert perspectives from a range of different companies and organisations (Patton, 2002). Out of the two approaches, Interviews were chosen as they allow for the participation of a larger number of experts, as the participants can answer questions at a time that suits them. Focus groups, on the other hand, require each participant to be available at the same time, which is especially hard when interviewing experts, as they may not have time to meet for lengthy focus group discussions and may be at their busiest at different points of the day. Finally, interviews provide the time for each expert to articulate their knowledge, unlike focus groups where some experts may be more vocal than others.

3.3.1.1 *Interview type*

Throughout literature, there are three common interview techniques: structured interviews, semi-structured interviews, and non-structured interviews. Each approach has its strengths and weaknesses. For example, non-structured interviews are very flexible and can provide detailed information on any topic, as the questions can be completely tailored to each interviewee (Babbie, 2014). By not having any pre-prepared questions, avenues not known by the researcher can be easily discussed, as any question can be asked (Patton, 2002). However, because of this flexibility data analysis becomes difficult as there is no common ground or answers to compare between interviews. Structured interviews, on the other hand, follow pre-planned questions, where everything said by the interviewer is identical for each interview. This strict structure allows for an easy comparison and analysis. However, due to the complete rigidity in questions asked, no probing queries can be used to elaborate on important points (Tracy, 2012). Thus, critical information may be missed. Additionally, as all questions are created before the interview, the direction of the conversation is entirely reliant upon prior knowledge of the researcher, who may not know the best questions to ask (Patton, 2002). Semi-structured interviews, take the advantages of both approaches, where a balance of flexibility and structure is achieved. Questions are prepared, but additional probing questions can be used to explore topics further if needed. Although additional questions are used, each interview still follows a general trend for easy data analysis (Patton, 2002; Sewell, n.d.). As semi-structured interviews take the advantages of both approaches and because they fit well with the exploratory but specific approach of the thesis, a semi-structured approach will be used.

3.3.1.2 *Qualitative sampling*

In addition to the type of interview, the range of participants, and how they are selected are critical to grasp as different sampling methods can significantly alter the outcomes and validity of the results. For example, sampling methods regulate what perspectives are gathered, and what are not, determining whether the collected information is representative of the population (Patton, 2002).

There are multiple ways of selecting participants. For example, people can be chosen randomly, purposefully, conveniently, or through other procedures such as snowball sampling (Biernacki & Waldorf, 1981; Wienclaw, 2015). Random sampling attempts to address this 'bias' as the researcher removes themselves from the

choice (Jadad, Enkin, & Jadad, 2007; Nastasi & Hitchcock, 2016). However, random sampling is not always practical or useful, especially when precise information is wanted from a small population of experts. This is because small sample sizes can produce biased viewpoints that are not representative of the population (Efron, 1971). Furthermore, since there are not many subjects to choose from in the first place, selecting a random sample would further reduce this selection to impractical size. Purposeful sampling, where key people from within the population are selected was also not chosen for similar reasons, as the sample size is once again too small. Instead, a convenience sampling method will be used, where every known expert is contacted. In addition, a snowball sampling method will also be used to increase the sample size further, where each contact is asked for the details of other experts they know. Overall the aim is to obtain a good selection of experts who can provide useful information that can improve the Cousins Model and fulfil objectives 1, and 2. Finally, In tandem with these various qualitative methods, quantitative methods will be used to determine the temporal magnitude of the highlighted contextual factors on overall repair times.

3.3.2 Quantitative Data Collection and Sampling

Many different quantitative methods can be used under the umbrella of mixed methods and pragmatism. Each practice has its strengths and weaknesses in different areas, where each procedure is designed for various purposes. For example, experiments, surveys, secondary data, and computer models can all be used (Creswell, 2014; Will, Bertrand, & Fransoo, 2002). Experiments are useful at identifying the impact from single sources or variables, but they are not good at working with more than one variable in unclear environments and can miss important contextual factors (Morrison, 2001). Surveys are useful for obtaining population statistics, and prevailing social trends. However, they are not helpful for the detailed, in-depth analysis of different variables, as answers to questions are limited. Furthermore, they are prone to low response and confusion where the respondent may misinterpret questions (Visser, Krosnick, & Lavrakas, 2000). Secondary data is useful for the fast acquisition of detailed information that provides additional research viability. However, it is hard to be confident in its validity as the context, and collection methods are often not included in databases. Furthermore, the data may already be generalised (Rabianski, 2003). Finally, computer models can be used to create scenarios or simulations that model reality,

allowing for the study of multiple variables simultaneously. However, computer models can only approximate reality, as they are limited to the number of variables that are included, and cannot predict all possible outcomes (Frenz, 2007). Overall since the aim of the study is to improve predictive calculations that factor in multiple variables, secondary data and computer models will be used, as they are the best and most suited methods.

3.3.2.1 Quantitative Data Sources

Throughout the research, multiple different secondary data sources will be used to develop the computer models. For example, lifeline asset information such as location; type; and vulnerability will be collected from contractors and asset managers, along with local ground conditions such as soil type and liquefaction risk. Additional information such as elevation will be downloaded from open source databases like Koordinates.com. Finally, current damage and predictive restoration models will be acquired from different research organisations and experts known by the researcher, following a convenience sampling method, where the most up to date and easily accessible data will be collected. Information will only be gathered from reputable sources with the aim of gathering information from the primary source, or as close as possible to the original source, to avoid collecting inaccurate data. Thus sampling will not be needed. Various downtime predictive models will form the foundation of the study, providing base calculations and assumptions that can be improved, such as the 'Cousins Model' discussed in Cousins (2013); Nayerloo and Cousins (2014), and platforms to compare the results to such as Mowll (2012). Any new information from the interviews will then be included into these base equations, where the outputs will be noted and compared with literature. However, before any computer models can be constructed or altered, the raw data must first be analysed.

3.4 Data Analysis

As discussed previously, both a constructivist and positivist understanding is required to fully answer the research questions as neither approach can individually address the regional and local contexts simultaneously. Therefore, both a constructivist and positivist investigation is needed. Because the structure of the research follows a sequential mixed methods approach, each method will be conducted separately, where the analysis from one perspective will inform the other (Teddlie & Tashakkori, 2006). In this research thesis, the qualitative

information will be analysed before the quantitative data, where the conclusions from the interviews will inform the alteration of the Cousins Model.

3.4.1 Primary Data Analysis Methods

The analysis of the primary data from the Interviews, can take many different forms, and focus on multiple different aspects. For example, the way things are spoken can be investigated. This analysis method is known as discourse analysis and is useful for understanding language and how it is used actively (Brown & Yule, 1983). Additionally, the narrative or story of what is spoken can be investigated, where individual experiences are explored, focusing on the interpretations, and the context around what is spoken and who is speaking (Herman & Vervaeck, 2005; Patton, 2002). Finally, the content of what is said can be analysed, where information is directly taken from quotations. The latter analysis method is the only procedure that can answer the research questions adequately, as it focuses on the information and knowledge provided directly by the experts. (Leech & Onwuegbuzie, 2008). By using a content-driven approach, like themes can be identified across multiple different interviews, as the topic, not the person is the focus. This identification of like themes will follow a thematic approach, where interviews are broken down into key ideas and similar responses.

3.4.1.1 *Thematic analysis*

Codes will first be developed, to conduct a thematic analysis. As Guest, MacQueen, and Namey (2012) states, there are two different techniques to thematical coding, exploratory or confirmatory. The exploratory approach is content driven, where codes are created from the data, taking an approach similar to grounded theory. Confirmatory techniques are hypothesis-driven, where the researcher uses predetermined codes and assumptions to code the data (Guest et al., 2012). Since the purpose of the research is to identify key ideas and explore avenues not well known by the researcher, an exploratory approach will be used. Once codes are created, the responses with the same codes will be grouped, and a summary table will be constructed. This chart will highlight all the reoccurring and main ideas raised from the various interviews, and summarise the varying perspectives on each issue.

However, like all data analysis methods, content analysis has limitations and biases. One of the biggest biases is the reliance on the researcher for selecting codes based

on how they see the text, which is a version of researcher bias (Johnson, 1997). By relying on the researcher, incorrect conclusions may be reached, as responses from individuals can be taken out of context to fit final inferences better. Attempts will, therefore, be made to be as objective as possible, to reduce this bias, taking everything said by the interviewee with the same weight. Also, each respondent will be given the opportunity to look at these conclusions, to make sure the correct deductions are made.

3.4.2 Secondary Data Analysis Methods

In addition to the interviews, the secondary data will need to be analysed before it can be incorporated into the Cousins Model. As most up-to-date lifeline data is stored in a geospatial format, the analysis of any collected secondary data is quite simple. For example, geospatial information can be analysed through a geographical information systems (GIS) software such as ARC GIS, where lifeline data can be directly downloaded from Council GIS viewers in a compatible format. Once downloaded, soil type, liquefaction vulnerability, landslide hazards, and pipe information can be combined based on location, which means that land conditions can be mixed with pipe vulnerabilities. ARC GIS is one of many different geospatial database and analysis programs available. For example, Bridge, Map Business Online, eSpatial and Tree Plotter along with many others can all calculate and work with spatial data (Capterra, n.d.). ARC GIS was chosen out of this list since most of the information available from the councils is compatible with it; it is commonly used by councils and experts, as it can perform complex analyses; and because it was freely available to the researcher.

3.4.2.1 *Simulations and mathematical models*

After analysing the interviews and secondary sources, key ideas and secondary data will be input into the Cousins Model, which is a mathematical model that uses simulations to predict possible water pipe damage and repair times. According to Will et al. (2002), there are two different categories for mathematical models, axiomatic and empirical quantitative. Axiomatic research takes a normative mathematical approach, with the aim of solving problems by exploring the relationships between multiple variables (Will et al., 2002). The empirical quantitative approach bases the model construction on empirical research and real-life observations, where casual relationships explored with the aim of validating current quantitative models. As observations from the various

interviewees will be used to improve current predictive models, an empirical observational approach fits the research better. Furthermore, the empirical observational approach allows for casual relationships to be explored (Will et al., 2002). By allowing for these casual relationships, a more exploratory “what if...” approach to investigating the repair time impacts can be conducted, where any new avenues that do not have much data can be tested.

There are however many limitations to using a computer simulated method. For example, the quality or validity of simulations is lower than other methods, because models include wide-ranging variables and causal relationships. However, computer models do provide a close approximation, in particular with the continual increase in computing power and more accurate data, maps, and models (Will et al., 2002).

Overall, this research aims to combine multiple different methods that come from a range of different perspectives. As a result, the integration of these methods can be quite confusing and complex. Therefore, the following section seeks to explain how and where each method fits, linking them back to the research questions and objectives.

3.5 Research Design

The research aims to improve the New Zealand repair-time predictive models by determining how much site-specific factors and interdependencies affect the bulk water-pipe repair process (section 1.6). To accomplish this aim, information from multiple different sources will be collected and incorporated into the Cousin’s Model, improving its accuracy. The diagram below, Figure (3.2), shows this overall process outlining what each data source will contribute towards, and briefly expresses how the different sources will be integrated together to address the various research objectives and questions. The following discussion then adds context to this image and gives a short explanation of the overall research design.

Objective one will be met by reviewing the literature (Chapter 2) and the interview responses (Fig 3.2). The investigation of literature, specifically around past earthquake events, will reveal what is required to repair the water pipes. Meanwhile, the interviews will provide first-hand knowledge of the repair process in a New Zealand context, revealing how local work crews fix damaged pipes and the tools and equipment they use.

Objective two will be met through the scrutinisation of the different factors identified in the interviews, the investigation of the interrelationships between lifelines, and the review of probable lifeline damage from an earthquake. Overall the investigation will reveal what should and shouldn't be considered as important, highlighting the key factors that need to be included in repair time calculations.

Objective three, like objective two, will be achieved by reviewing literature, where multiple different studies and damage predictive models for the Wellington Region will be explored to understand how lifelines are likely to be damaged and their state after an earthquake. The results from the original Cousins Model will also be used to obtain a comprehensive understanding of the possible damage from a Wellington Earthquake event.

Objective four will be addressed through the combination of multiple information sources and methods. Firstly, the key ideas identified from objective two will be included in the Cousins Model. This will involve obtaining as much information around these factors as possible, such as quoted times or experiences from the interviewees. These quoted times will then be added to the final repair time calculations, adding or removing time to the final considerations. Secondly, secondary data like geological conditions and additional pipe information such as the alternative water sources not considered in the Cousins Model will then be incorporated into the calculations. This inclusion allows for a deeper analysis, as the influence of each key factor raised from the second objective can be calculated and compared between the different Wellington water sources. Furthermore, the inclusion of geological information permits the investigation of how landslides can affect pipe repairs.

Finally, by including the information from the various sources, objective five, can be addressed where the new model can be run to estimate which water source has the best repair times for different scenarios.

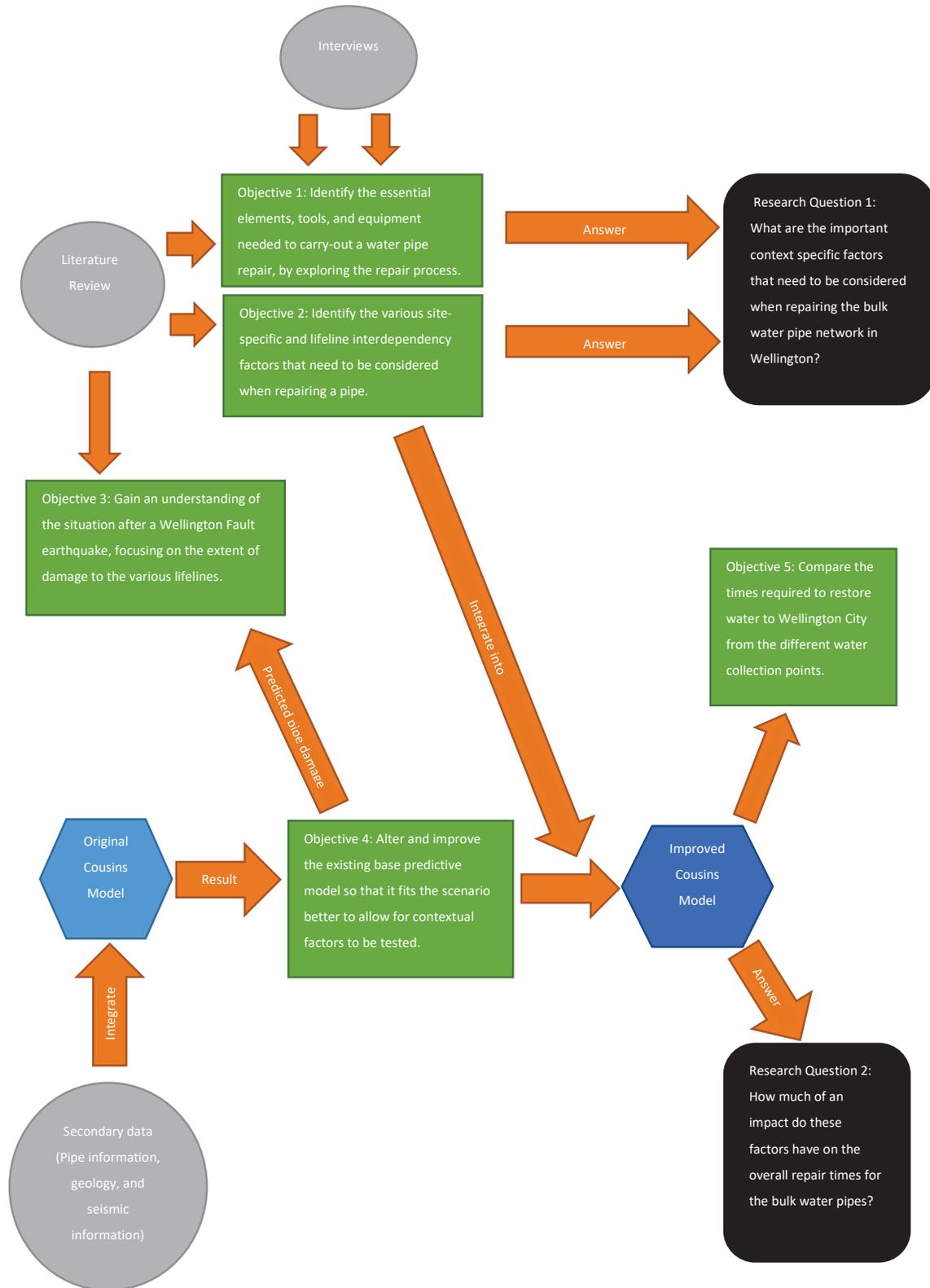


Figure 3.2 Methods conceptual map, showing how each method answers the research questions. The arrows represent flow of information and the grey bubbles are the various information sources.

3.6 Ethics

Taking entire research processes into account, as there will be close interaction with the stakeholders, it is crucial that the ethical guidelines for human research must be followed to make sure that people, or the businesses that they represent, are not impacted. To make sure that people are not affected, a low-level human ethics application will be applied for, and only when approval is received will the research commence. Also, all research will follow Massey University's Code of Ethical Conduct for Research, where the code must be fully understood by the researcher. All participants in the investigation will be sent information on what the research involves, its purpose, what to expect, and how to contact the researcher or university if there are any concerns, to reduce the likelihood of any impact. This form can be found in the Appendix (a). Additionally, since the conversations are recorded, each contact will be sent a form to sign, asking whether they are comfortable with the research and if they consent for it to be recorded. Only when consent is given is the interview then allowed to begin. Finally, the interviewee's identities will never be revealed.

3.7 Summary

Overall two different paradigms are brought together to understand the impact of contextual factors on water pipe repair times. Throughout the study, a pragmatic approach is used, as it allows for the combination different and contradictory methods, and focuses on what works, rather than the intricacies of each approach. By combining the depth obtained from semi-structured interviews with the breath obtained from predictive modelling, a much more comprehensive analysis of pipe behaviours can be reached. Integration between the qualitative approach and the quantitative methods occurs both during the middle of the research and at the end, following Teddlie and Tashakkori (2006)'s sequential mixed methods structure. This integration involves the use of thematic coding to highlight areas of interest that should be further investigated using computer-simulated models. From these models, conclusions on repair times can be made (Fig 3.2). Overall the methods selected have various limitations and biases, but they do provide the best and most useful findings. The steps for each of these methods are elaborated in the next section.

Chapter: 4 Data Collection and Analysis

The following chapter describes the data collection and analysis procedures, where each step and calculation is described in detail. The chapter begins by discussing the primary data collection and analysis processes, unpacking and explaining where and how data were obtained and analysed. Then, the secondary data collection and analysis methods are discussed, explaining what was collected and how it was used to improve the Cousins Model. Once an understanding of Cousins Model and its improvements are reached, the integration process between the qualitative data and quantitative methods is then described, where the various calculations used to predict pipe breakages and repair times are explained. Finally, the different factors highlighted in the interviews are discussed, detailing how they affect the water pipe repair process and how they have been incorporated into the Cousins Model.

4.1 Primary Data Collection and Analysis

As discussed previously, a combination of snowball and expert sampling methods was used to select twenty different key stakeholders, involved in the maintenance of local lifelines around New Zealand, for interviews. The twenty contacted experts included four researchers at Stronger Christchurch Infrastructure Rebuild Team (SCIRT), three experts at various City Care Ltd's, three Wellington Water specialists, three Christchurch City Council staff members, Four Hawkes Bay Regional Council members, two New Zealand Transport Authority (NZTA) officials, and one contractor with Higgins, a New Zealand civil engineering and construction business. Only five of these contacts had the time for a 40-minute phone interview due to their busy schedules. Those five included: one Christchurch City Council staff member, one Higgins contractor, one City Care Ltd official, one NZTA expert, and one Hawkes Bay Council member. Each of these respondents had direct experience with repairing the lifelines, being involved both in the field repairing the infrastructure and managing the overall repair endeavours. Furthermore, as discussed in Section (5.1) some of these respondents also had first-hand experience with repairing the damaged lifelines after an earthquake, and so understood the difficulties and complexities involved in a disaster situation.

4.1.1 Interview Structure and Questions

In general, each interviewee was asked a range of different questions around the various processes and requirements for pipe repair to fulfil objectives 1 and 2

(Section 1.7). In total, 15 different discussion points were addressed in a variety of ways with divergent probing questions (see Appendix 7.1). Not all queries were discussed during each discussion, as each participant had experience in different areas. However, the main discussion topics and primary questions remained the same. During the interviews, the interviewer did not take any notes. Instead, each conversation was fully recorded and later transcribed. This process allowed the interviewer to concentrate on the discussion, and permit them to ask more in-depth questions.

4.1.2 Interview Procedure

Before the interviews were conducted, a literature review around lifeline behaviour in earthquakes, lifeline interdependency, and current predictive models was completed. Once an understanding of literature had been obtained, the interview questions were then written. In total 29 questions were developed, addressing 15 different main topics (see Appendix 7.1). During the question writing phase a low level, human research ethics application was sent to Massey University. Only a low-level ethics application was required as the information requested from each expert was non-confidential, and there was no concern around harming those involved, as the respondents would remain anonymous and the questions were focused on technical data, not personal information. Once the ethics process was completed, emails containing a project summary, research aims, an interview consent form, and ethics information, were sent out to the various selected experts. Each expert was asked if they had time for an interview, and if they knew of someone else who would be interested and willing to take part in the interview process. Many of the contacts were unfortunately very busy, due to the recent 2016 Kaikoura Earthquakes, and the Hasting water contamination event. Overall five of the twenty contacts were available to take part in the interview process.

4.1.2.1 *Information Sheet and consent forms*

Before each interview, the participant was asked to fill out an ethics consent form, stating whether they were happy with the interview process and if they consented for it to be recorded. All five responded that they were fine with the process and had no reservations about recording the conversation.

4.1.2.2 *Transcribing interviews*

Once recorded, each conversation was then fully transcribed by the interviewer, using a denatural approach. A denatural transcription involves removing pauses; filling words like um, ah, like, look, suppose; and vocal repetitions from the transcript, to improve the readability and to capture the speakers actual meaning (Oliver, Serovich, & Mason, 2005). By removing these fillers a more useful transcript, than one with full quotations, is created.

4.1.3 Analysis of Interview Transcripts

Once all transcripts had been completed a thematic analysis was completed by coding the responses using nodes in NVIVO, a qualitative analysis program. The first phase of coding involved automatically adding 21 nodes to the transcripts, based on the person talking and the question being addressed. This process was done through NVIVO's automatic coding tool. Then to break up the interviews for a more in-depth analysis, the responses to each question were then manually coded. This involved: Creating 52 nodes and then filtering the responses into these categories. For simplicity, multiple codes were used on the same text. For example, a statement that discusses access problems around Wellington, after an earthquake that blocks the roads, resulting in slower aid and equipment influx; was coded as, problem, access-(road), acquisition, equipment (use), and Wellington. Each node defined either the locational context; the perspective, positive or negative; the topic, such as inspection or pipe repair, and the infrastructure in question, such as pipes, or roads. The positive or negative perspectives towards the topic were coded as either a "problem" or a "solution". Problems were any statements that alluded to difficulties in repair, or where extra time would be needed in the repair process. Solutions included statements that discussed simple ways around the problem or suggested that there was no problem. Overall most of the codes used are self-explanatory, as they refer to one specific idea.

4.1.3.1 *Summary table*

Once the transcripts were coded, the raw spoken statements were then summarised into key points to allow further analysis. For example, the quotations below by respondent 1, 3, and other similar statements discussing availability of parts for universal pipes, were summarised into the sentence "Common pipe diameters have premade available parts and proper clamps" (Table 5.3)

Respondent 1: "There are that many different things that you can actually buy to do your repairs, where there are maxis, and there are gibaeult joints, and there are clamps etc. The materials that I use here like I keep a stock of just about everything. We have 125 mains; we have 175 mains..."

Respondent 3: "A lot of the pipe works are fairly standard, so I mean if you had a 150mm standard PVC pipe up in Wellington it's exactly the same as in Auckland or in Christchurch. It's all standard AVs standard materials. There would be quite a reasonable stock of the reticulation pipes."

These summary statements were then placed into different tables, based on the topic they addressed, so that an overall picture of the various perspectives around each topic could be understood. Similar statements referred to remarks on the same issue or discussions with similar codes. For example, all comments with the code 'politics' were grouped in one table, and all discussions around the 'inspection process' were combined in another. In most instances the positive and negative perspectives, or statements coded as 'problems' and 'solutions', on the same subject, were grouped, producing a well-balanced understanding.

By repeating the above steps, as elaborated in the Figure (4.1), multiple perspectives from the different respondents were summarised in different statements which were then clustered in separate tables. Overall the different key contextual factors that should be included in the Cousins Model were highlighted, fulfilling objective 2.

By completing this process, 12 different summary tables were produced that contained multiple statements from the interviews on 12 different topics. These topics were, oddball pipes; the damage inspection process, staff logistics; access problems; power requirements; valves and water pressure; equipment acquisition; politics; vulnerability and pipe attributes; health and safety; environmental impacts; and topography and ground damage. Out of these 12, only four were included in the Cousins Model as not all topics had enough information; had potential significant effects; or could be directly incorporated into the calculations. The four that were chosen were considered vital by most respondents, as they were discussed by the respondents multiple times throughout the interviews; were simple to incorporate into the model, as specific information was given; were topics that could have a significant impact on the repair times, and or were not already considered in the Cousins Model's calculations. The four selected were: the damage inspection process; uncommon diameters; staff logistics; and 'landslides and access'.

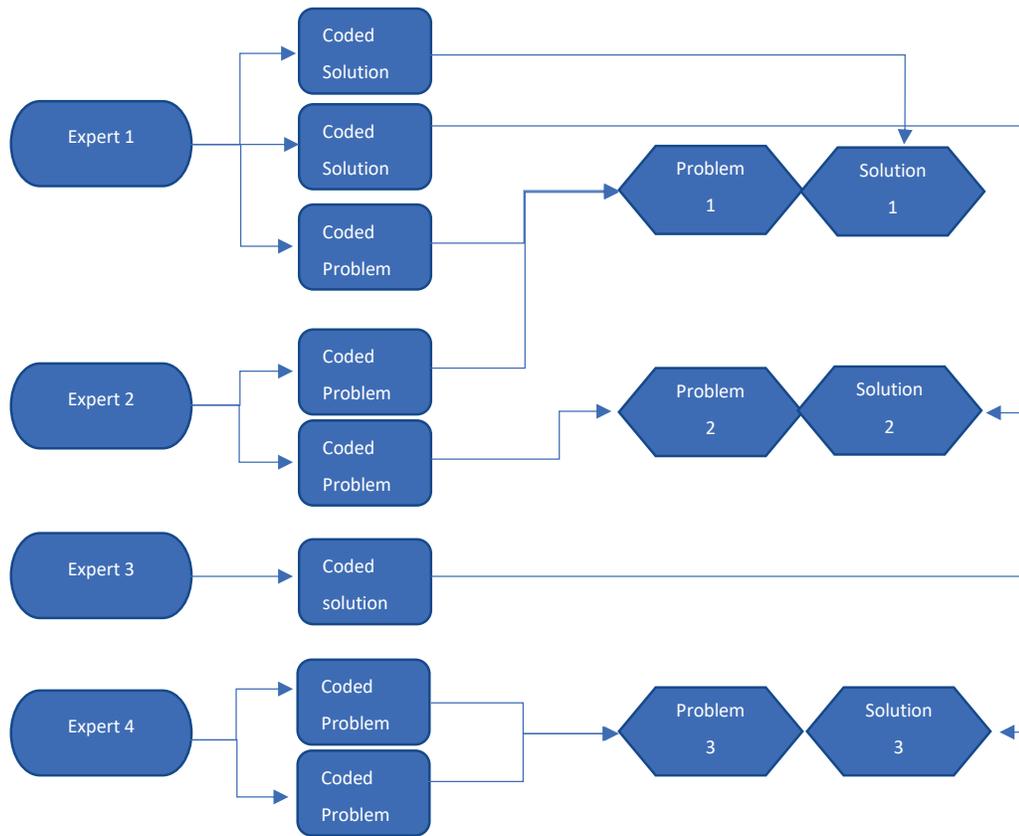


Figure 4.1 Figure 4.2 The process of how each coded statement from the interviews is summarised and tabulated with other statements. Problem and solution bubbles represent the final summarised sentences that are included in the summary tables in Section (5.3).

The damage inspection impacts were incorporated into the Cousins Model due to its common occurrence in the interview discussions and because specific repair times were quoted by the respondents of which provided a well-established foundation for calculations.

Uncommon diameters, or “oddball pipes” were added into the Cousins Model as specific information, that could easily incorporated into the model, was quoted by the respondents (Section 5.3.1). This specific information, such as what diameters to look out for, was then used to develop the calculation methods shown in Section (5.3.1.1).

Staff logistics was selected due to its importance as a topic, being raised many times by most respondents, and because there were not many solutions mentioned. Overall most experts stated that working with, and organising different individuals and corporations was difficult (Section 5.3.3).

The impacts from landslides, and their influence on the accessibility of damaged pipes, were included, as access problems were said to have the potential to increase the overall repair times significantly. In addition the landslides and access topic addresses the complexities around the interdependency and inter-relationships between the water pipe and transportation networks, addressing the second research objective.

Overall each selected topic was included into the Cousins Model to improve its accuracy. However, before any calculations could be conducted around the actual impact of these contextual factors, the possible earthquake damage had to be estimated first to understand the post-earthquake environment, fulfilling research objective 3.

4.2 Secondary Data Collection and Analysis Methods, Improving the Cousins Model

The possible damage from a local earthquake was calculated by combining pipe asset information with local ground conditions. Pipe asset information was directly taken from the Cousins Model in Nayerloo and Cousins (2014), which contained all the required asset information in a summarised form. For example, the material type was condensed from around 20 types into four categories. Such a classification allowed for simpler equations and larger sample sizes as the pipes were less spread out. Although accuracy may have been compromised to some extent, most fragility models or damage calculation equations available include only a few categories regardless. Thus there was no advantage of keeping the original, diverse material types. Unfortunately, the Cousins' data had a couple of missing pipe segments closer to the treatment plants. However, these sections are small, and only had a minor effect on restoration times.

4.2.1 Overview of Data Collected from the Cousins Model

Taking a closer look at the pipe attributes, provided in the Excel spreadsheet, revealed that the pipes from Wainuiomata (Fig 2.3) are the most vulnerable to failing. This adherence to failure is because the pipes have the highest percentage of non-ductile pipes such as cement and iron pipes, and contain the oldest joints (Table 4.1). Interestingly, all other water sources consisted of mainly ductile materials, where brittle materials spanned less than 0.5%. The most resilient pipes

were associated with the Kaitoke source as they are mostly made of ductile materials with large diameters and young couplings.

Table 4.1 Pipe attributes from each source. Cement pipes include brittle materials such as concrete and asbestos cement. Steel and Iron contain all the different variants of steel and Iron pipes. Plastic pipes include plastic materials such as polyvinyl chloride and polyethylene. Mains refer to pipes larger and equal to 600mm in diameter. Branches are pipes smaller than 600mm. Old couplings are pipes with non-welded joints that were created in 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 |

4.2.2 Allocation of Geological and Land Conditions to the Pipes

Once collected, the pipes were then split into 20m segments using ARC GIS, a geographic information systems (GIS) editing software, to combine local ground conditions with pipe information. A 20m length ensured that each segment received the correct ground influences, as ground conditions can change dramatically over short distances. For example, in Christchurch during the Mw6.3 2011 February earthquake, houses on one side of street experienced much more severe liquefaction than those on the other (Fig 4.2). Furthermore, it was assumed that when repairing water pipes, repair crews could attend to all breakages along a 20m section at the same time. Therefore, by splitting the pipes into 20m segments, a more accurate number of separate repair endeavours was calculated. Each segment was then converted into a singular point, and given locational, New Zealand Map Grid (NZMG), coordinates. These points were then spatially joined to an elevation map so that the influence of altitude and slope could be explored.

4.2.2.1 Elevation

This elevation map was created by firstly downloading, a topographic 50,000 contour map from the Land Information New Zealand (LINZ) database. Once downloaded it was then converted into a triangulated irregular network (TIN) layer, and then transformed into digital elevation model (DEM) using the TIN to raster tool in ARC GIS. The slope was then calculated by creating a gradient layer from the TIN, using the slope tool. This slope layer was then spatially joined to the segmented pipe layer. Overall, the elevation and slope maps show that most of the bulk water pipes are located in shallow gradients with slopes lower than 10 degrees. Only a small group of pipes near Wainuiomata lie in steep slopes that have angles up to 20 degrees. These steeper angled regions correspond to areas with higher elevation. Thus, the higher the altitude, the steeper the slope (Fig 4.3 & 4.4).

4.2.2.2 Liquefaction and Landslide Hazards

Local ground conditions were then added by using a Visual Basic (VBA) code and hazard map. The VBA code added soil conditions to each pipe by linking it to the closest known Cone Penetration Test (CPT) site, while the hazard map gave each pipe a land sliding hazard number based on the pipes location. Overall each pipe received a value from 1 to 5 representing the different soil types, (Table 4.2) and landslide and liquefaction susceptibilities, where zero referred to no potential risk and five, high.

Table 4.2 Soft soil amplification factors.

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

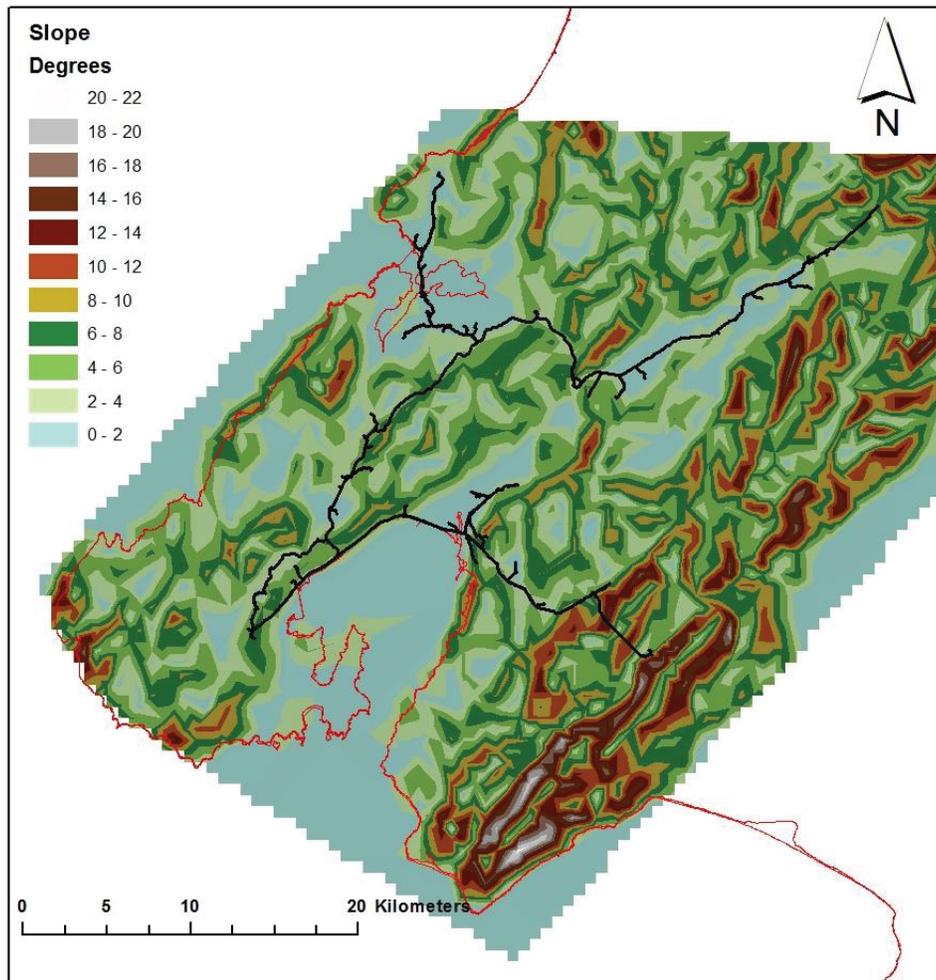


Figure 4.3 Wellington Region slope map. The thin red line represents the coast, while the black lines show the location of the bulk water pipes. The Elevation information is from Land Information New Zealand (2017), and the Coastal lines are from Greater Wellington Regional Council (2012).

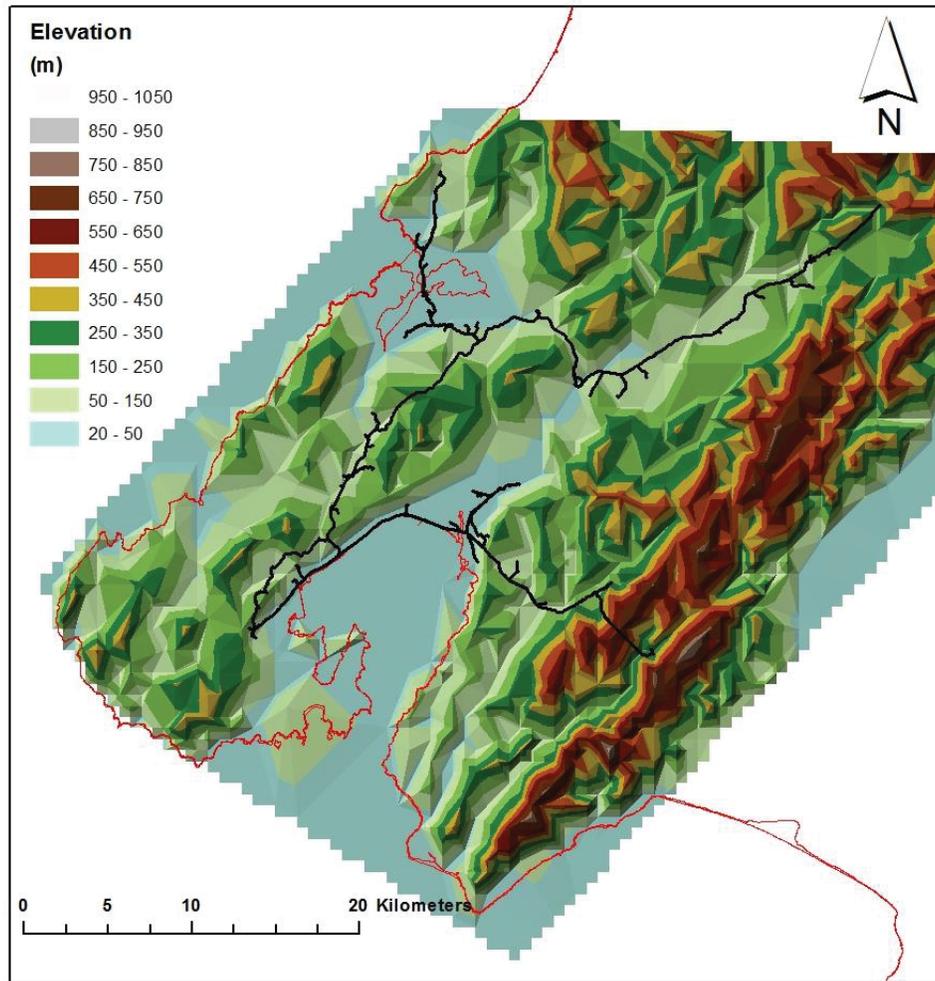


Figure 4.4 Wellington Region elevation map. The thin red line represents the coast, while the black lines show the location of the bulk water pipes. The elevation data is from Land Information New Zealand (2017), and the coastal lines are from Greater Wellington Regional Council (2012).

These liquefaction and land sliding numbers were then altered and changed to a smaller scale. Classes zero and one were combined and classified as zero, or no risk; classes two and three were classified as class one, or low; class four was classified as class two, moderate; and class five as class three, high risk (Table 4.3). These changes agree with the conclusions in 1) Sherson (2015), where it was discovered there was not much variation in damage between low and moderate liquefaction classes and 2) with the calculations in the pre-altered Cousins Model, which used only four categories to define landslide and liquefaction impacts (Cousins, 2013; Nayerloo & Cousins, 2014).

Table 4.3 The difference between the original and new liquefaction and land sliding classes.

| Original Class | New Class |
|----------------|-----------|
| 0 | 0 |
| 1 | |
| 2 | 1 |
| 3 | |
| 4 | 2 |
| 5 | 3 |

When looking at the landslide hazard map, most of the bulk water network is situated in low to moderate zones. Only small segments around State Highway 2, Wainuiomata, and Ngauranga Gorge lie in highly prone regions (Fig 4.5 & Fig 4.6). Interestingly, the most vulnerable areas are those with previous landslide scarps shown by the circular red localities along State Highway 2 (Fig 4.6). The next most prone region is along the Ngauranga Gorge where State Highway 1 and 2 connect. Overall the pipes taking water from the three Lower Hutt sources, along State Highway 2, are the most vulnerable to landslides. Liquefaction hazards also follow a similar pattern where the most vulnerable pipes are those located in the Hutt Valley, and along State Highway 2 (Fig 2.3).

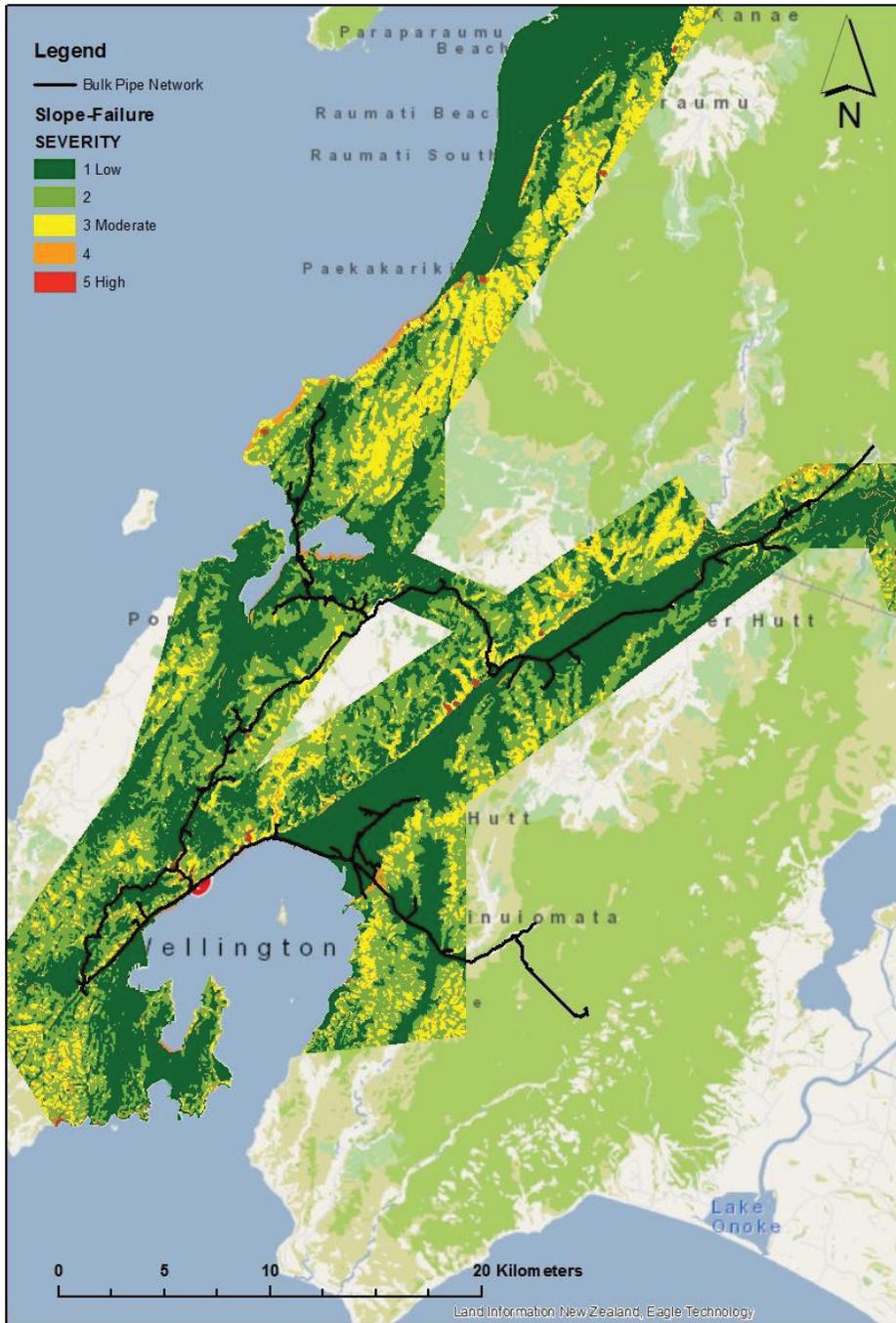


Figure 4.5 Landslide severity map of the Wellington region. The slope hazard information is from Kingsbury (1994)

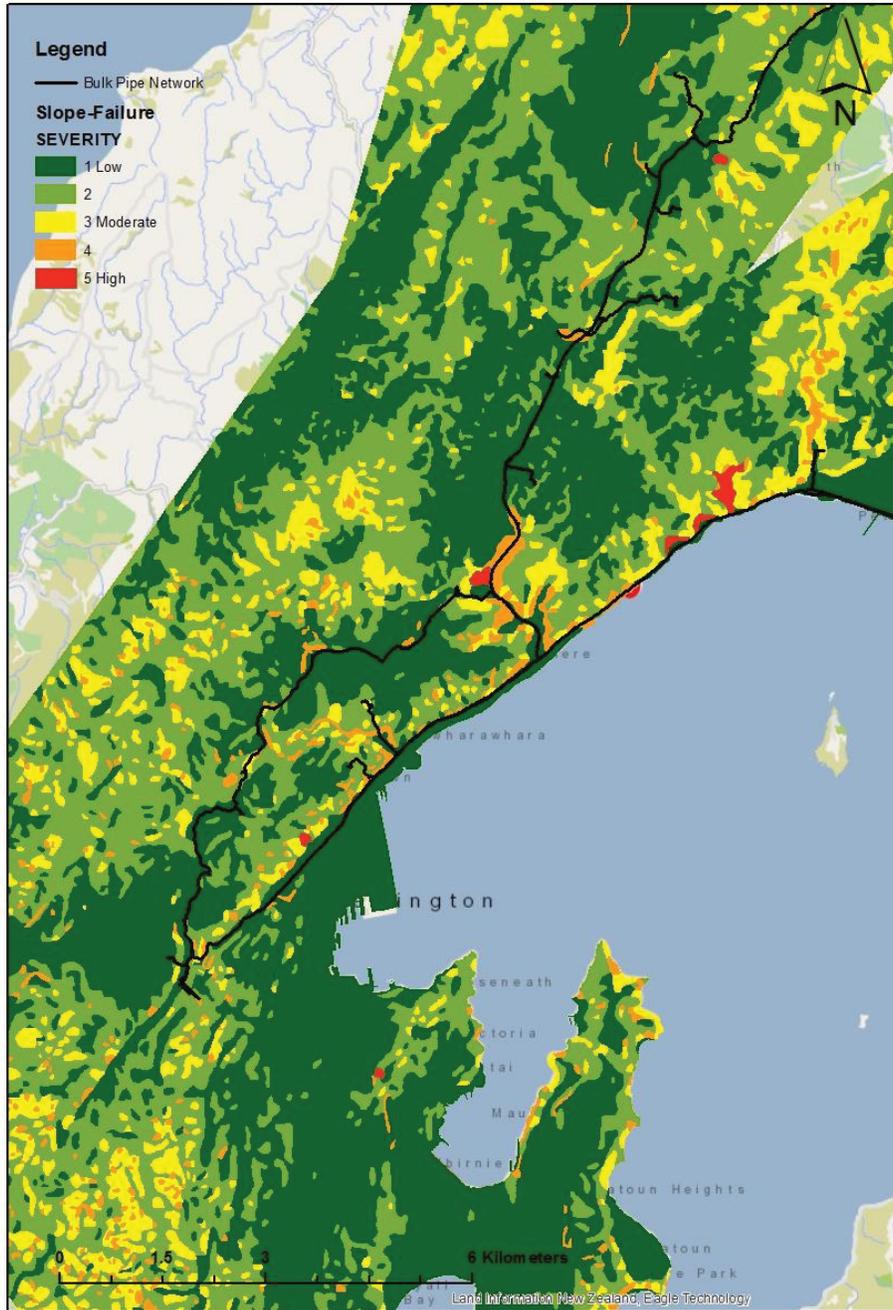


Figure 4.6 Landslide severity map of Wellington City. The slope hazard information is from Kingsbury (1994)

4.2.3 Addition of Source Identifiers, Bypass Pipe locators, and Redundancies

Once ground conditions were added, three new fields were given to each pipe. The first determined which water source the pipe was connected to, either Wainuiomata, Waterloo, Gear Island or Kaitoke. The background and layout of these sources can be found in Section (2.5). The second was used to identify bypass pipes, which are small curved pipe sections, that offshoot main pipe segments, and often signify the location of shut-off valves. The third and final number termed 'child number', signified how many different routes water could travel to get to the same point, defining the redundancies of the network. For example, network segments with two pipelines, a main and sub-main, that carried water to the same location, were given the number 2 to represent the fact that both pipelines would need to fail to stop the supply of water. The headwords pipes that supply the treatment plants with water were also given a range of different child numbers as they are constructed with branch-like structures that syphon water from a range of streams sources. Overall It was assumed that only one of these water collection points would be required to provide water for the inspection and repair process (Fig 4.7a). The broken pipe in Figure (4.7b) is a good example of this branch like situation where a minimum of three other breaks is required to stop the supply of water to the treatment plant.

The overall aim of including child numbers is to model reality, where small amounts of water can be utilised. Pump stations were not given "child" numbers despite the number of pipes part of their system, as it was assumed that they need all their pipes to function. Also, the complexity of their pipe layout makes it difficult model the flow of water accurately.

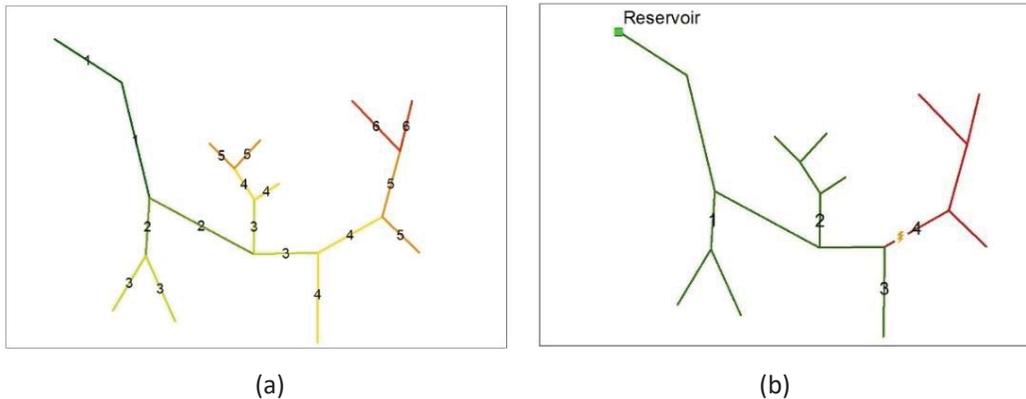


Figure 4.7 (a) Displays the child number for each pipe. Each new fork increases the child number by one. The treatment plant is in the top left corner, and the water sources are located at the tip of each other line. (b) Explains how the child numbers are calculated by demonstrating what happens when one of the pipes breaks. The yellow lightning bolt and red pipe represent the broken pipe, while the three other possible routes water could flow are in green.

4.2.4 Changes to the Damage Calculation Process

After adding the fields and spatially joining the water pipes with land conditions, the collected Wellington pipe information was added to the Cousins VBA model. Various changes had to be made to the model's calculations and VBA code, as it was not suitable for achieving the research objectives. Originally the code was used for calculating how long it would take to restore water to each Wellington reservoir. As the focus of this study is on how contextual factors impact repair times, having multiple endpoints would lead to confusing results, where the exact influence of each contextual factor would be hard to define. Also, the required calculations would become far too complex. Furthermore, by using one endpoint, the repair times from the four different Wellington sources can then be compared to determine the lowest total repair time, fulfilling the fifth research objective.

Out of the many endpoints available, the Karori Reservoir was chosen because of its ideal location at the foot of bulk water pipe network where the multiple pipes, used for transporting water from each source, combine (Fig 2.3). By calculating repair times after this confluence, each water source was able to be included in repair time calculations as the endpoints were the same. Additionally, as most of the network and each source were included, the behaviour of the entire network could be easily understood. Finally, in the original Cousins Model, Karori was predicted to receive a repair time close to the median time for all Wellington

reservoirs (Cousins, 2013). Thus, when used in calculations, Karori could represent the whole Wellington Region.

Including each water source involved firstly changing the number of assets the code could calculate. Then, anything that related to the multiple reservoirs quoted in Cousins (2013); Nayerloo and Cousins (2014) was removed and replaced with references to the four different water sources. Each source was treated separately to reduce complexity, where all the pipes from each source to the final endpoint were included in the calculations. This separation meant that some pipes were addressed multiple times. For example, the ring south of Ngauranga Gorge was present in all four calculations (Fig 2.3). For ease of computation, the different sections involved in each calculation, such as the Ngauranga ring, and the line up to Kaitoke were modelled for damage and repair times individually, then added together to give the total for each source (Fig 2.3 & 2.4)

4.2.4.1 Shaking Intensity Calculations

Overall the main damage calculation created by Cousins was kept the same. Firstly, the damage was predicted by calculating likely shaking intensities expected from a Wellington Fault Mw 7.5 event. This prediction was accomplished by using the Dowrick and Rhoades Model, to create Modified Mercalli (MMI) isoseismals, based on the type of faulting, faulting mechanism, and depth of rupture (Dowrick & Rhoades, 1999). Then shaking intensities were given to the pipes based on the isoseismal that they fell inside. Once the base MMI was calculated for each segment, the impact from the soil around each pipe was then incorporated.

4.2.4.2 Soil Amplification Considerations

Each soil type amplifies the shaking by a different amount. For example, softer soils increase the seismic amplitude or intensity, due to loose easily mobile structures. While more rigid soils or rock, decrease the amplitude (Cousins, 2013). This amplification effect decreases with magnitude, as the base shaking intensity becomes more dominant with increasing earthquake size. In the model, each soil type was given a different amplification number that waned with magnitude (Nayerloo & Cousins, 2014)(Fig 4.8). The various equations and calculations for this amplification are explained below.

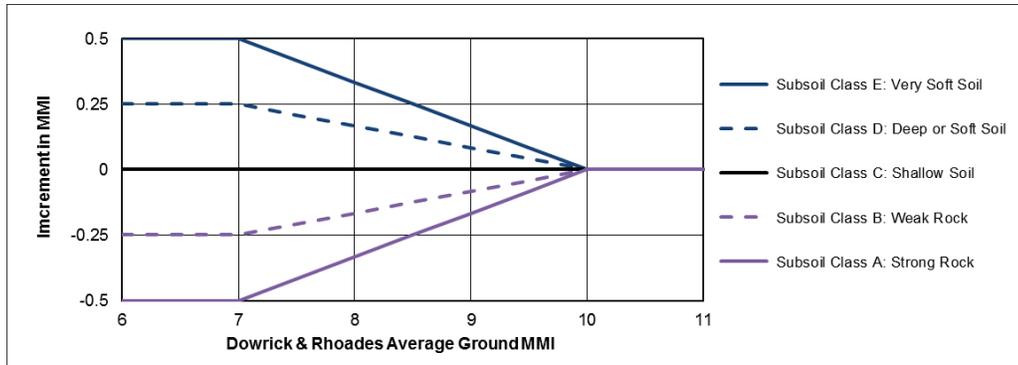


Figure 4.8 The increments made to the Dowrick and Rhoades MMI because soft soil amplification. The diagram is based on Cousins (2013).

Three equations, based on the Cousins Model, were used to calculate this amplification. Slight changes were made to the original equations from Cousins (2013) based on a discussion with the author whom after doing more research found flaws in his original design. Unfortunately, this new research was never published.

1) The soil amplification for low MMI's, smaller than seven, was:

$$AMP(< 7) = 0.25 \times (X - 3) \quad (\text{Eq 4.1})$$

Where X is the soil base number (Table 4.2)

2) For pipes located in moderate MMI's, from seven through to ten, the amplification equation was:

$$AMP(7 - 10) = ((-0.166667 \times MM) + 1.666667) \times \left(\frac{x - 3}{2}\right) \quad (\text{Eq 4.2})$$

Where mm is equal to the base MMI obtained from the isoseismals.

3) Finally, for MMI's greater than 10, an amplification factor of zero was used.

$$AMP(> 10) = 0 \quad (\text{Eq 4.3})$$

Once calculated, the amplification factors were then applied to the predicted MMI values. The resulting altered magnitudes were used in all further equations such as pipe break rates.

4.2.4.3 Break Rate Estimations

To calculate the predicted break rates the Cousins Model was used. This model firstly calculates failure rates based on the MMI only, then applies amplifiers that increase or decrease the failure rate.

$$\text{Average Fail_rate(s)} = \left(1600 \times 10^{\left(\frac{-40}{MMI-0.6} \right)} \right) \times \text{multipliers} \quad (\text{Eq 4.4})$$

4.2.4.4 Redundancies

One of these multipliers specified in Eq (4.4) is the child number. The child number was placed on the end of the calculation and divides the fail rate by the total number of breaks that need to occur. By dividing by the child number, the likelihood of failure lowers, as each child pipe must break for the section fail. For example, if the child number is two, then the probability of failure is cut in half. This method of calculating the redundancy was used instead of the more widely used equation (4.5) from Opus International Consultants Ltd (2017), due to the fact that it is not known which pipe segments along the parallel or redundant pipe will break in an event. Therefore, it is hard to know what probabilities to include in the calculation (Fig 4.9).

$$\text{Probability Including Redundancies} = 1 - ((1 - x_1)(1 - x_2) \dots) \quad (\text{Eq 4.5})$$

Where x stands for the probability of failure of one parallel pipe line or segment.



Figure 4.9 The relationship between parallel or redundant water pipes and the segmented network. Each different colour represents a different 20m pipe segment.

4.2.4.5 Other added amplifiers

Other amplifiers include material type and diameter influences, which were added together, and then included into the equation as the segment multiplier. The amplification factors for each pipe attribute are shown in Table 4.4) below.

Table 4.4 Pipe attribute multipliers. Each of these numbers adds towards the segment multiplier.

| Nonductile materials | Old Couplings | Diameter < 600mm | Welded Steel Pipe |
|----------------------|---------------|------------------|-------------------|
| 6 | 2 | 1.5 | 0.2 |

The landslide and liquefaction influences were then added, by placing them as exponents in equation (4.6) following the assumptions made in Nayerloo and Cousins (2014), and the conclusions around liquefaction damage in Sherson et al. (2015).

$$\begin{aligned} \text{LIQ} &= 2.5^X \\ \text{LS} &= 2.5^Y \end{aligned} \quad (\text{Eq 4.6})$$

Where X is the liquefaction susceptibility value, and Y is the predicted landslide hazard value.

Finally, the equation is then multiplied by the segment length, to convert the fail rate into a probability. This probability then divided by 1000 to convert it into kilometre units.

$$\text{Final Fail Probability} = \frac{\left(\left(\frac{(-40)}{1600 \times 10^{(MMI-0.6)}} \right) \times SM \times LIQ \times LS \times \text{Segment length} \right)}{\frac{(\text{Child Number})}{1000}} \quad (\text{Eq 4.7})$$

Equation 4.6 was used for every single pipe segment, except for sections that crossed the Wellington Fault, or pipes that lay in potential landslide drop-out locations, as pipes in these sensitive areas were assumed to fail automatically.

Once the fail probability had been calculated, each pipe segment was then given a random number between 0 and 1. If the random number fell in the range of the probability from 0 to 1, then pipe segment failed. If not, the pipe survived. The break rate was then calculated by dividing the number of failures over the total length.

4.3 Repair Time Calculations

After the damage was approximated, repair times to Karori were then estimated. Firstly prospect times were calculated, by assuming that 0.1 days per km of pipe, was needed for locating broken pipes from surface observations (Cousins, 2013; Nayerloo & Cousins, 2014). Then base repair times were calculated by giving each segment that broke a different time based on the pipe's diameter. Large pipes with a diameter greater than, or equal to 600mm were assumed to take between two

and three days to repair, while a standard value of one day was used for pipes with diameters less than 600mm, following the procedures in Cousins (2013) & Nayerloo and Cousins (2014).

4.3.1 Integration of Contextual Factors

Once the base repair times were calculated, following the calculations and procedures from Cousins (2013), the impacts from the various contextual factors raised in the interviews, were then incorporated into the model. This integration was accomplished by taking any stated repair times and adding them to repair time calculations. For example, the respondents stated that difficult to find pipe damages could take up to five days to locate (Section 5.3.2). Thus to account for this extra time, a calculation method was created which gave additional time to broken pipes in more complex regions such as in slopes (Section 4.3.2.1).

In the event where there were no specific repair times mentioned in the interviews, a calculation method was produced based on the different perspectives and stories gathered from the interviews and wider literature. For example, an additional three days were added to the repair times of the small pipes with unusual diameters, as replacement parts would have to be manufactured since only the more common diameters had replacement parts already available. See section (5.3.1) for more information. Three days was chosen as standard manufacturing times take between one to two days, and shipping from another region, not impacted by the quake, takes around one to two days, assuming the pipes were accessible (un-accessibility is accounted for in further calculations). Overall, integration involved converting the qualitative statements into definitive, quantifiable information.

4.3.2 Added Factors

As stated in section (4.1.3), four contextual factors identified from the interviews were integrated into the Cousins Model. How these factors were included into the Cousins Model's calculations are discussed below, where the landslide and access impacts are discussed separately in Section (4.3.4).

4.3.2.1 *Damage Inspection*

Overall, to calculate the additional time needed for inspecting pipe damage, extra time was given to broken pipes with small diameters that lay in steep slopes as they

were more likely to cause problems. See section (5.3.2) for more information. Overall, each pipe that failed received an additional time based on the slope of the land that it lay in, and its diameter, where random numbers were used once again to determine a value between a maximum and minimum number derived from the interviews. For example, as in Table (4.5), if a small pipe located in steep slopes was predicted to break in the model, then the repair times would increase by between 1.5 and 3 days. Overall the final added inspection time from each source was calculated by adding up each of the inspection times from each broken pipe associated with each source together. For example, if there were 15 broken pipes from the source to the reservoir, 2 of which were classified as small pipes in moderate slopes, 1 as a large pipe in steep soil, and the rest in shallow slopes, then the added overall time would be somewhere between 2.5 and 5 days ($2 \times 0.75 + 1$) and ($2 \times 1.5 + 2$)

Table 4.5 Inspection time amplifiers for broken pipes. Each number adds time to repairs based on the slope of the land the pipes lay in and the diameter of the segments. Factors are picked using a random number, somewhere between the maximum and minimum. Steep slopes are slopes from 15 to 20 degrees, moderate slopes from 10-15 degrees, and shallow slopes are those less than 10 degrees. Branches are pipes smaller than 600mm in diameter. Mains are those greater than or equal to 600mm.

| | 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 |

4.3.2.2 Uncommon Diamameters

In addition to the damage inspection process, the impacts from pipes with uncommon diameters were also incorporated into the Cousins Model. Additional time was given to each broken pipe based on how common the broken segment's diameter was. Pipes were considered, uncommon, or 'oddball' if the diameter spanned less than 1km, or covered less than 0.6% of the network. Each oddball pipe was assumed to require extra time to repair as no backup parts would be available. Overall it was expected that an additional 0.5 to 0.75 days would be needed to alter clamps to fit larger pipes, while two or three days would be required to create new parts or clamps for smaller pipes (Table 4.6). These additional times were based on responses from the interviews which are discussed in Section (5.3.1).

Table 4.6 Additional repair times based on the commonality of different pipe diameters.

| Diameter | Total Length in Network (km) | Added Time per Break (days) |
|-----------------|-------------------------------------|------------------------------------|
| 550 | 0.01 | 0.75 |
| 345 | 0.01 | 3 |
| 720 | 0.01 | 0.75 |
| 675 | 0.02 | 0.75 |
| 100 | 0.03 | 3 |
| 500 | 0.03 | 0.5 |
| 150 | 0.09 | 3 |
| 1400 | 0.12 | 0.5 |
| 450 | 0.13 | 3 |
| 800 | 0.21 | 0.5 |
| 975 | 0.26 | 0.5 |
| 400 | 0.29 | 3 |
| 200 | 0.38 | 3 |
| 250 | 0.43 | 3 |
| 1000 | 0.73 | 0.5 |
| 1200 | 0.83 | 0.5 |
| 300 | 1.02 | 0 |
| 500 | 1.28 | 0 |
| 650 | 1.69 | 0 |
| 600 | 1.79 | 0 |
| 1100 | 1.98 | 0 |
| 375 | 2.19 | 0 |
| 700 | 3.38 | 0 |
| 525 | 16.33 | 0 |
| 1050 | 16.96 | 0 |
| 900 | 28.91 | 0 |
| 750 | 35.93 | 0 |

4.3.2.3 Staff Logistics

One of the last factors considered when calculating pipe repair times was staff logistics. Staff logistics encompasses anything around the management of the repair crews and includes concerns such as, working with professionals who conduct repairs differently, the loss of expertise from staff turnover, personal requirements, and data management. Overall, to account for the potential difficulties around the turnover of staff, and the loss of essential knowledge, a random number, between 0 to 0.5 was given to each broken pipe. The hope was to

simulate repair crews having trouble finding vital infrastructure such as shut-off valves, as newer crews would not have the knowledge of exact locations.

In addition, to account for the clashing of different procedures from working crews, initial repair times were doubled 10% of the time. This doubling accounts for the fact that repair crews would have to redo occasional jobs to the right standard after other crews rushed the job or completed it to a different standard, following the patterns seen in the aftermath of the Christchurch earthquakes, where many contracted jobs were redone multiple times to repair poorly done work (Broadstock, 2016; Young, 2016).

Finally, headworks repair, securing situation, assembling of plant & materials, and inspection & planning times from (Cousins, 2013) were kept the same. This stagnation was because there was not enough data or time to investigate these numbers in more depth.

4.3.3 Fault Repair Times

Once these additional times were calculated, fault repair times were added for every pipe that crossed a fault. Fault repairs were assumed to take somewhere between 5 to 20 days, depending on the crossing. Random numbers were used to assign repair times, for each fault, between the maximum and minimum values in Table (4.7). Since the location of each fault crossing was already known, pressure and the damage inspection process would not be required, and thus each crossing could be repaired simultaneously. Therefore only the crossings with the longest repair times were added to the final repair times for each source. Overall the Silverstream crossing was used for the Kaitoke Source and the Thorndon crossing for the three Lower Hutt Sources.

Table 4.7 Time required to fix fault crossings with one repair crew. Numbers based on Cousins Model and McCarthy (2009).

| | 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 |

4.3.4 Overall Repair Times

The final repair times were then calculated by combining initial pipe repair times with all other additional factors such as headworks repair, planning, staff logistics, prospect times, inspection times, and fault repairs. Each source was calculated individually, where only the pipes associated with the source in question were included.

4.3.5 Landslides and Access

Lastly to these final times, the influence of landslides was incorporated. Overall It was assumed, based on the risks in Wellington and the experiences from the 2016 Kaikoura earthquake, that some of the broken pipes in a Wellington Fault Earthquake would be buried under a landslide, and thus difficult to reach when conducting repairs (Hancox & Perrin, 2010; New Zealand Transport Agency, 2017). As a result of this burial, repair times would increase as temporary alternative pathways would need to be deployed until the landslide debris could be removed safely.

To calculate the specific impact on the repair times, pipes that had the possibility of being buried had to be identified first. This identification was accomplished by giving pipes located in landslide runout zones quoted by Hancox and Perrin (2010), an id number. Only landslides that had the potential to cover the pipes were included. Thus, possible dropout locations were ignored as they had already been incorporated into the damage model. Each broken pipe located in a potential landslide runout zone, was assumed to take two weeks longer to repair as it would take additional time to plan the procedure; bring in equipment; dig; connect the new temporary section to the old; and place the new section in a safe place, out of the way of future works on the landslide. For example, if there were three pipes located in landslide runout zones then the additional time needed to repair the pipes would be 42 days (3 x 14). However, as the additional repair times have no basis, being a very rough estimate, they will not be included in the final times. Instead, the outcomes and calculated times will give an indication of the possible factors to consider.

4.4 Summary

Different analysis methods were discussed in this chapter where each step is described in detail. Overall technical approaches and methods were outlined including the main damage and restoration equations. Each key factor raised in the interviews were described, where calculations and ways of incorporating these factors were discussed. No final restoration times were included. These will be explored in the next section.

Chapter: 5 Results

This chapter describes and combines the results from the interviews and the altered Cousins Model, where quantitative and qualitative paradigms are merged and integrated. Multiple factors raised in the interviews are examined, looking at their effects on the overall repair times. The chapter begins by giving a brief overview of the interview data collected. This summary is then followed by a look at the secondary data and a discussion around the results from initial alterations to the Cousins Model. After this discussion, the impact from each factor raised in the interviews is explored separately, starting with the influence of diameter on repair times. After the diameter, the effects of slope and water pressure on inspection times are explained. After exploring possible additional inspection times, various staff logistics impacts are investigated. Finally, pipe access problems, specifically the impact of landslides on the repair process, is explored.

5.1 Overview of the Interview Data Collected.

Every expert interviewed provided valuable information based on personal and professional experience working with, and around pipe repairs. Each respondent also gave a slightly different perspective, which helped more accurately define local impacts and vulnerabilities. For example, respondent 4 provided insight from a managerial position, while respondent 1 presented knowledge from a hands-on experience. In addition, two of the interviewees had direct experience with the Christchurch Earthquakes, providing valuable practical knowledge around widespread losses in service.

Experience with the Christchurch earthquakes varied between respondents, where two were directly involved, two had in-direct knowledge, and one had only a limited exposure. Interestingly the respondent with almost no experience, respondent 5, gave the most positive attitude towards pipe repair, where statements identified as solutions (positive attitudes or easy fixes) occurred three times more often than problem statements (negative attitudes, or anything that could extend repair times) (Fig 5.1). All the other interviewees, who had experience with the Christchurch earthquakes, had a similar number of positive and negative statements (Fig 5.1). Those with more earthquake experience also had longer and more in-depth answers, where they alluded to more personal stories and experiences. The more experience, the longer the conversation and thus the more

statements coded (Fig 5.1). Overall, despite some differences in experiences, each expert provided useful information that provided a solid base to explore different avenues around repair times.

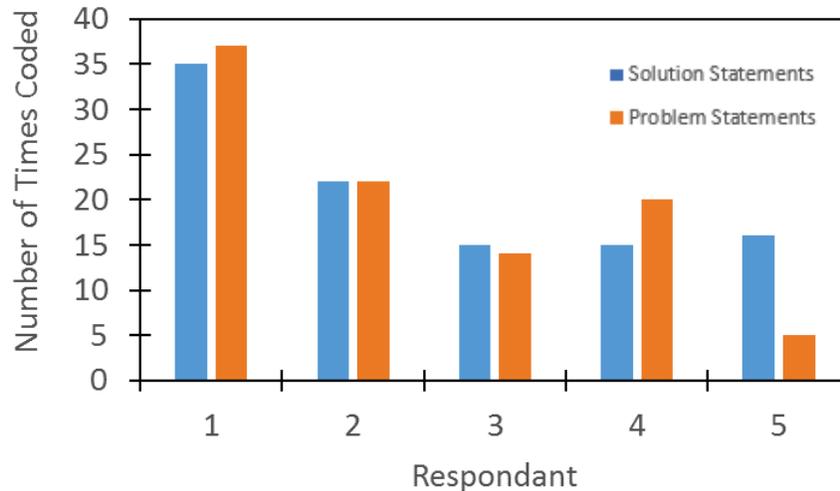


Figure 5.1 Number of problem and solution coding occurrences in the interviews. Blue refers to solutions and orange problems.

5.2 Predicted Pipe Damage Results

After running the altered predictive model for the first time, the total number of pipeline failures from a Mw 7.5 Wellington Fault Earthquake, outside of additional factors, ranged from 10 to 51 breaks depending on the source. Interestingly Kaitoke experienced the lowest number of failures, despite having the longest length of pipes exposed to earthquake conditions. This difference could be linked to the resilience of the pipes, as Kaitoke has the best combination of pipe attributes. This conclusion is backed up by Wainuiomata having the highest number of breaks, failing five times more often than Kaitoke and three times more than Waterloo and Gear Island (Table 5.1). However, many variables can affect pipe behaviour, most of which are explained below in Section (5.3).

Table 5.1 Pipe repair times based on the prospect times and raw pipe failures. Factors such as staff logistics, landslides, inspection times or fault ruptures are not included. Pipe redundancy or child numbers are not considered. Base repair times refer to the number of days' the repairs would take with one repair crew working on each break one at a time.

| Source | Total Length from Source (Km) | Prospect Time (days) | Number of Failures | Base Repair Time (days) |
|----------------------|-------------------------------|----------------------|--------------------|-------------------------|
| Hutt River (Kaitoke) | 58.91 | 5.89 | 10.27 | 29.35 |
| Wainuiomata | 44.89 | 4.49 | 50.47 | 76.56 |
| Waterloo | 31.08 | 3.11 | 37.93 | 46.80 |
| Gear Island | 21.96 | 2.20 | 36.50 | 46.10 |

5.2.1 Redundancy

By Incorporating redundancy into the network fail rates reduced by more than 30% for all sources apart for Kaitoke, where there was almost no change, suggesting that parallel pipes or redundancies mostly exist along the Lower Hutt section of the network (Table 5.2). Interestingly despite these reductions for all the other sources and no change from Kaitoke in Table (5.1), the pipes from Kaitoke still had the lowest predicted number of failures. Furthermore, most patterns observed before adding the redundancies also occurred after including child pipes. For example, the hierarchy of damage remained the same. The only noticeable change in pipe failures, outside of 30% reductions, was the difference in the gap between Wainuiomata and Waterloo, which suggests that Wainuiomata contains more contingencies than Waterloo. Overall adding redundancy reduced repair times universally. Further changes are expected to occur from the influence of factors highlighted in the interviews.

Table 5.2 Pipe repair times based on the prospect times and raw pipe failures. Factors such as staff logistics, landslides, inspection times or fault ruptures are not included. Pipe redundancy or child numbers are considered. Base repair times refer to the number of days' repairs would take with one repair crew working on each break one at a time.

| Source | Total Length from Source (Km) | Prospect Time (days) | Number of Failures | Base Repair Time (days) |
|----------------------|-------------------------------|----------------------|--------------------|-------------------------|
| Hutt River (Kaitoke) | 58.91 | 5.89 | 9.40 | 24.90 |
| Wainuiomata | 44.89 | 4.49 | 34.47 | 49.52 |
| Waterloo | 31.08 | 3.11 | 29.80 | 35.14 |
| Gear Island | 21.96 | 2.20 | 27.93 | 32.23 |

5.3 The Impacts of the Key Factors Raised in the Interviews.

One of the important themes that came out of the interviews was the order of repair. Most of the experts revealed that after an earthquake, repairs would have to be made consecutively out from the source, as water pressure is required to identify pipe damage.

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: "Once you get an area pressurised up, that it is holding pressure, then you go and open the next part and then find out where all the holes are, you just basically spread your way out from the pumping station, until you get enough holes fixed and you've got enough water"

Water pressure is critical, as the most common method of identifying leaks is through surface manifestations, where the water leaking from the pipes is used to pinpoint the damage locations.

Respondent 4: The subtle difference is 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. That's the subtle difference between an ordinary day where the pumps are working really hardout you have a blow up in the street, it's pretty obvious where it's gone because there is enough pressure behind it, to take the road apart, and also to continue flowing, to show where the problem is. In an earthquake if there is that many holes, there is not enough pressure in the pumps, to be able to push out the holes, so you actually have to go and close those areas off, relatively close to the pumping station, to get enough pressure in the system to be able to show where the holes are."

Once the damage had been found, the water would then have to be turned off to allow the workers to fix the pipes without interruptions, to preserve water, and to stop further damage to the surrounding environment from the flowing water.

Respondent 1: "But if it is a major break in the main you will find it. You can either hear it or the road will bubble up, or the ground will bubble up, and the leak might not come out right there, but you will definitely find it, or you will be walking along and then disappear. That little bit extra weight and the ground will break away from underneath you because all the silts and all that get washed away. Either a tomo comes from under the ground sometimes and, or you go around the corner, and there is a big geyser, yeah it's roaring up to the power lines or something like that. You go 'oh my God we have a problem here all right'. That has happened before as well."

Then, once the section is fixed, the water is turned back on, and the cycle repeated until the network is functional once again.

5.3.1 Uncommon Pipe Diameters

In addition to the repair process intricacies, the effect of pipe diameter on restoration times was also highlighted by interviewees. It was found that odd pipe diameters take longer to repair, as the equipment and replacement parts needed are not locally available or easy to acquire. Thus, extra repair time is required because replacement joints or clamps must first be manufactured (Table 5.3).

Table 5.3 Interview summary table. The overview of all perspectives from the interviews around the effect of oddball pipes on overall repair times. The condensing of interview statements follows the procedure in section 4.1.2.4. The black text represents identified problems related to the topic, and the red text solutions.

| Odd Ball Sized Pipes | |
|--|--|
| Problems and Concerns Expressed | Possible Solutions |
| There are no easy to acquire replacements for oddly sized pipes. Thus, parts need to be specially made. | Parts can be created by any local engineer or manufacturer depending on equipment available. Prior plans to create these parts have been already set up. |
| Maxi clamps cause damage when wound down. | Common pipe diameters have premade available parts and proper clamps. |
| | Gibault joints and maxis work on a broad range of materials. |
| | Unorthodox methods can be used temporarily such as welding steel plates over breaks or using Totara pegs to block leaks until the specialised parts can be made. |

Some experts did state that alternative repair methods that could save time, such as the use of Totara pegs to plug holes, metal sheets to cover holes, and the universal use of maxi clamps. However, all these alternative methods would take additional time to implement and are temporary. Furthermore, some respondents stated that Maxis, clamps used to wind down and cover pipe breaks, were not appropriate for all pipes, especially small pipes, as the Maxis had to be wound down too far, and often twisted.

Respondent 1: There are that many different things that you can actually buy to do your repairs, where there are maxis and there are gibault joints and there are clamps etc. The materials that I use here like I keep a stock of just about everything. We have 125 mains; we have 175 mains. We have all oddball stuff around here actually, and I've actually, even on some of them I've actually had to have gibault joints actually reamed out to actually fit the particular fitting cause they are not

imperial or metric, the old style stuff. There is quite a few in between mains that we have had like I am doing an oddball PVC main for a supplier at the moment and it's the PVC, the OD on it is 170, which is really oddball. I've actually got some ordinary PVC gibault joints and got them reamed out so that they will actually fit over that fitting, cause one thing I don't like to do on PVC, like you can get maxi fits. I don't know whether you know maxifits? The do reams of materials, like they fit AC, cast iron, steel, PVC and all this sort of stuff, and they are good if you are going from AC or cast, which are the old imperial ODs which is what the metric material is nowadays. The biggest, if you go like I do anyway, if you go from AC or cast to PVC you can use maxis. I don't normally have a problem with that. But if you are going from PVC to PVC 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, but that's just what I've found."

Overall to account for oddball pipes and the possible use alternative methods, a small amount of time was added for each broken pipe with an odd diameter.

5.3.1.1 Impact on Repair Times

After running the model 15 times, additional repair times ranged from 0.3 to 1.6 days depending on the source (Table 5.4). The highest added times are from Gear Island and Kaitoke, while the lowest are from Waterloo and Wainuiomata. This hierarchy is opposite to predicted repair times where Wainuiomata has the highest number of failures, and Kaitoke the lowest. However, since the differences between sources are not very significant, as Kaitoke is expected only to gain 0.5 days more than Wainuiomata, and since small odd pipes can add three days to repair times (Table 4.6) it cannot be confidently concluded that there are any significant differences. Overall, due to the low results, oddball diameters do not have a noteworthy impact on overall repair times.

Table 5.4 Total repair times for fixing oddball pipes from each source. Time is averaged across 15 runs of the model.

| Source | Average Time Added (days) |
|----------------------|---------------------------|
| Hutt River (Kaitoke) | 0.93 |
| Wainuiomata | 0.47 |
| Waterloo | 0.30 |
| Gear Island | 1.60 |

5.3.2 Elevation and Inspection

Another factor highlighted in the interviews is the difficulty in locating the broken segments. As stated by multiple respondents, pipe damage is observed through

pressure changes and surface manifestations. At low pressures, which often occur because of multiple pipe failures, surface manifestations can be influenced by the gradient of the land, where water can flow downhill and rise to the surface away from the breaks.

Respondent 1: "Oh it comes up out of the ground. The only problem you have got is if is on a hill and trying to trace it because I have dug up where water has come up out of the ground somewhere. So you dig down to it, and there is nothing wrong with it, and you can see that it is coming up from the road, so it could be 50 or 100 odd metres up the road. So if we dig up one that is on a hill for instance, and it's not exactly there. The first thing normally we would do, we would go and check the hydrants and the valves and see if there is water in the boxes for instance. And I'd normally think if you went 50 metres up the road and that hydrant box or whatever was filled with water, it was not actually spilling over, it was going down through the ground, or down the trench. We will then know the water leak is further up the road. So you know you either don't dig there, or if you have already dug, at least you know that it is further up, and then you would then go to the next house connection maybe, or where the next side line comes off, and have a look."

Therefore, broken pipe sections can be difficult to find, and in extreme circumstances, take up to 5 days.

Respondent 1: "I spent, to be honest with you, must be 6 weeks ago here on race course road we got in Waipukurau and we spent 5 days digging up the road going round and round in circles trying to find this water leak. And it turns out it was an old 20mm service that went across to a property that had not been there for 30 odd years apparently, it was just a copper service. It just had a hole in the bottom, and it had gone down to a level in the ground where it was hard, because they rebuilt the road and they put a shingle road over the top. Probably 5 or 600 mm of metal over the top of it. Built straight on top of the old road, and it was tracking all over the place. Normally you would dig it up, and the water is coming from this direction sort of thing, well ok you know the leak was over there. But we just did one section and thought "oh yeah weve got it" next minute water started pouring out of another one. But oh look, as I said, we spent five days, we were digging round all over."

However, most of the time there is enough pressure and volume of water for leaks to be discovered easily. Furthermore, as shown in Table (5.5), many experts stated that there are lots of solutions and ways of identifying leaks other than surface manifestation such as loop locators, prior knowledge, predictive maps, and the use of hydrant boxes. Overall, after taking all perspectives and experiences into account, additional repair times were only given to small broken pipes in steep slopes. Larger pipes or pipes in shallow gradients are expected to create easily seen surface manifestations, where no additional or negligible added time is required to identify faults.

Table 5.5 Interview summary table. The overview of all perspectives from the interviews around the damage inspection process. The condensing of interview statements follows the procedure in section 4.1.2.4. The black text represents identified problems related to the topic and the red text solutions

| Inspection Process | |
|---|--|
| Problems and Concerns Expressed | Possible Solutions |
| Because water can run downhill and rise to the surface away from leaks and as leaks are often identified by looking at surface manifestations, repair crew may struggle to find the exact location of pipe damage, halting the repair process. | <p>Loop locators and diviner rods can be used to find leaks.</p> <p>Water hydrant boxes can show how far the water has travelled downhill (shows water level underground).</p> |
| <p>It is much harder to find leaks in non-pressurised pipes, like wastewater pipes, as there is no bubbling or geysers.</p> <p>Earthquakes can create multiple holes which can reduce the pressure needed to push the water to surface for identification.</p> | <p>Previous experience with vulnerable regions can also increase inspection efficiency as the most likely areas of damage can be inspected first.</p> |
| <p>Pressure is needed to find leaks. Therefore, each section has to be shut off when conducting repairs as too many holes make pressurisation impossible.</p> | <p>Predictive maps can be used prior to the event to show areas of likely damage.</p> |
| <p>House tobys are usually turned on, adding to more pressure losses.</p> | <p>Leaks can be found using telemetry systems that track pressure changes using GPS and GIS systems.</p> |
| <p>Liquefaction increased the difficulty of identifying the leaks in Christchurch due to the amount of water on the surface. Thus, the inspection process had to wait for a day for the liquefaction water to reside before turning the water supply back on for inspection. This liquefaction impact could occur in Wellington</p> | <p>Damage often leads to significant amounts of water gushing to the surface as a geyser. Thus, finding leaks may be quite simple.</p> |

5.3.2.1 Impact on Repair Times

Overall after running the model, using the calculations in Section (4.3.2.1) the calculated additional repair from all sources averaged around three days. Interestingly all the Lower Hutt sources gained similar times, while Kaitoke received almost no extra time, suggesting that the most at-risk pipes are those shared by the three Lower Hutt sources along State Highway 2 (Table 5.6) (Figure 4.3 & 4.4)

Table 5.6 Total inspection time from each source, calculated from the model.

| Source | Inspection Time (days) |
|----------------------|-------------------------------|
| Hutt River (Kaitoke) | 0.05 |
| Wainuiomata | 4.25 |
| Waterloo | 4.15 |
| Gear Island | 4.15 |

5.3.3 Staff Logistics

One topic addressed quite frequently by the respondents was staff logistics. This topic was raised by the interviewees even though there were no pre-prepared interview questions around staff logistics and its effects on repair times (see Appendix 7.1) Many of the concerns raised by the experts were around working with people from different organisations and with various levels of experience. One interviewee, for example, stated that experts from different regions have their own terminologies and ways of doing things, and when these professionals join in with the response, discrepancies around the repair process can arise (Table 5.7). Problems around staff logistics within organisations were also highlighted. For example, one expert stated that staff turnover could lead to losses in experience and valuable information, such as the location of vital shut-off valves. These losses are further exasperated by poor documentation and inaccurate databases.

Not everything raised by the interviewees was negative, however, as plans around these problems were discussed such as the continual improvement of various databases, and plans to be able to house workers from other regions. Overall, inconsistencies from exterior workers, inexperience and hard to find valves, lead to increases in repair times.

Table 5.7 Interview summary table. The overview of all perspectives from the interviews around staff logistics. The condensing of interview statements follows the procedure in section 4.1.2.4. The black text represents identified problems related to the topic and the red text solutions.

| Staff Logistics | |
|--|---|
| Problems and Concerns Expressed | Possible Solutions |
| Staff turnover leads to the loss of experience around efficient pipe repair and critical valve locations. | |
| <p>Ineffective and subpar databases cause confusion and slow down repairs.</p> <p>Discrepancies can occur from outside repair crews doing things their own way. This discrepancy is not helped by the fact that pipe information databases are unique to each region where they all use different methods of storing and analysing data.</p> <p>Sometimes the information from databases do not line up with reality, slowing down repairs because the pipes are not where they are stated to be, or their attributes are different.</p> | Councils and other organisations are becoming better with GIS and GPS systems. |
| The pre-set plans to spring into action are in need of improvement. | Wellington has plans already set in place. |
| Accommodating workers from other regions may be difficult. For example, it may be hard to find beds, shelter, and transport, especially when others in the region are without a place to live as a result of the damage to infrastructure. | Campsites and naval ships often offer their services. These ships can also carry equipment if needed. |
| Each region has different terminologies for things which can cause confusion between responders. | |
| When responding to an event, responders are removed from other commitments and jobs that may be important. | |

5.3.3.1 Impact on Repair Times

After including staff logistical implications through the calculation in Section (4.3.2.3), pipe repairs are estimated to take an additional three to nine days depending on the source. Overall, the water sources with a higher predicted degree of damage, such as Wainuiomata, are predicted to take more time to repair, while those with a smaller amount of damage are expected to take less. Interestingly the difference in added time between sources in Table (5.8) is very like the differences

in base repair times in Table (5.1). In initial repair predictions, Wainuiomata is predicted to incur five times more breaks than Kaitoke, and Waterloo and Gear Island are predicted to have three times more. Overall, these additional repair times from staff logistics are quite significant, as adding nine days to repair times, increases base repair times by more than 25%, adding more time than any factor mentioned so far.

Table 5.8 Total calculated time from staff logistical impacts. Logistical considerations include the impact of not knowing where shutoff valves are located and from having to redo jobs because of discrepancies.

| Source | Average Time Added (Days) |
|----------------------|----------------------------------|
| Hutt River (Kaitoke) | 2.84 |
| Wainuiomata | 9.28 |
| Waterloo | 7.61 |
| Gear Island | 7.15 |

5.3.4 Power Needs and Generators

In addition to staff logistics, the requirement of electricity for repair and function of the pipes was discussed in the interviews under interdependency. However, in contrast to the previous factors mentioned, electricity was not included in the model, even though most experts identified the need. This conclusion was made because many simple solutions were raised by the interviewees. For example, multiple respondents stated that most pump stations have backup generators and most repair crews carried their own generators to power their equipment (Table 5.9). Therefore, the repair crews are not reliant upon the regional electricity supply. Some concerns around these backup generators were highlighted by the respondents such as the requirement of fuel and possible access problems. However, as there was not enough data or time to explore these factors to a sufficient depth, and because pipe damage may not be accessible if generators are inaccessible, the impact of electricity was left out. A more in-depth discussion around electricity can be found in Section (6.1)

Table 5.9 Interview summary table. The overview of all perspectives from the interviews around electricity and generator requirements. The condensing of interview statements follows the procedure in section 4.1.2.4. The black text represents identified problems related to the topic and the red text solutions.

| Power Needs and Generators | |
|---|--|
| Problems and Concerns Expressed | Possible Solutions |
| Water pumps rely on the electricity supply to function. | Generators are common, and the electricity cables are quite resilient (fixed within a few days after the Christchurch earthquakes). |
| Generators have a short fuel supply that often need to be refilled. | Prior planning is often done by councils, where areas at high risk are supplied with more fuel than their less susceptible counterparts. |
| Generators and pumps can be damaged. Generators require immediate access after an event to be refuelled. | The work trucks the repair crews use often carry generators for powering their tools and other equipment. |

5.3.5 Landslides and Access, Addressing the Interdependency Between the Water Pipe and Transportation Networks

The ability to get to generators and pump stations was not the only access concern raised by the interviewees. Difficulties around reaching damaged pipes and the entrance into and out of Wellington City were also highlighted. For example, one expert stated that in a significant local earthquake, multiple large landslides could occur that would block off the main transport routes, or cover pipes (Table 5.10). These landslides could be a similar size to those observed during the 7.8 Kaikoura Earthquake in November 2016 and therefore could take a substantial amount of time to remove. In addition, another respondent stated that pipes could be in hard to reach areas, either being under buildings, buried too deep, or located under other lifelines.

Many solutions were coined by the experts to address these issues. For example, it was suggested from experience, that bulldozers could be pulled up, and across hilly terrain, paths could be cut through the rugged land, caterpillar tracks could be fitted to diggers, and roll-on roll-off barges could be used to transport equipment. However, although useful, these solutions would still require additional time to implement, and may not be viable for large landslides.

Table 5.10 Interview summary table. The overview of all perspectives from the interviews around the access requirements. The condensing of interview statements follows the procedure in section 4.1.2.4. The black text represents identified problems related to the topic and the red text solutions.

| Access | |
|---|---|
| Problems and Concerns Expressed | Possible Solutions |
| Road damage can make some locations completely inaccessible. | Diggers and bulldozers can tug each other up hills and across rough terrain. Paths can also be dug out, and diggers can pull themselves over hills by their bucket. Rubber tires and caterpillar tracks can also be used to make access easier. Finally, helicopters can be used to move supplies around. |
| <p>A total of 28 large slips occurred along roads in Kaikoura. The same result can easily happen in Wellington.</p> <p>In Kaikoura getting rid of these 28 landslides was difficult as the debris could not simply be pushed into the sea for safety reasons, etc. Overall, the banks of each landslide had to be shored up before the slips could be carefully removed, which took time.</p> <p>In Wellington, if there are properties above landslides, cautionary approaches would need to be taken to make sure the properties are not damaged, slowing down repairs.</p> | Construction of Transmission Gully will reduce the impact 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. |
| 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. | |
| 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. | |
| These landslides will stop large equipment and parts necessary for the repair process from reaching areas in need. | |
| Pipes are sometimes too deep or are hidden behind other pipes, thus can't be accessed easily. | Most water supply pipes are not deeply buried 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. |

| Problems and Concerns Expressed | Possible Solutions |
|--|---|
| The Wellington Port is currently damaged, so it is not expected to be useful after an event. | Roll-on roll-off barges can be used instead. |
| The rail lines are not an option either due to predicted damage (see Kaikoura). | The airport can also be used if needed. |
| Some regions like Wainuiomata have only one route in and out. Thus people may become stranded. | |
| The roads must be closed for pipe repairs to allow for diggers to work. | Lifeline groups already have collective plans and understanding around how to approach the repair process. |
| | Additionally, there is usually at least one lane available when repairing pipes, as the process does not take up the entire road. |
| | Repairs should only take a couple of hours (3-4). |

Interestingly, there was no universal agreement around the size of the impact. Some experts believed after an earthquake; access would not be a significant problem, as most roads would still be usable and pipes would be simple to reach. Others believed that access would be a major issue, where many important roads would be closed, and multiple pipes would be difficult to reach. However, despite these clear differences, there was a universal agreement on the existence of the problem itself.

5.3.5.1 Landside Impact on Repair Times

After running the predictive model 15 times, average landslide impacts ranged from 28 to 98 days depending on the source (Table 5.11). See section (4.3.5) for calculation. The upper end of this range is around twice as long as the original repair times (Table 5.1), and more than the combined impact of all the other additional factors explored. Interestingly there is no difference in added repair times from Wainuiomata, Waterloo and Gear Island, as they all have the same number of failures. This similarity suggests that all failures associated with landslides occur along the shared State Highway 2 pipes. Kaitoke is expected to receive much lower impacts. However, this makes sense, as the most vulnerable regions are along State Highway 2 (Fig 4.5 & 4.6).

Table 5.11 The calculated additional times needed to create alternative routes around the broken pipes buried 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 |

5.4 Fault Ruptures

Fault ruptures are expected to take between 15 and 17 days to repair based on the predictions in (Cousins, 2013) and the calculations in Section (4.3.3). These additional times are significant, adding between 44% and 59% to base repair times (Table 5.12 & 5.2). Pipes from Kaitoke are predicted to take less time compared to the Lower Hutt sources, which were all calculated to take the same time.

Table 5.12 Calculated fault rupture repair times, in days from each source

| Source | Fault Repairs (days) |
|----------------------|----------------------|
| Hutt River (Kaitoke) | 14.82 |
| Wainuiomata | 17.26 |
| Waterloo | 17.26 |
| Gear Island | 17.26 |

5.5 Miscellaneous Factors

Finally, the additional planning and inspection times used in Cousins (2013) & McCarthy (2009) were added (Table 5.13). These extra numbers were included as they address important factors. Headworks incorporates the time required to repair the water treatment and collection infrastructure. Securing of saturation refers to the personal time needed for each worker re-orient themselves after a disaster, checking on family and loved ones. Assembling of materials is the time required to organise equipment regionally. Finally, 'inspection and planning' refers to the regional planning between multiple parties. It was decided by the researcher to include these numbers in addition to staff logistics, as they address different factors.

Table 5.13 Additional factors used in Cousins (2013) & McCarthy (2009).
Numbers are in days.

| Source | Headworks | Securing Situation | Assemble Plant & 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 |

5.6 Total Repair Time from Each Source.

The combination of each factor, including those already included in the pre-altered Cousins Model, such as fault crossings, added an average of 30 days to base repair predictions, showing that repairs are much more than just engineering procedures (Table 5.1 & 5.14). When looking specifically at the impact of the factors raised in the interviews, the repair times increased from an average of 66 to 77 days, adding between 3 and 13 days depending on the source.

Out of all factors, the largest impact on repair times was from fault ruptures and staff logistics, increasing base repair times by 46% and 25% respectively. The factor with the greatest impact, land sliding, was not included in final repair time considerations as there was not much evidence for the numbers given. However, it could be expected that repair times would take on average 80.5 days longer (Table 5.14).

Overall water restoration times are extensive and could be longer if all factors in the interviews were included. However, due to time constraints and difficulties around modelling, some factors were left out.

Table 5.14 Final repair times, showing the added time, in days, from each factor investigated. Numbers have been rounded to the nearest day.

| Source | Base Repair + Prospect Times | Headworks | Securing Situation | Assemble Plant & Materials | Inspection and Planning | Fault Repairs | Totals Before Adding Interview Factors | Extra Inspection | Oddball Sizes | Find Valve | Total (days) | Landslide Burial Impact (days) | Totals With Landslide Impacts |
|-------------|------------------------------|-----------|--------------------|----------------------------|-------------------------|---------------|--|------------------|---------------|------------|--------------|--------------------------------|-------------------------------|
| Kaitoke | 30 | 6 | 1 | 1 | 2 | 15 | 56 | 0 | 1 | 3 | 59 | 28 | 87 |
| Wainuiomata | 54 | 6 | 1 | 1 | 2 | 17 | 82 | 4 | 0 | 9 | 95 | 98 | 193 |
| Waterloo | 38 | 6 | 1 | 1 | 2 | 17 | 66 | 4 | 0 | 8 | 78 | 98 | 176 |
| Gear Island | 34 | 6 | 1 | 1 | 2 | 17 | 62 | 4 | 2 | 8 | 75 | 98 | 173 |

5.7 Contextual Factors Identified in the Interviews that were not Included in the Model

There were many other important factors raised in the interview process that are important to consider when repairing the water pipes. For example, environmental impacts, politics, and health and safety are all important. Unfortunately, none of these factors could be included in the model due to the time constraints, limited information, and because of the difficulty of incorporating them into the mathematical model (Table 5.15). For example, political impacts, such as interdepartmental communication was too difficult to model because there were too many variables to consider. Secondly, shut-off valves, could not be included in the analysis because there was not enough information on their location. Finally, difficulties around equipment acquisition were not included, outside of assumptions in Cousins (2013), as there was not sufficient time to explore the effects.

5.8 Summary

The interviews provided a significant amount of useful information that was valuable for updating the Cousins Model. Many of the key influences raised in the interviews such as staff logistics, access and damage inspection, were included into the predictive model and their influence explored. Overall, it was found that all factors, apart from pipe redundancy and oddball sizes, increased pipe repair times by a significant amount. Local ground conditions were also deemed vital. For example, fault ruptures increased repair times by around 46%, and land sliding increased repair times by more than 100%. However, the impact from landslides could not be included as there was not enough evidence for the numbers given. As a collective, these additional factors, doubled base repair times, showing that contextual factors are important.

Table 5.15 Factors highlighted in the interviews that were not included in the calculations. The condensing of interview statements follows the procedure in section 4.1.2.4. The black text represents identified problems related to the topic and the red text solutions.

| Problems and Concerns Expressed | Possible Solutions |
|--|--|
| Valves and Water Pressure | |
| Need to be able to turn the valves off quickly enough to stop the loss of water. | The repair process is relatively easy once the leak is found. |
| Inexperienced staff may not know where shut-off valves are located. | |
| Valve sites can be hard to find. | |
| Large pipes sometimes have to be re-pressurised using bypass pipes before valves can be opened due to the immense pressure of water from one side prohibiting the movement of the valve mechanism. | |
| There may not be enough valves to turn off, only the areas required to repair the pipes. Thus, large areas may have to be turned off instead, affecting lots of people. | New valves can be cut in. Also, Wellington has plans with the Port and Airport to ship potable water into the region when the supply is down. |
| Air can get into the pipe during repair and cause problems when the water is turned back on. Thus repair crews have to be careful when turning the water back on. | |
| The water may not be able to be turned off for a range of reasons which makes repairs hard, as repair crews will have to work around gushing water. | Repair crews can hammer Totara pegs into holes to stop water gushing, allowing for repairs to be made when the pipes are pressurised. |
| Old pumps often send shockwaves down the pipes when turned on, due to the sudden change in pressure, which can damage the pipes. | New variable speed motor pumps can solve this problem. |
| Equipment Acquisition | |
| There is a possibility that manufacturing sources do not have the required equipment or the resources to create the needed parts locally. | Wellington has a prior understanding with quarries to use their earthmoving equipment in emergencies. Equipment is also available from the Transmission Gully works. |
| Large road construction equipment, may not be available locally, as they may be being used in other regions. | |
| Politics | |
| Different organisations working together can cause problems if communications are not well conducted. Poor funding can lead to bad repairs as shortcuts are made. | |

| Problems and Concerns Expressed | Possible Solutions |
|---|--|
| Vulnerability and Pipe Attributes | |
| Damage to reservoirs can make shut-off valves irrelevant as the water can be lost from the reservoir through cracks regardless (see Kaikoura). Thus, a large amount of water can be lost from the system. | |
| The network is full of older pipes like galvanised iron and asbestos cement which are more likely to be damaged. | Presently Wellington is undergoing the slow process of updating and improving its pipes. |
| Health and Safety | |
| The boom of digger working under or near live wires can arc if it hits, or gets too close to power cables. | |
| Donated water trucks can cause sicknesses if not properly sterilised. | Councils will stick with already set up procedures to supply water (using port and airport). |
| Environmental Impacts | |
| Further damage can occur to the roads and the surrounding areas when using equipment like earthmovers, as that can leak oil and diesel. | |
| Damage to the roads can also occur from the earthmover's caterpillar tracks as they can chew up the ground. | Smaller equipment with rubber tyres can be used instead instead. |
| Earthquakes and landslides produce a lot of waste that needs to be dealt with. Extra time is therefore required to process the spoil. | |
| Further environmental and structural damage can occur as water from the recently damaged water or wastewater pipes can seep out. | |
| Topography and Ground Damage | |
| Failures on hillslopes, near reservoirs for example, usually affect more people than smaller pipes in flat land near cities. | |
| Large ruptures along the Wellington Fault can cause significant surface damage. | Prior knowledge of at-risk regions can make the repair process faster as prior planning can be done. |
| Uplift and fault rupture can cause pipes to misalign, altering their gradients, which is especially a problem in gravity fed, non-pressurised pipes. | |
| Large land movements can redefine catchment areas. | |

Chapter: 6 Discussion and Conclusions

This chapter begins by discussing the roles each lifeline has in relation to the functionality of the water supply network. Then, the meaning behind the results is addressed, integrating the interviews with the created predictive model. Next, the overall patterns and key themes identified through the research are compared to the wider literature and former models, where the advantages and disadvantages of the research approach are explored. A general picture of the restoration process is then explained fleshing out some of the specific ideas raised from the interviews. Afterwards, the overall impacts from the final model are discussed, where small, and large-scale effects are described. From these impacts, the solutions and possible methods of increasing the resilience are discussed. Then the limitations of the study are stated, where feasible recommendations are mentioned. Finally, a conclusive statement is given, wrapping up the study

6.1 Role of Other Lifelines and Interdependency

As the results show, local and contextual factors can have a substantial impact on the water pipe repair process, significantly increasing restoration periods. Thus, to be able to predict the repair times accurately and to fulfil objectives 1 and 2, a good understanding of the overall restoration process and repair requirements are needed. Firstly as discussed, no lifeline acts in isolation as they each depend on each other to function (Rinaldi et al., 2001). For example, the water supply relies on the electricity network, the electricity network on the transportation system, and the transportation network on the power supply. Generally, the water supply relies on electricity to be able to collect, process, and distribute water to people, places, and businesses (Buxton & Pringle, 2014). As the water supply relies on power to provide a service, the electricity network can be considered a critical requirement, and thus should be included in resilience and restoration calculations. In this study, electricity was left out of calculations, due to the revelations from the interviews and because of its resilience against earthquakes. Many of the interviewees responded that a majority of the water pumps used for pressurising and distributing water have backup generators that can be used when required, and contain enough fuel for at least a day of continual use (Table 5.9). Furthermore, most of the maintenance vehicles used for pipe repair carry generators that can be employed if needed. Therefore, it is not necessary for the electricity network to be functional

for the initial inspection and repair processes. Though, due to landslides and road damage, access to the generators for refuelling can become a problem. However, since the water pipes and the cables follow the same vulnerable corridors, the access problems that arise from the electricity network will also occur for the water supply pumps and pipes themselves, as the broken pipes would not be able to be repaired in the first place (Fig 2.3 & 2.4). Thus, the transportation network is the main factor in this instance, not the electricity supply. Overall because of the availability of generators, the resilience of the electricity network, the required 6 days to repair the water supply headworks, and because Christchurch and Kaikoura only took 10 days to restore electricity to 90% of the network, most of the network will already be reinstated before electricity is needed (Eidinger & Tang, 2012; Marlborough District Council & Marlborough CDEM Group, 2017).

6.1.1 Telecommunications

Telecommunication impacts were also left out of the calculations for similar reasons. For example, multiple backup alternate communication mediums can be used in a disaster. The use of social media is a case in point, where it is a common communication method between those in need after significant events (Yates & Paquette, 2011). Furthermore, satellite phones and radios can also be used, all of which are common tools for repair crews and emergency services (Porter, 2016; Tait Communications, 2012). Like the electricity supply, the telecommunications network is expected to be one of the first lifelines to be restored, due to its resilience, where emergency levels of service can be reached within ten days of the main event (Mowll, 2012). Difficulties can arise from organisations switching and using alternative methods they are not used to. However many of these challenges only add a small amount of time to repair processes, the effect of which has already been included into the staff logistics calculations (Sections 4.3.2.3 & 5.3.3)(Porter, 2016). Therefore, because of the resilience and multiple mediums available, telecommunications were not considered as an essential factor to consider when calculating water pipe repair times.

6.1.2 Transportation

The transport network, however, was considered in calculations, as it has a significant impact on overall repair times (Table 5.11). For example, it is expected that all main transport routes including the roads, rail, port, and airport will fail in

a Wellington earthquake scenario (Ministry of Civil Defence & Emergency Management, 2010). The main roads are projected to be closed as a result of massive landslides, which could also bury water pipes (Hancox & Perrin, 2010). Due to burial, repairs will likely take an additional 28 to 98 days, depending on the source (Table 5.11). These final times could be longer, as it is hard to know the overall impact road closures could have, especially if landslides are as large as those that occurred in the 2016 Kaikoura earthquake (Table 5.10) (New Zealand Transport Agency, 2017). According to Hancox and Perrin (2010), some of the possible landslides in Wellington have the potential to deposit as much as 10^5 cm^3 of material, which is a similar size to the largest slips along State Highway 1 north of Kaikoura (Hancox & Perrin, 2010; New Zealand Transport Agency, 2017). Landslides of this scale could close transport routes for many months, prohibiting access to the pipes and separating Wellington from the rest of the nation slowing down the movement of needed equipment and resources. Because of the potential magnitude of these impacts, many solutions have already been devised.

6.1.3 Possible Access Solutions

Many different solutions to these access problems were discussed in the interviews. For example, roll-off and roll-on barges were suggested as alternative methods for transporting needed materials into and out of Wellington and reaching blocked off pipe segments along State Highway 2 (Figure 2.3 & 2.4) (Table 5.10) (Hancox & Perrin, 2010; Mowll, 2012). Another solution included acquiring the essential resources and parts from local suppliers and manufacturers. However, in an earthquake, using these manufacturers may not be an option because they require running water, electricity, and access to raw materials to function which may not be immediately available after an event (Lam et al., 2009). Thus, replacement parts may need to be created elsewhere and shipped in, lengthening repair times.

Besides raw materials, large earth moving equipment will also be required to remove debris and dig down to the broken pipe sections. Gaining access to earth moving equipment may be difficult, especially if the roads and rail lines are not functional. Roll-on roll-off barges can be used along coastal areas to transport this equipment. However inland areas may be difficult to reach due to the conditions of the roads (Ministry of Civil Defence & Emergency Management, 2010). To address these problems, the respondents highlighted multiple backup plans, such as

agreements with local quarries like Kiwi Point and current road building projects like Transmission Gully to provide digging and earth moving equipment (Table 5.10). Although, even with the earthmoving equipment it would still take additional time to gain access to blocked off areas.

6.2 Meaning of Results

One of the more interesting patterns observed in the results was the hierarchy of damage and repair time from each source. For example, the water pipes from Kaitoke consistently received the lowest added time from each factor, outside of oddball factors (Table 5.15). Furthermore, Kaitoke gained almost no additional time from inspections despite laying in moderately steep soil along Ngauranga Gorge (Fig 5.2). In addition, Kaitoke received more than three times fewer failures than Wainuiomata despite having the longest length of pipe exposed to earthquake conditions (Table 5.2). Usually, it would be expected that the greater the exposure, the higher the number of faults. However, this is not the case, as the vulnerability of the pipes and the geology is not uniform.

The following sections give evidence to why this hierarchy and other phenomenon occur. Overall the impacts from different factors such as pipe attributes and fault crossings are discussed further, linking the outcomes to literature and explaining why calculations like those used for predicting the impact of staff logistics were done in a certain way.

6.2.1 Pipe Attributes

Pipe attributes such as diameter, material type, age, and joint type, as shown in the results, can have a significant impact on how pipes behave during an earthquake. For example, non-ductile pipes in Christchurch experienced between five to eight times more damage than ductile pipes, depending on the liquefaction severity (Eidinger & Tang, 2012; Sherson et al., 2015). In addition, cast iron pipes in the 1995 Hyogoken-Nambu earthquake, experienced more than four times the number of breaks than their resilient ductile iron counterparts. Also, in the same earthquake, pipes with smaller diameters had break rates four times greater than large pipes. (Kitaura & Miyajima, 1996). Thus, to represent these differences, amplifying factors were given to the pipes in the predictive model based on their attributes, where the worst-case combination, outside of geological factors, lead to pipes being 90 times (6x2x1.5x5) more likely to break (Table 4.4). The result of these amplification

factors, in tandem with Kaitoke's higher percentage of ductile and large pipes, is one of the main causes for the significant differences between Kaitoke and Wainuiomata and their repair times, providing answers for the fifth research objective.

The physical attributes of the pipe also have a significant impact on overall repair times. For example, the material type and diameter of the pipe can influence the repair process. For instance, some materials like steel can be easily clamped or welded, while other materials like asbestos cement cannot be easily clamped as the damage is often too high, where whole sections need to be replaced instead (Eidinger & Tang, 2012). Not only are clamps inappropriate for some material types, they can also cause damage and not work effectively on smaller pipes (Table 5.3).

Respondent 1: "But if you are going from PVC to PVC 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"

In addition, as discussed in section (5.3.2) pipes with smaller diameters can increase damage inspection times, as smaller pipes in steep soils can produce surface manifestations downhill from the broken segment, causing confusion and slowing down repairs. Overall, pipe attributes have a significant impact on the pipe repair times, but are not the only factors that need to be considered.

6.2.2 Fault Ruptures

One of the most impactful factors outside of pipe attributes and landslides was the influence of geological influences such as fault ruptures which added between 14 to 17 days to repair times, depending on the source and the type of crossing (Table 5.14 & Figure 2.2 & 2.3). Interestingly all sources from Lower Hutt received the same additional time, as the pipes converge into one pipeline before reaching the Wellington Fault. Kaitoke received slightly lower additional times as it encounters the Wellington fault at different locations where less damage is expected. Overall fault rupture times are anticipated to be quite significant, adding at least two weeks from each source. These long times agree with the wider literature which predicts four to five-metre horizontal and one-metre vertical movements along the Wellington Fault as a result of a Mw 7.5 event (Mowll, 2012; Nayerloo & Cousins, 2014). One of the more vulnerable fault crossings is the Silverstream Bridge that crosses the Hutt River. In an earthquake event, this bridge could take up to a few

weeks to repair, and thus potentially slow the overall repair process (Cousins, 2013).

6.2.3 Staff Logistics

One of the more difficult impacts to model is the influence of people on repair times, as qualitative and contextual impacts are not easily incorporated into mathematical models. For example, in the event of the disaster, many unknowns can occur, such as having to redo work previously done; working with and housing people from other regions; poor communication mediums; required people missing; and planned procedures failing (Section 5.3.3) (Broadstock, 2016; Cole et al., 2015). Because of these complexities, a standard randomised time was added to each repair job to mimic the unknown (Section 4.3.2.3). Using a random number can be considered a crude way of implementing unexpected difficulties. However, it does improve repair time predictions overall as the possible impacts from unforeseen events are included.

Christchurch is a good example of the impact of the unexpected. The liquefaction experienced in Christchurch was much higher than anticipated due to contextual factors such as a shallow water table, high artesian water pressure, and the susceptibility of local soils (S. Cox, Personal communication, February 23, 2015; Cubrinovski et al., 2013). This liquefaction caused severe damage to infrastructure, specifically buried assets, where damage was higher than anticipated for a Mw 6.3 event (Eidinger & Tang, 2012; Sherson et al., 2015). In addition, many people in Christchurch had to have their house repaired multiple times because of poor and inconsistent repairs and bad communication between companies and stakeholders where there was confusion around who was responsible (Broadstock, 2016). Although lifelines are different to privately owned houses where large corporations oversee their maintenance and repair, similar problems can still arise. It is these unexpected factors and local impacts, such as loss of access to the pipes that need to be addressed and included in current models.

6.3 Contribution from Research Findings to Reduce the Research Gap.

The aim of the research was to improve current predictive calculations by incorporating the impact of these site-specific factors and interdependencies. It was found that many of the current predictive models such as Cousins (2013);

Mowll (2012), do not fully address the influence of site-specific factors and contain many assumptions around lifeline interdependency. For example, contextual factors such as staff logistics and the planning around repair endeavours are either only briefly mentioned or are not discussed at all. Furthermore, access to the pipes is assumed, where it is expected that the pipes or any needed equipment can be quickly accessed after an event. Despite missing many of these factors, the models do provide very comprehensive evaluations on the expected damage and therefore were used as a base for the study. The localised factors and interdependencies were then added as additional information, and their influence measured, answering the third research question.

6.4 Alteration of Current Models, and Comparisons with Literature

Through including the impact of additional contextual factors, repair times from each source, increased by ten days on average (Table 5.14). However, despite including these impacts, final repair times outside of landslide effects were very similar to the pre-altered Cousins Model, and wider literature estimates of 52 and 65 days respectively (Cousins, 2013; Mowll, 2012). These similarities exist because slight alterations were made to the damage calculations and redundancies were included into the model.

6.4.1 Why Redundancy was Included

Redundancy, as discussed in sections (4.2.3 & 5.2.1), is the influence of backup or alternative pathways on the probability of failure, where in some regions multiple pipes are required to fail to stop the flow of water. During the aftermath of a disaster, the repair crews aim to restore water as quickly as possible to those in need (Beban, Doody, Wright, Cousins, & Becker, 2013). Thus if at least one pipe is still functional, repair is not immediately needed. Instead, repair crews can shut off broken segments and repair them after an emergency level of supply is established. In most instances, multiple repair crews can be utilised. Thus, some repair crews can work on restoring the emergency supply, making sure pressure is holding, while others can work on restoring the network to full capacity, repairing pipes that are not immediately necessary (Cousins, 2013). By including the influence of redundancy, the number of overall failures dropped significantly, cutting the number of needed repairs in half for most sources (Table 5.1 & 5.2)

6.4.2 Why the Cousins Model Damage Calculations Were Altered

Altering the amplification factors, also changed damage predictions. The pre-altered Cousins Model assumed that brittle materials were two times more likely to fail than their ductile counterparts, and small pipes, with diameters smaller than 600mm, were four times more likely to fail than large pipes, greater than 600mm (Cousins, 2013). After studying damage from the Christchurch earthquakes it was discovered that non-ductile materials are instead six times more likely to break, and small diameters are only 1.5 times more likely to break (Sherson, 2015; Sherson et al., 2015). By altering the amplification factors, the number of predicted failures changed, where pipes from Kaitoke, without the influence of redundancies, were predicted to have half the number of breaks than the original model (Table 5.1)(Cousins, 2013). Through this alteration not only were the impact of including redundancies, and the impact of pipe attributes revealed, but a more accurate model that better represents reality produced, fulfilling the fourth research objective (Section 1.7).

6.5 Further Damage if the Landscape and Scenario Were Different

In certain circumstances, the influence of these additional contextual factors can be quite significant and in some contexts, even more significant than what was shown in the results. For example, when working with tiny pipes on steep slopes, repair times can easily escalate as one respondent stated.

Respondent 1: "I spent, to be honest with you, must be 6 weeks ago here on race course road we got in Waipukurau and we spent 5 days digging up the road going round and round in circles trying to find this water leak. And it turns out it was an old 20mm service that went across to a property that had not been there for 30 odd years apparently, it was just a copper service. It just had a hole in the bottom, and it had gone down to a level in the ground where it was hard, because they rebuilt the road and they put a shingle road over the top. Probably 5 or 600 mm of metal over the top of it. Built straight on top of the old road, and it was tracking all over the place. Normally you would dig it up, and the water is coming from this direction sort of thing, well "ok you know the leak was over there". But we just did one section and thought "oh yeah weve got it" next minute water start pouring out of another one. But oh look, as I said, we spent five days, we were digging round all over.

If this same scenario was to occur multiple times in a disaster, repair times could drastically increase. Luckily most of the bulk water pipes in Wellington are located

on shallow slopes and are large (Fig 4.3). Thus, the overall impact of water moving downhill is low (Table 5.6). If the predictive model was shifted to another region with smaller pipes that lie in steep slopes, the impact could be much more extreme. For example, if all the Wellington bulk water pipes lay in only moderate and steep slopes, (all the shallow gradients were converted to moderate slopes and all moderate slopes steep slopes), inspection times could increase by up to 41 days (Table 6.1). In addition, if all pipes were assumed to be small, inspection times could increase by around half a day.

Table 6.1 Possible changes to damage inspection times if ground conditions were different. 'All small diameters', assumes that all pipes are 'small' and applies the small pipe considerations to each pipe (see Section 4.3.2.1). 'Altered slope conditions', assumes all pipes lie in sloped areas, where all moderate slopes were treated as steep slopes, and all flat land as moderate gradients. Thus, each broken pipe received some form of additional time.

| Source | Original Times | All small Diameters | Altered Slope Conditions |
|-------------|----------------|---------------------|--------------------------|
| Kaitoke | 0.00 | 0.08 | 8.67 |
| Wainuiomata | 3.78 | 4.27 | 41.04 |
| Waterloo | 3.78 | 4.17 | 36.03 |
| Gear Island | 3.78 | 4.17 | 34.16 |

Another good example of the impact of localised factors is poor documentation and planning which often occurs in small towns and regions. For example, as explained by Respondent 1, because of poor planning, critical valves can be easily blocked off when buildings are built over top.

Respondent 1: "because there are some mains in some stupid places, we have got a few of them here as well, that come down through people's properties, fences, and it's under garages. There has been the odd occasion, where you end up having to run mains around the garage because it was broken in underneath the garage. And you know cause years ago, nobody bothered about where everything was, and this neighbour sold off his little bit of property, so the other fella, he just started building, so he built his house, and nobody realised the main was under there, you know it's all those sort of scenarios. It wouldn't happen today, but unfortunately, it's stuff that had been there for years, that people don't know about. We have got one here I know in town, where they extended the classroom block on the high school, and they built over one of the main valves that shut the line off. It comes in through one street and then through another, and the main runs through the school. The valve under the building is actually off now. Before you could isolate valves and keep the school running off different ends, but cause this valve is off, if it breaks on one side of the school compared to the other that means there is no water at the school, and so if you've got a problem. You either wait till the

school is out or hope that it will happen sometime when schools not there. God only knows what will happen if the main broke underneath the prefab that is on it now”

However, due to the vulnerability of the pipes in Wellington; strong funding, local expertise; and size of the city, where the exact location if each pipe must be known; the asset databases in Wellington are well maintained. Though as stated, this may not be the case in other regions.

Overall the surrounding land can significantly impact overall repair times. Thus, to reduce the likelihood of losing vital lifelines for extended periods of time, different management practices must be considered.

6.6 Recommendations for Management Decisions That Need to be Done Considering Findings

The results have shown that contextual factors can have quite a significant impact on the overall repair times and thus, have a considerable impact on people, communities, and businesses. To reduce this impact, five different recommendations are given below, based on the results and wider literature.

6.6.1 Recognising the Risk

One of the first management steps that needs to occur when planning for disasters is recognising the risks so that plans can be implemented to deal with the possible situations (Coppola, 2015). The current plans in Wellington, such as Ministry of Civil Defence & Emergency Management (2010); Mowll (2012), look at the disaster from a regional perspective, and only briefly mention contextual factors, where local impacts such as landslides and staff logistics are mentioned but not included in calculations. As discussed, local and contextual factors can have a significant impact on overall repair times. Therefore, these impacts need to be considered. If the impacts from landslides and staff logistics are better understood beforehand, plans can be made to better deal with likely the situations. For example, plans can be made to bypass massive landslides with temporary pipes, so that water can be restored faster, to use roll-on roll-off barges, and to coordinate with other authorities for the use of helicopters. Overall, if research and plans are put in place before a disaster, organisations will be much more prepared to respond when one hits (Coppola, 2015).

Currently, the Greater Wellington Regional Council (GWRC) are planning and implementing strategies for the water supply that deal with the potential impacts from disasters like earthquakes. For example, upgrades to the vulnerable Silverstream Bridge have been commissioned, an alternate bulk water pipeline is currently under construction through Wellington Harbour, providing an alternative connection to Lower Hutt sources, and Transmission Gully, an alternative route for State Highway One is being built to reduce access problems (Greater Wellington Regional Council, 2015; Mowll, 2012). Overall these projects reduce the vulnerability of the Wellington Region by improving particularly susceptible sectors. However, there are many more improvements that can also be made.

6.6.2 Improve lifeline Resilience

In order to increase the resilience of the network, the most vulnerable materials can be replaced with more ductile equivalents, effectively reducing the likelihood of failure for each replaced pipe by six times (Table 4.4)(Sherson et al., 2015). Furthermore, better-engineered fault crossings can be implemented by replacing vulnerable pipes with joints that can withstand large horizontal and vertical movements, following the engineering procedures used in Blair (2014). By improving fault crossings, less damage would be expected, and therefore repair times would be much lower. Also, improvements to the transportation network can be made. By improving critical infrastructure such as the port, which was damaged in the Kaikoura Earthquake, access problems can be significantly reduced or removed altogether, drastically reducing overall repair times. Additionally, many of the most vulnerable slopes in the Wellington Region can be strengthened to resist slipping (Hancox & Perrin, 2010). By increasing their strength, the likelihood of damage to surrounding lifelines, the chance of burying damaged pipes, and the probability of closing off important transport routes for extended periods of time can be reduced.

6.6.3 Update Databases

As well as physically improving networks, the methods of storing data and conducting repairs can also be enhanced. Many councils throughout New Zealand use different methods of storing and managing information. Some councils keep well maintained GIS databases like the Christchurch City Council, while others, specifically smaller councils like Wairoa, use PDFs and CAD drawings (Canterbury

Geotechnical Database, 2013; Sherson, 2015). These differences can lead to variations of how jobs are conducted, and the amount of information recorded during a repair. Inconsistencies in repairs can result in poor jobs that have to be redone (Broadstock, 2016). Furthermore, when there is not enough information recorded, tracking what was done and to what level can become difficult, to the point where databases no longer line up with the actual network. One example of this happening was the repair crews in the Christchurch earthquakes, who were not very consistent with the information they sent to SCIRT. During repairs, some workers did not even state how they repaired the pipe, or what material they used (Eidinger & Tang, 2012; Sherson et al., 2015). If better more consistent data keeping across different organisation and authorities was conducted, many of these problems would be avoided.

6.6.4 Adapt Communication and Aid Procedures

Not only is data management necessary, but the communication and organisation of assistance from external and internal sources needs to be well coordinated. Often in disaster events, many people and businesses want to help by sending personnel and resources to the catastrophe area. Generally, this aid is beneficial. However, difficulties can arise when trying to facilitate all the resources and people. For example, trying to house additional workers after a large group of people have already been displaced is quite difficult as housing facilities may be stretched. In addition, these workers can get in the way of local procedures and chains of command, where outside help can become more of a problem than good. One good example these potential additional problems is the following statement by respondent 4.

Respondent 4: "People are happy about giving you a truck to cart water but you have got to be careful that there are no bugs in the truck otherwise you end up with [more problems]. In that last one in Havelock or whatever it was, someone had supplied a [water] truck, but it had bugs in the tank. that was always a fear for us. These are sort of things where people come and help, but they actually make a bigger problem than was originally there".

In order to coordinate well, those involved must be able to communicate effectively. Therefore many backup communication plans are needed as it is expected that main communication lines such as phones, email, and video conferencing will be temporarily unusable following a significant event (Ministry of Civil Defence & Emergency Management, 2010). Therefore authorities need to plan

for using alternative mediums such as social media, which is becoming more of an integral platform during disasters (Yates & Paquette, 2011). Backup plans such as the use of radios and satellite phones are in use currently, however, these systems are not always ideal and miss the advantages of being able to communicate directly with the community.

6.6.5 Public Education About the Risks

Finally, education around the possible earthquake impacts and how to prepare for the loss of critical lifelines can be implemented to make the community more resilient and less reliant on potentially failing systems. Currently, local civil defence groups such as the Wellington Regional Emergency Management Office, run multiple workshops that help people prepare for and know what to do in the event of a disaster, alerting people of the risk in Wellington and the need to store water. Also, national organisations such as MCDDEM, run many campaigns that educate people about what to do in a disaster such as the ‘Drop Cover Hold’ and ‘If Long or Strong Get Gone’ campaigns (Ministry of Civil Defence & Emergency Management, 2017). Overall these campaigns are instrumental and should continue to be utilised. However care should be taken when educating people as too much education, in tandem with close calls, or the over exaggeration of the risks can cause people to become complacent. For example, during Hurricane Katrina, many people stayed at home and as a result got trapped because they were under the impression that they would be okay, having lived through multiple storms before (Cole et al., 2015; Huret, 2014; Moynihan, 2009). Overall, many things can be, and should be, done to reduce the likely damage, repair times, and impact on people.

6.7 Limitations and Future Research

The research revealed that many different factors need to be considered when calculating down times, many of which have a significant impact on the final predictions. For example, the difficulties around staff logistics can increase repair times by up to nine days (Table 5.14). However, although specific times were calculated, these figures should be taken lightly as the research was conducted with limited data over a short timeframe. Important considerations were highlighted, but the full influence of these factors requires further inquiry. For instance, most of the added factors were based on insights from the interviews where ballpark figures were used. For accurate predictions, more in-depth studies that look into

these estimates are necessary. For example, accurate predictions around the impact of landslides cutting off access and burying broken pipes are required. Difficulties do arise however in becoming more fine-tuned with the predictions as the local environment is full of unpredictable factors and variables that make accurate predictions extremely difficult, and in some cases dangerous, as qualitative factors can be treated quantitatively. Overall more research is required around the impact of local and contextual factors, creating models that can accurately predict these local impacts in tandem with the interdependencies between lifelines.

6.8 Conclusions

It is well known that a Mw 7.5 earthquake along the Wellington Fault will cause widespread damage to lifelines, halting critical services and preventing resources from reaching individuals, communities, and businesses. Of particular importance, is the water supply which is a fundamental need for survival. In Wellington, the water supply is quite vulnerable as the pipes reside in landslide-prone corridors and cross the Wellington Fault multiple times. The repairs to these pipes were found to not only be dependent on engineering principals and the severity of the earthquake, but also on the relationship with other lifelines. For example, a functioning transportation network is required to access the damaged pipes, and a working communication matrix is needed to coordinate the repair endeavours. Currently, most predictive models ignore or only briefly touch on these interdependencies. Furthermore, most of these models do not incorporate local influences such as staff logistics or equipment needs on overall repair times.

Multiple interviews with local experts were conducted to calculate the impact of these contextual factors and to identify the specific problem areas that need to be addressed. From these interviews, it was discovered that there are countless issues that repair crews face when conducting repairs, ranging from the difficulties of finding leaks to politics and the difficulties around funding. Out of these 12, 4 of the most common and prominent factors were selected and added to the Cousins Model. After running the model multiple times, it was concluded that these contextual factors, add between 3 and 13 days to repair times depending on the source, and when incorporating land sliding, between 31 and 111. Therefore, contextual factors have a significant impact, and thus should be integrated into downtime considerations.

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Appendices

Appendix 6.1 Interview Questions

Below are the questions that I will probably be asking during the interview. I will mostly be sticking to these questions, diverging or skipping questions when necessary.

Inspection

- What is the standard damage inspection process for the water supply network?
- What are the differences in this inspection process after a significant event such as an earthquake?
- Can the system know if there is a broken pipe, or do you have to wait until there are visible signs or a warning from a community member?
- Are there any equipment or resources needed for inspection, and if so what are they?
- What level of electricity and road access is needed for inspection?
- How much pressure is needed for Inspection?

Repair of local reticulation network

- What is the usual method of repairing an entirely broken reticulation pipe?
- What is the usual method of repairing a partially broken pipe?
- Are there differences in how pipes are repaired after a large event such as an earthquake?
- How often are replacements used instead of repairs, and in what circumstances are they usually implemented?
- What resources are needed to repair a pipe, such as replacement parts and digging equipment etc.?
- How long does it take to acquire this equipment?
 - Who supplies it?
 - On average, how many of these equipment parts are in Wellington?
 - What happens if there are no freely available parts?
- What level of road access, electricity and communications (telecommunication cables, etc.) is needed to repair the pipes?
- On average, how long does it take to repair a pipe
- How do you repair pump stations?
- Does the dimension of the pipe effect repair?
- Our damage models (fragility models) usually can predict number of breaks per kilometre length or so. Will be useful in your repair strategy?

Repair of bulk water supply network (main pipes from source to city, also known as trunk mains)

- What are the differences between the repairs on a large bulk water pipe and the local reticulation network?
- Are there any differences in equipment needed, and if so what is needed?
- How long does it usually take to repair a bulk water supply pipe?
- What level of service is required for the water to be turned back on?
- How long did it take to repair the electricity cables etc?
- How does liquefaction effect pipe repair?
- How does topography effect pipe repair?
- Damage to port?
- Land sliding damage

Appendix 6.2 Sample Emails sent to Participants

Hi _____

_____ from _____ suggested that you would be a good contact to talk to in regards to my masters thesis.

I am Andrew Sherson a student working with GNS science on a Masters thesis on lifeline interdependency in Wellington. We are specifically looking at accurate repair times of water supply pipes after an earthquake, looking at how the water supply pipes rely on the other lifelines such as electricity and road access to be repaired. I was wondering if I could ask you, or someone who is knowledgeable about the repair process of water pipes etc., a few questions around the repair process, and what is required to repair the water pipes after an earthquake?

I have attached some more info to this email

Kind Regards

Andrew Sherson

Hi _____

I am Andrew Sherson a Masters student at Massey University I have been in contact with _____, asking about calling or meeting up with people knowledgeable about the water pipe assets in New Zealand. Peter gave me your phone number and this contact address to get in contact with you.

The purpose of my studies is to understand the interdependencies of the lifelines better, looking at what the water supply pipes are dependent on to be repaired after an earthquake. The field of study is in Wellington, and is part of a much bigger project that is occurring at GNS science.

I was wondering when would be the best time to give you a call, to ask some questions around the water pipe network. The conversation will probably take between half an hour to an hour to complete.

In this email, I have attached an ethics statement and some more information about the project and what to expect.

Kind Regards

Andrew Sherson

Appendix 6.3 Consent Form Sent to Participants

Project Title: Water Supply dependency on other lifelines for function and repair after a Wellington Earthquake.

Researcher: Andrew Sherson, Masters Student Massey University

- I have read the Information Sheet and have had the details of the study explained to me. My questions have been answered to my satisfaction, and I understand that I may ask further questions at any time.
- I understand that any information I provide will be kept confidential and accessible only to the researcher and his supervisors.
- I understand that the published results will not use my name or my organization name, and that no opinions will be attributed to me or my organization in any way that will identify me or my organization unless prior permission is granted.
- I understand that the data I provide will not be used for any other purpose or released to others.
- I understand that all the data will be destroyed within five years after the completion of the project.

Please underline or circle your choices below:

I agree/do not agree to participate in this study under the conditions set out in the Information Sheet.

I agree/do not agree to the interviews being sound recorded.

I wish/do not wish to have transcripts of the recordings returned to me for verification.

Signature:

Date:

.....

Full Name - printed

.....

Appendix 6.4 Research Information Sheet Sent to Participants



Water Supply Dependency on Other Lifelines for Function and Repair After an Earthquake in Wellington INFORMATION SHEET

Researcher(s) Introduction

I am Andrew Sherson, a student at the Joint Centre for Disaster Research, Massey University, studying a Masters in Emergency Management. I am conducting a short Master's thesis project with GNS science around the interdependencies of the lifeline networks, specifically how they depend on each other for functionality and repairs after an Earthquake.

What is the aim, and what does the project involve?

The aims of the research is to increase the accuracy of current lifeline repair-time predictions, with a particular focus on water supply in a Wellington context. Falling under a much larger GNS Science project that concentrates on the interdependencies of the various lifelines, this project will focus on the dependency of the water supply pipes on other lifelines, both during the repair process and during normal function. Questions such as what are the necessary requirements to repair the pipes, for instance, electricity supply, replacement parts, or road access, will be addressed, where the damage to other networks and their repair times will be integrated into the water supply repair-time calculations. To answer these

questions, the researcher will interview key stakeholders involved in the repair and maintenance in New Zealand. From these interviews, any information provided will be integrated into the current damage and repair models, updating the calculated repair times with more accurate predictions. Once updated, a couple of scenarios will be investigated, calculating the time taken to fix the pipes from the Wellington Water Source to various businesses around Wellington City, bearing in account the damage and shortages of other networks. These new repair times will give more insight into the potential effects of a large Wellington earthquake, and will provide a localised contextual understanding of lifeline interdependencies (both a New Zealand and Wellington context) that can be used for multiple different hazards.

How you were chosen for this invitation

Experts in lifeline maintenance and repair that were known by the researcher, or were known by council staff members who know the researcher were contacted and invited to participate

What will participation involve?

Taking part in this research will involve a semi-structured interview through a phone conversation or by face to face, **and will take up to one hour in time.** Considering that the interview may occur during work time, it may be appropriate to seek approval from your manager before participation.

What are the benefits of participation?

By participating in this research you will be joining in an opportunity to further the knowledge of lifelines management, improve the understanding of potential damages in a Wellington Earthquake, and help a student learn how to research and develop his research skills.

What are the risks of participation?

The conversations and interviews will be recorded using a recording device so that any relevant information missed by the interviewer is not lost, and that anything said is properly understood and not misquoted. Only the researcher will have access to these recordings. Later these comments will be aggregated for data analysis and reported as a combined whole without any identifying information unless permission is given. In rare cases, some quotes may be used in the final write

up, but these will not be linked to you, where no identifying information is given unless prior permission is obtained.

What are your rights if you participate?

This participation is fully voluntary. Therefore there is no obligation to participate, go through the whole interview process, or answer any question. You have the right at any time to withdraw from the study, decline to answer a question, or request the information not to be used.

Where will the data be stored and managed?

The recordings and data will be stored in password protected files, and will be kept for five years after the completion of the project, and then permanently deleted.

Whom should you contact if you have any concerns or questions about the research?

Researcher

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Email: R.Prasanna@massey.ac.nz

Yours sincerely

Andrew Sherson

"This project has been evaluated by peer review and judged to be low risk. Consequently it has not been reviewed by one of the University's Human Ethics Committees. The researcher(s) named in this document are responsible for the ethical conduct of this research.

If you have any concerns about the conduct of this research that you want to raise with someone other than the researcher(s), please contact Dr Brian Finch, Director (Research Ethics), email humanethics@massey.ac.nz. "

Te Kunenga
ki Pūrehuroa

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