Wellington Without Water – Impacts of Large Earthquakes

J. Cousins

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ABSTRACT

Metropolitan Wellington Region is vulnerable to large earthquakes. It is bisected by large active faults, and after a major earthquake on any one of them could become isolated because all of its supplies have to be transported along a small number of lifelines. All are vulnerable to earthquake damage. The potential for total loss of water and food supplies is real and, without mitigation, could render large areas uninhabitable for weeks to months.

Models have been developed for the bulk water-supply system, including pipelines into Wellington City and water storage, and on the consumption side the buildings and people. In the model they were exposed to a suite of large earthquake scenarios, followed by computation of the numbers of breaks in the pipelines, the consumption of stored water, restoration of supply to the reservoirs and thus emergency-level water supply, and the expected shortfalls in supply. Outputs were the numbers of people without water, for how long, and the amounts of water that would be needed to meet the shortfalls.

Only conventional sources of water supply were included in the modelling, because one of the desired outputs was estimates of the quantities of water that might need to be derived from unconventional sources, following large earthquakes near Wellington.

Key findings for a magnitude 7.5 earthquake on the Wellington-Hutt Valley segment of the Wellington Fault (Wellington Fault Earthquake) were:

- The bulk supply lines would suffer about 100 breaks and be rendered completely inoperative.
- Stored water could last 2-6 weeks depending on the rate of consumption and assuming that 50% of the original stored volume would be lost immediately after the earthquake because of damage to reservoirs.
- Bulk water would be restored progressively, taking about 3 weeks to reach Tawa (the suburb closest to source) and 10 weeks to reach Miramar (the suburb farthest from source).
- For a consumption rate of 20 litres per person per day, the number of people without water would peak at 150,000 (80% of residents), and the shortfall in supply would peak at 3 million litres per day. For a consumption rate of 6 litres per person per day the peaks would be 50,000 people and 0.3 million litres per day.
- The times for which people could be without water would be long, for instance 40,000 people without water for 40 days, and 80,000 for nearly 30 days.

Two ways of reducing the water deficits were modelled, with results as follows:

- Supplying water from a new source at Whakatikei, west of the Wellington Fault, reduced the restoration times by about 2 weeks, and the numbers of people without water by 30 to 50%.
- Replacing fragile pipes with robust pipes reduced the restoration times by 5 to 50 days, 5 days for Tawa and 50 days for Miramar, approximately halving the times for which people farthest from the water intakes were without water.

- In each case the times for which people could be without water remained long, for instance 40,000 people without water for nearly 30 days, and 80,000 for 15 days. However, combining both measures reduced the restoration times to levels that were potentially acceptable, i.e. the remaining shortfalls in supply were small enough that they should be able to be filled using alternative sources of water.

The recurrence interval for the Wellington Fault Earthquake is 1000 years (10-15% probability in 100 years). Shaking intensities in the central business district of Wellington are expected to be MM10 or greater (where MM is Modified Mercalli intensity). Lower levels of shaking, MM9 or MM8, have higher probabilities of occurrence, i.e. return periods of 400 years for MM9 and 120 years for MM8. Consequences of the lower levels of shaking are much less severe than for the Wellington Fault event, as follows:

- MM9 shaking: 40,000 people without water for about 15 days, and 80,000 for 8 days.
- MM8 shaking: Loss of supply in some areas, with restoration of supply being completed before stored water has been consumed.
- MM7 shaking: Minor loss of supply in some areas, with restoration of supply being completed well before stored water has been consumed.

Sources that are capable of generating high levels of damage to the water supply system are the Wellington-Hutt Valley segment of the Wellington Fault, the Wairarapa Fault (which last ruptured in 1855 and so is unlikely to rupture again in the near future), the southern segment of the Ohariu Fault, and probably the Hikurangi Subduction Zone. In all cases it would be necessary to find ways of providing large quantities of emergency water (hundreds of thousands to millions of litres per day) to sustain tens of thousands of people for one to several weeks.

However, there are only a few earthquakes sources capable of causing such problems. For shaking levels below MM9 the modelling indicates that it should be possible to restore bulk supply before stored water is depleted. Local fault sources in that category include the Whitemans, and the Akatarawa-Otaki Faults, and the Tararua East segment of the Wellington Fault.

Even for the four most damaging events, the modelling indicates that it should be possible to lower the shortfalls to reasonable levels using a combination of a new water source at Whakatikei and replacement of fragile pipes in pipes in the bulk-supply network with robust types. Water from alternative sources, like drainage water from a local rail tunnel and rainwater harvesting, also could make large contributions, but have not yet been included in the modelling.

KEYWORDS

Earthquakes, infrastructure, lifelines, water-supply, risk, Wellington

1.0 INTRODUCTION

Urban Wellington Region is vulnerable to large earthquakes. Not only is it bisected by large active faults, but it is extremely isolated, with all supplies being transported along a small number of lifelines (CAE, 1991; Brunsdon, 2002). The potential for total loss of water and food supplies following a major local earthquake is real and, without mitigation, could render large areas within the Wellington urban area uninhabitable for weeks or even months. Possibly the most important consideration is security of water supply following major earthquakes close to Wellington, in particular an earthquake involving rupture of the Wellington-Hutt Valley segment of the Wellington Fault because the current bulk-supply pipelines cross the fault at five places (Figure 1.1).

GNS Science has modelled the damage expected to the bulk water supply pipelines from such an earthquake (Cousins et al., 2009, 2010). Staff from Greater Wellington Regional Council (GW) then used the results to estimate the times needed for restoration of the bulk water supply to main delivery points throughout the region (McCarthy, 2009). GW is actively working to mitigate known problems, including (a) preparing for rapid bypassing of sections of the bulk supply main where it is expected to be ruptured by the fault, and (b) evaluating new sources of potable water for urban Wellington Region, i.e. the cities of Wellington, Porirua, Upper Hutt and Lower Hutt.

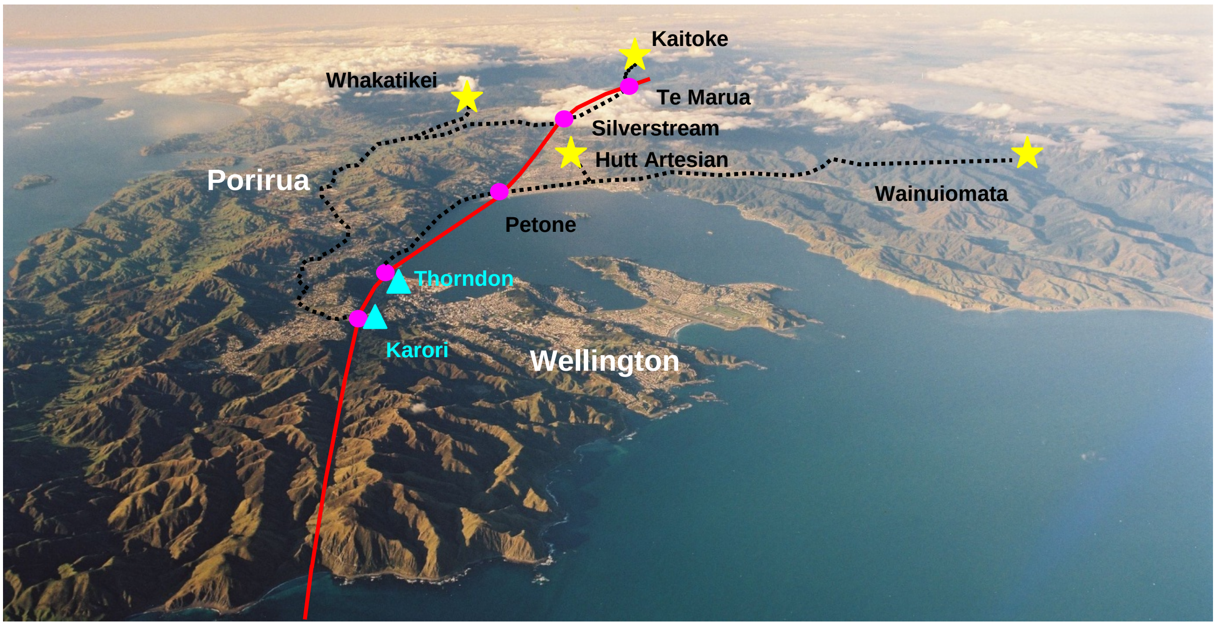

Figure 1.1 Wellington area bulk water supply system showing water sources (yellow stars) (Wainuiomata, Kaitoke, Hutt Artesian, proposed Whakatikei), bulk mains (dotted black lines), places where the bulk mains cross the Wellington Fault (purple circles) (Te Marua, Silverstream, Petone, Thorndon, Karori), main supply points for eastern Wellington City (blue triangles) (Thorndon, Karori), and the Wellington Fault (red line). Two of the main cities of the region, Wellington and Porirua, are labelled. Of the two other, Hutt City, occupies the valley containing the Hutt Artesian water source, and Upper Hutt lies between Silverstream and Te Marua (base photo by Lloyd Homer).

Modelling priority has been given to Wellington City because of its high population and lack of access to alternative supplies of water (with, for example, the nearest large rivers being several kilometres away in the Hutt Valley and Wainuiomata). One key finding from the work was that the shortest time needed to get a limited supply back into central Wellington would be eight to ten weeks. A second finding was that constructing a new supply dam west of the Wellington Fault could lower the restoration time by about two weeks, largely through the avoidance of two pipeline crossings of the Wellington Fault. The present bulk water supply pipeline from the Kaitoke water intake crosses the fault at either end of Upper Hutt and once more in Wellington (Figure 1.1). The proposed Whakatikei source would avoid the two Upper Hutt crossings so that there would be no crossings between the Whakatikei source and the western suburbs of Wellington, and only one crossing for the CBD (Central Business District) and eastern/southern suburbs. A third finding was that restoration of bulk supply from Kaitoke was significantly quicker than from either of the other two sources, i.e. from Hutt (artesian) or Wainuiomata (Cousins et al. 2009, 2010, McCarthy 2009).

In more recent work on the potential water losses, the modelling was extended to cover the likely social impacts of extended water loss, including the numbers of people without water, for how long, and the quantities of water that would be needed to meet the shortfall in conventional supply (Beban et al., 2012). Stocks of water within existing reservoirs, plus any held in hot water cylinders and in personal emergency stocks, were combined as a source of emergency water following the rupture of the Wellington Fault. The length of time that the stored water would last, and then the likely times that people would be without access to water, were calculated based on re-supply at an emergency level being delayed until the existing Kaitoke bulk water main could be reinstated to the reservoirs. The calculations were also undertaken for the scenario in which bulk supply was taken from the proposed Whakatikei Dam. Because of limitations in time and budget the modelling was restricted to just the four suburbs, viz. Tawa, Karori, the central business district, and Miramar.

A key purpose of the modelling was to estimate the quantities of water that might need to be provided from sources other than stored water, until such time as the bulk supply system could be reinstated to at least an emergency level. Hence, water from unconventional sources like, for example, rainwater harvesting, or desalination, was not included in the modelling.

The modelling showed that for all four suburbs the existence of the Whakatikei Dam would make a significant improvement in the provision of emergency water post a large earthquake. In particular, the suburbs of Tawa, Karori and the Wellington CBD would all have a considerable reduction in both the number of people without access to emergency water supplies and the duration for which people would not have access to water. In Tawa, the Whakatikei Dam would ensure that all residents would have uninterrupted access to an emergency water supply. However, even with the Whakatikei Dam constructed, both the CBD and Karori would have peaks of between 11,000 and 16,000 people respectively who would not have access to emergency water for a period of time.

Miramar is the farthest suburb from both the existing Kaitoke bulk water supply network and the proposed Whakatikei Dam. For this suburb, there would be approximately 15,000 people without access to emergency water for between 43 days (Kaitoke) and 31 days (Whakatikei Dam) following a large earthquake on the Wellington Fault (assuming a consumption rate of 20 litres per person per day (lpppd). While the Whakatikei Dam could reduce the amount of time which people in this suburb would not have access to emergency water by 12 days,

there remained a considerable period of time where the residents of Miramar would not have access to even an emergency-level water supply.

For all of the suburbs, the number of people without access to emergency water was considerably reduced assuming a consumption rate of 6 lpppd instead of the previous of figure of 20 lpppd. However, 6 lpppd represents a survival level of consumption as opposed to 20 lpppd which allows for some washing and hygiene practices to be undertaken.

The above modelling has now been extended to include (a) all of Wellington City, and (b) lesser earthquakes than the Wellington Fault event. Figure 1.2 shows the main features of the modelled area. Note that only the Kaitoke and Whakatikei sources have been included in the modelling because, as noted above, supply from them can be reinstated earlier than supply from either the Hutt or the Wainuiomata sources (Cousins et al., 2009, 2010).

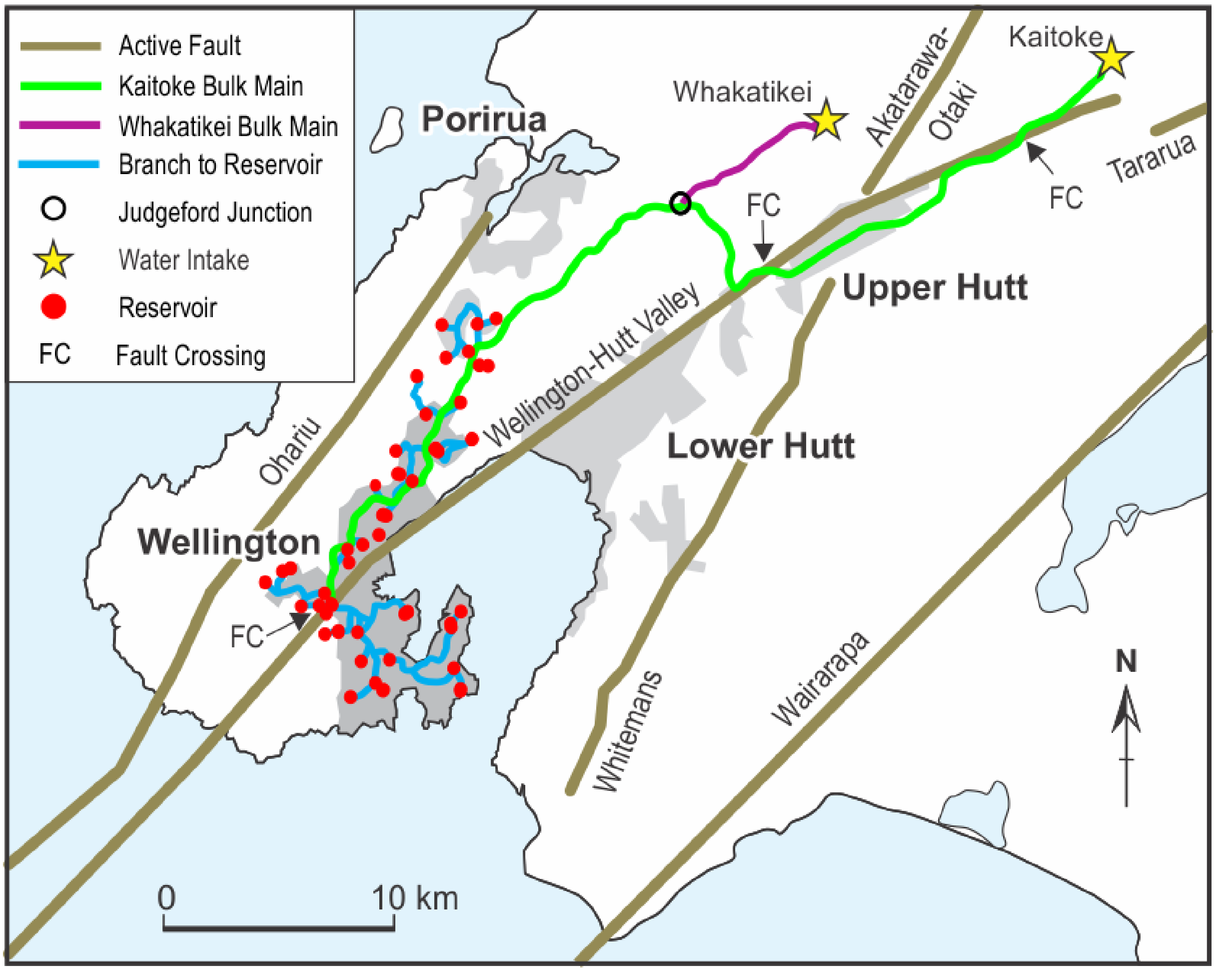

Figure 1.2 Components of the Wellington City water supply system involved in the current modelling. Judgeford junction is where the bulk supply pipelines from the Kaitoke and proposed Whakatikei intakes meet. Fault sources of the scenario earthquakes are plotted, except for the subduction zone source which lies approximately 25 km beneath the mapped area. "Wellington-Hutt Valley" and "Tararua" are two segments of the Wellington Fault. With the exception of the Whitemans Fault, the plotted faults extend beyond the mapped area.

The body of the report that follows contains information that is directly needed in the water loss modelling and the principal results. Ancillary information and detailed results are given in appendices.

The main topics covered in the body of the report are:

- Section 2: The earthquake scenarios.
- Section 3: The assets at risk – pipes and people.
- Section 4: Stored Water, and consumption post-earthquake.
- Section 5: Damage to and restoration of bulk supply pipelines, water shortfalls (brief overview only)
- Section 6: Results, including (a) numbers of people without water, and the size and duration of any water shortfall, for a variety of modelling conditions, (b) the potential benefits of some mitigation options.
- Section 7: Discussion and Conclusions.

Information provided in the Appendices comprises:

- Appendix 1: Details of the earthquake scenarios and hazard modelling.
- Appendix 2: A review of damage to bulk water supply systems in historical earthquakes.
- Appendix 3: A review of methods for modelling earthquake damage to bulk water supply pipelines.
- Appendix 4: Application to the Wellington bulk water supply system, including estimates of numbers of breaks, and times to restore emergency-level supply.
- Appendix 5: Tables of results: numbers of breaks and restoration times.
- Appendix 6: Tables of results: water shortfalls and durations.
- Appendix 7: Plots of results: numbers of repair crews required.

2.0 HAZARD MODELS

2.1 EARTHQUAKE MODELS

Nine earthquake scenarios have been considered. The first was one that can almost be considered a standard worst-case event for New Zealand, i.e. a magnitude 7.5 earthquake generated by rupture of the Wellington-Hutt Valley segment of the Wellington Fault, with the epicentre approximately 3km north-east of the CBD (Figure 2.1). Five other fault sources also were modelled, being a selection of the likely most damaging active faults close to Wellington. In decreasing order of damage potential they were the Wairarapa Fault, the southern segment of the Ohariu Fault, the Whitemans Fault, the Akatarawa-Otaki Fault, and the Tararua East Segment of the Wellington Fault (Figure 1.2).

There were also three events with locations and magnitudes chosen arbitrarily so as to give shaking intensities of about MM9, MM8 and MM7 over the key parts of the water network, the aim being to estimate the impacts of more probable levels of shaking than the worst-case of MM10 (Figure 2.1). Note that "MM" refers to the Modified Mercalli intensity scale for earthquake shaking (NZNSEE, 1992; Dowrick, 1996; Hancox et al., 2002).

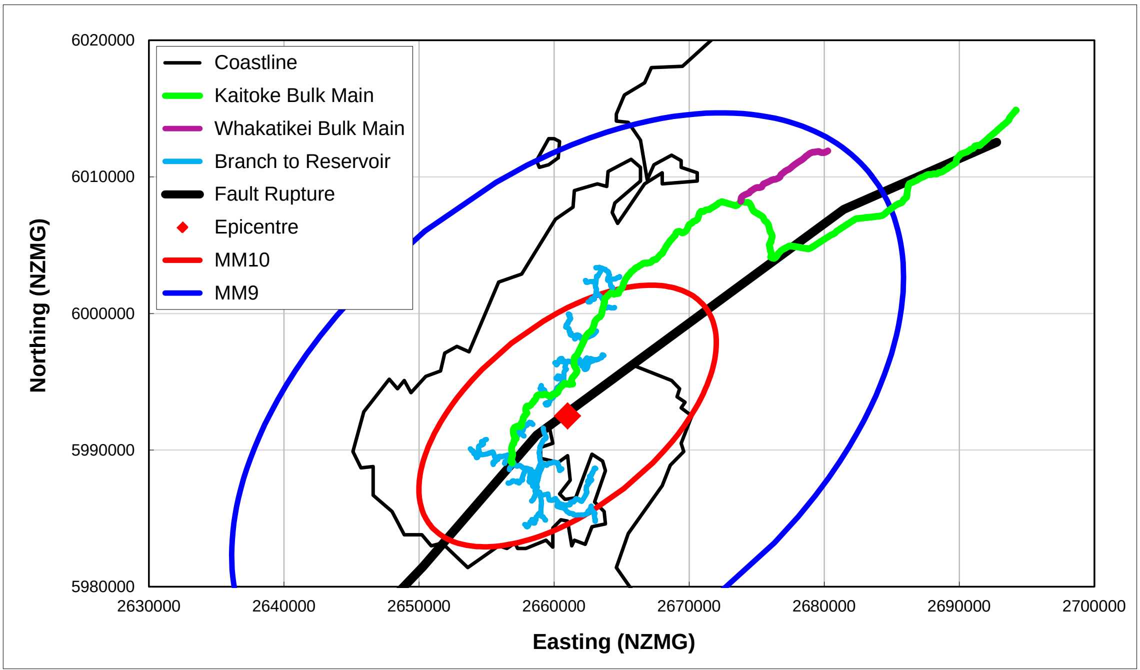

Figure 2.1 Isoseismal map for a magnitude 7.5 earthquake resulting from rupture of the Wellington-Hutt Valley segment of the Wellington Fault. The estimated recurrence interval for such a rupture is about 1000 years (e.g. Stirling et al., 2012) with a likelihood of rupture of 10-15% in the next 100 years (Rhoades et al., 2011).

Two other faults of importance but which are not modelled here are the Hikurangi Subduction Zone and the Moonshine Fault. Shaking from the Hikurangi Subduction Zone is not well modelled by the MMI attenuation model for New Zealand (Dowrick and Rhoades, 2005), but given that the fault plane is 25 km deep below Wellington is likely to generate shaking intensities of about MM9 over the central Wellington Region. The details of the MM9 earthquake were chosen to provide a reasonable simulation of the shaking expected over the water supply system in a large subduction-zone event.

The current bulk supply line from Kaitoke crosses the Moonshine Fault near Judgeford Junction (Figure 2.2), and then runs along it, with potentially many crossings, for about 15 km. Hence rupture of the Moonshine Fault could obliterate about 15 km of the current bulk supply line common to both sources. The bulk supply line from the proposed Whakatikei source also would run along the Moonshine Fault, but presumably would not be constructed across the fault. Given the probable severity of damage to the Kaitoke bulk supply line following rupture of the Moonshine Fault it is likely that the first restoration of water into Wellington would have to be from the Wainuiomata and Hutt Artesian sources (Figure 1.1). Modelling that situation would require a different bulk-supply model to the one used for the work reported here. Fortunately, the likelihood of an earthquake on the Moonshine Fault is low, given its recurrence interval of 13,000 years (Stirling et al., 2012).

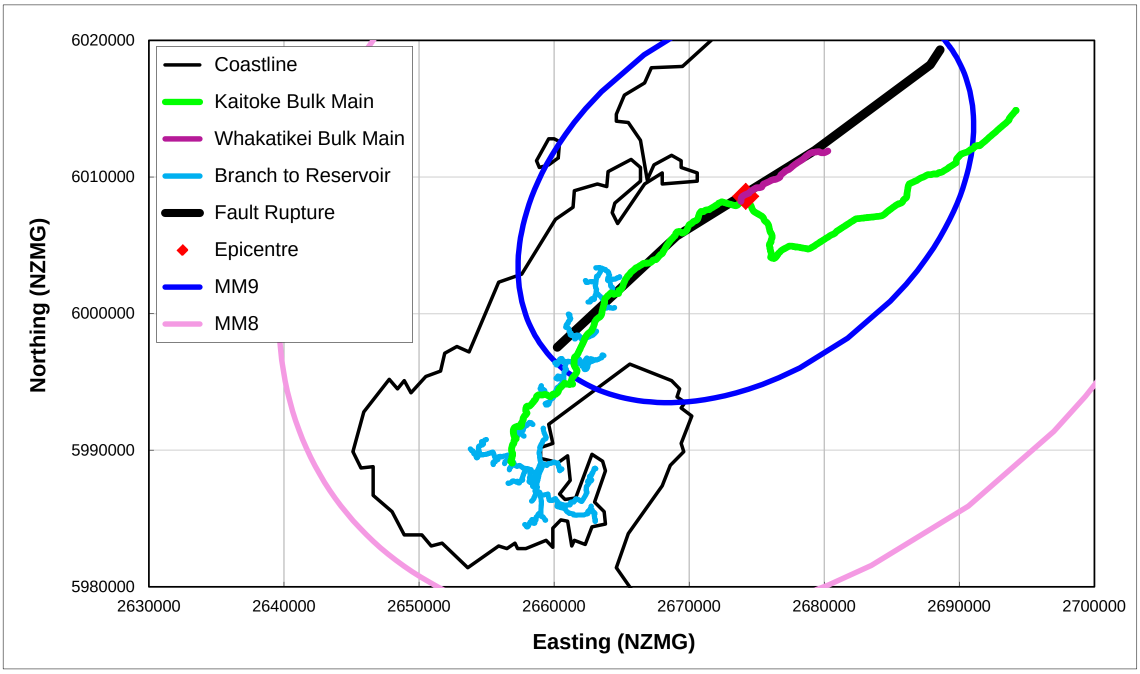

Figure 2.2 Isoseismal map for a magnitude 7.1 earthquake on the Moonshine Fault. The estimated recurrence interval for such an earthquake is 13,000 years (Stirling et al, 2012).

Details and maps for all of the scenario earthquakes are given in Appendix 1. For convenience the earthquakes are from here on named as per Table 2.1.

Table 2.1 Sources of earthquakes used in the modelling, and the names used throughout the report for the resulting earthquake scenarios.

Source Name	Magnitude	Earthquake Name
Wellington-Hutt Valley segment of the Wellington Fault	7.5	Wellington Fault
Ohariu Fault, southern segment	7.4	Ohariu South
Wairarapa Fault (last ruptured in 1855)	8.2	Wairarapa 1855
Whitemans Valley Fault	7.0	Whitemans
Akatarawa-Otaki Fault	7.5	Akatarawa-Otaki
Tararua segment of the Wellington Fault	7.3	Tararua
Arbitrary source chosen to give MM9 shaking in study area	7.85	MM9
Arbitrary source chosen to give MM8 shaking in study area	7.1	MM8
Arbitrary source chosen to give MM7 shaking in study area	6.3	MM7

2.2 SHAKING ATTENUATION AND MICROZONATION

In all cases the shaking fields around the epicentres were modelled using the MMI attenuation model of Dowrick and Rhoades (2005), which predicts shaking intensities for average ground. Actual intensities in non-average ground, i.e. soft soil or rock, can be higher or lower than the average-ground case as a result of microzonation. Various factors can be involved in microzonation, including amplification of shaking by soft soils, liquefaction and landsliding. Amplification by soft soils is important at low intensities of shaking, MM7 and below, and the other two at high intensities, MM8 and above. Note that because the Dowrick and Rhoades model is for average ground there can be a reduced level of shaking on ground that is firmer than average, i.e. on rock. All three factors were taken into account in the modelling. Soft-soil amplification (and rock de-amplification) were accommodated be increasing (or decreasing) the estimated average-ground intensity. Liquefaction and landsliding, both of which could potentially give rise to very large increases in damage on very susceptible ground, were accommodated by the use of multiplicative factors on the average-ground failure rates. The factors ranged from 3 to 27. Appendix 1 contains details of how the microzonation factors were modelled and implemented.

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3.0 ASSETS MODELS – PEOPLE, BUILDINGS, PIPES, AND RESERVOIRS

To assess the impacts on people of prolonged loss of reticulated water caused by a large earthquake we need to know where the people will be in relation to their supplies of water, particularly where they will be living. Because many will not be able to go to their usual workplaces in the weeks following a large event they will essentially be "at home". We also, therefore, need to know the state of the home, i.e. is it habitable, how much water might be stored there, and how far is it from the nearest reservoir with water.

Reservoirs are clearly important because they will be by far the most important sources of water in the first days to weeks following shaking that is strong enough to disrupt both the bulk supply and the distribution (reticulation) water systems. People will have to travel to the reservoirs to collect water until such time as the distribution pipes have been repaired, or until some other way has been found to transport water from the reservoirs to the people.

The bulk water supply system, the main pipelines that deliver water to the reservoirs, is vital because it provides firstly emergency-level water that the people can collect from nearby reservoirs, and then some time later, when the distribution pipelines have been repaired, reticulated water. Emergency-level water is needed for people to survive, reticulated water for them to return to normal living.

3.1 PEOPLE AND BUILDINGS

The people and buildings models were taken from RiskScape, which is a multi-hazard loss modelling package that is being developed jointly by GNS (Institute of Geological & Nuclear Sciences) and NIWA (National Institute of Water and Atmospheric Research) (King et al., 2008). One of its key components is a suite of detailed assets models that eventually will cover all of New Zealand and include several classes of asset, in particular buildings, people and infrastructure. At present the buildings and people models have been developed for about three quarters of New Zealand, including urban Wellington Region. The model is basically at a building-by-building scale for the buildings, with people allocated to the buildings for night-time and workday scenarios. "Night-time" is the same as "at home", which is what is required for the current modelling.

For buildings, the loss modelling procedure within RiskScape is to:

- Select an earthquake model (magnitude, location, mechanism of rupture).
- Estimate the MM intensity at each asset location using the Dowrick and Rhoades (2005) attenuation model.
- Adjust the MM intensity to allow for microzonation (shaking amplification, liquefaction, landsliding).
- Estimate the damage state for each building using damage state vs. MMI curves developed by Spence et al. (1998). Both the habitability of a building and the security of any water stored in it depend on the damage state that it is in after the earthquake.

3.2 PIPES

The pipes model covered bulk-supply pipes from the existing Kaitoke and the proposed Whakatikei water sources to storage reservoirs (56) throughout the city. It was constructed from shape file data and drawings provided by (a) Greater Wellington Regional Council and (b) Capacity (a local-authority trading enterprise that manages the reticulation networks in Wellington and Hutt Cities). The original data consisted of pipe segments with attributes of diameter, length, material, joint type and installation date attached to each pipe segment.

For the modelling undertaken in this report:

- Pipe segments longer than 100 m were divided into 100m (maximum) lengths.
- Pipe segments were overlain on geotechnical hazard maps, so that geotechnical hazard ratings could be attached, i.e. NZS1170.5 2004 ground class (derived from GNS databases), liquefaction susceptibility and landslide susceptibility. The liquefaction and landslide maps were developed for the project by Graham Hancox, Nick Perrin and Biljana Lukovic of GNS, using a combination of GNS databases, aerial pipeline surveys, and personal knowledge (Cousins et al., 2009; Perrin et al., 2010; Semmens et al., 2010a, 2010b, 2011).

Basic statistics on the pipes are provided in Table 3.1 to Table 3.3. In brief, most of the large-diameter pipes were of steel construction, with about one-third having welded joints, and the remainder being connected with "Johnson Couplings". About half of the small diameter pipes were brittle materials (asbestos cement, cast iron and concrete), and most of the remainder were steel with welded joints. Most of the large-diameter pipes were installed before 1960, whereas most of the small-diameter pipes were installed after 1960. 1953 was an important year because nearly 80% of the large-diameter pipes were installed then. Most of the pipes were in ground classified as Rock or Shallow Soil, and with low susceptibility to either liquefaction or landslide.

Table 3.1 Statistics on material and joint type for pipes of the Wellington bulk water supply network, for pipes of large (≥ 400 mm) and small (< 400 mm) diameter.

Pipe Material and Joint Type	Length (km)		Length (%)	
	≥ 400 mm	< 400 mm	≥ 400 mm	< 400 mm
Brittle - Coupled	6.2	32.2	8.2	51.5
Steel - Coupled	45.5	3.6	60.1	5.8
Steel - Welded	24.0	26.7	31.7	42.7
Totals	75.7	62.5	100.0	100.0

Table 3.2 Statistics on ages for pipes of the Wellington bulk water supply network, for pipes of large (≥ 400 mm) and small (< 400 mm) diameter.

Age Band	Length (km)		Length (%)	
	≥ 400 mm	< 400 mm	≥ 400 mm	< 400 mm
1900 to 1959	63.0	22.0	83.2	35.2
1960 to 2010	12.7	40.5	16.8	64.8
Totals	75.7	62.5	100.0	100.0
1953	58.3	3.7	77.0	5.9

Table 3.3 Statistics on ground hazards affecting the bulk supply network, for pipes of large (>= 400 mm) and small (< 400 mm) diameter.

Ground Hazard	Hazard Class	Length (km)		Length (%)	
		≥ 400 mm	< 400 mm	≥ 400 mm	< 400 mm
Subsoil Class	Class A - Strong Rock	0.0	0.0	0.0	0.0
	Class B - Rock	38.6	42.6	51.0	68.1
	Class C - Shallow soil	20.4	13.5	26.9	21.6
	Class D - Deep or soft soil	16.0	2.6	21.1	4.2
	Class E - Very soft soil	0.7	3.8	0.9	6.1
Liquefaction	None to Low	71.9	47.9	95.0	76.5
	Moderate	2.6	6.6	3.4	10.5
	High	0.5	6.5	0.7	10.4
	Extreme	0.7	1.6	0.9	2.5
Landslide	None to Low	66.6	25.2	88.0	40.4
	Moderate	3.9	30.2	5.1	48.2
	High	4.5	6.1	6.0	9.8
	Extreme	0.7	1.0	0.9	1.6

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4.0 WATER STORAGE AND CONSUMPTION

4.1 STORED WATER

It was assumed that, post-earthquake, people would have access to stored water from three sources, (a) water retained in reservoirs, (b) water in hot water cylinders, and (c) personal stored water. Rainwater was not included in the modelling because the quantity currently stored, 0.5 million litres (Abbott et al., 2012), was small in comparison with the other sources, though obviously it could be expected to make a useful contribution after an event through impromptu capture of roof water by home owners. Table 4.1 gives the approximate amounts of water stored in Wellington. The origins of the numbers are discussed below.

Table 4.1 Approximate quantities of stored water in Wellington City.

Location	Volume (millions of litres)	Percent of Total
Reservoirs	106.6	91
Hot water cylinders	8.8	8
Personal emergency water	1.4	1
Total	116.8	100

4.1.1 Water Stored in Reservoirs

Most of the available water is that which is stored in reservoirs. Table 4.2 provides basic information about the reservoirs in Wellington, mostly drawn from Anon (2010). One of the key unknowns is the amount of water that will be retained in any given reservoir after a major earthquake. The first assumption made was that the starting amount of water would be the average amount of water stored in a reservoir, and not its capacity. A second was that after strong earthquake shaking (MM9 or greater) reservoirs without auto-shut valves would lose all of their contents within hours of the earthquake because of leakage from damaged reticulation pipes. This assumption was applied to both the reservoirs known not to have auto-shut valves (e.g. Aro, Brooklyn #2), and also to those for which no information was available (e.g. Alexander Road, Beacon Hill HL). All were small reservoirs so that only about 4% of the overall stored water was lost through this mechanism. However, the loss did make a significant difference to the distances people might have to carry water (Table 4.3). After the earthquake 6.2% of people were more than 1.5 km from their closest water-containing reservoir, compared with 3.4% pre-event.

A third assumption, given the lack of seismic assessment for many of the remaining reservoirs and the advanced ages of some, was that some water would be lost either as a result of damage causing leakage or from sloshing effects. Hence the modelling was carried out for three cases, i.e. for 100%, 75% and 50% of water originally in the reservoirs being retained after the event and available for people to use.

Table 4.2 Reservoir details.

Reservoir Name	Date of Construction	Seismic Performance Status (1)	Auto Shut-Off Valve?	Capacity (cub-m)	Assumed Minimum Storage (%)	Assumed Maximum Storage (%)
Alexander Rd	1959	-	-	21	80	0.95
Aramoana	2005	A	Y	6,500	80	0.95
Aro (GW Asset)	1962	D	N	2,235	80	0.95
Beacon Hill	1977	D	Y	1,125	80	0.95
Beacon Hill HL	1989	-	-	135	80	0.95
Bell Road	1911	D	Y	9,000	80	0.95
Broadmeadows	1977	B	Y	1,420	80	0.95
Broadmeadows HL	1988	-	-	240	80	0.95
Brooklyn #1	1995	A	Y	4,000	80	0.95
Brooklyn #2	1933	D	N	1,140	80	0.95
Brooklyn West	1989	A	Y	600	80	0.95
Carmichael	1960	D	Y	7,820	30	0.7
Chester	1958	D	N	682	45	0.7
Churton North	2000	A	Y	1,500	80	0.95
Churton Park	1985	D	Y	1,000	80	0.95
Croydon	1926	-	-	223	80	0.95
Frobisher	1990	A	Y	600	80	0.95
Grenada North	1976	D	N	1,130	80	0.95
Grenada North HL	2001	-	-	150	80	0.95
Grenada South	1985	D	N	600	80	0.95
Highbury (3)	2010	-	-	220	80	0.95
Highland Park	1954	D	N	900	80	0.95
Johnsonville #1	1955	D	N	2,250	80	0.95
Johnsonville #2	1973	D	Y	4,500	80	0.95
Johnsonville West	1988	A	Y	1,500	80	0.95
Karori South	2000	A	Y	800	80	0.95
Karori West	1978	D	Y	750	80	0.95
Karori West HL	1989	-	-	240	80	0.95
Kelburn	2003	A	Y	3,500	80	0.95
Lincolnshire	2008	A	Y	500	80	0.95
Linden	1970	D	Y	4,570	80	0.95
Macalister Park	1992	A	Y	20,000	80	0.95
Maldive #2	1980	C	Y	4,500	80	0.95
Maupuia #1 & 2	1971	D	Y	1,427	80	0.95
Melrose #1	1910	D	N	820	80	0.95
Melrose #2	1954	D	Y	1,090	80	0.95
Messines	2011	A	N	6,000	80	0.95

Reservoir Name	Age of Construction	Seismic Performance Status	Auto Shut-Off Valve?	Capacity (cub-m)	Assumed Minimum Storage (%)	Assumed Maximum Storage (%)
Mount Albert	2006	A	Y	3,500	30	0.85
Mount Crawford	1983	-	Y	500	80	0.95
Mount KauKau	1984	-	-	250	80	0.95
Mount Wakefield (3)	1938,'62,'72	-	-	494	80	0.95
Newlands #1	1960	C	Y	2,230	80	0.95
Newlands #2	1987	C	Y	4,500	80	0.95
Ngaio	1969	D	Y	2,275	80	0.95
Onslow #1	2004	A	Y	1,320	80	0.95
Onslow #2	1946	C	Y	4,500	80	0.95
Redwood (timber)	1984	-	-	500	80	0.95
Roseneath #1	2005	A	Y	2,200	80	0.95
Roseneath #2	1936	D	N	910	80	0.95
Rossaveel	2006	A	Y	550	80	0.95
Seatoun Heights (2)	1926, 1936	D	N	845	80	0.95
Tawa	1956	D	Y	2,272	80	0.95
Wadestown	2001	A	Y	1,800	80	0.95
Wilton (Pembroke)	1954	C	Y	1,090	80	0.95
Woodridge	1999	A	N	1,500	80	0.95
Wrights Hill	1971	D	Y	2,275	80	0.95
Totals				127,199		

Note 1: Seismic performance status.

A = post-1986 design (NZS 3106)

B = seismically assessed and either accepted or structurally upgraded

C = seismically assessed and pending upgrade works

D = not assessed)

"-" = no data (small reservoirs, less than 500 m^3 capacity)

Because the reticulation system can be expected to be out of service for some time after strong shaking, people will likely have to collect their own water from reservoirs, at least until temporary means of distribution are devised. Hence we have estimated the shortest distances to reservoirs for all households, using radial distance only because time and computing constraints precluded doing anything better (Table 4.3 and Figure 4.1). The results were not used in the consumption modelling developed below, though they may well affect the amount of water consumed because water consumption decreases sharply if water has to be carried more than about 1 km (e.g. Cairncross and Feachem, 1993). The quantities of water available to people, from their closest reservoirs, are summarised in Table 4.4.

Table 4.3 Numbers of people living within various distances of reservoirs with water. Note that the distances are radii, not distances by road.

Shortest Distance to a reservoir	Normal time		Post-Earthquake	
	Number	Percent	Number	Percent
Less than 0.5 km	50,010	27.8	39,181	21.8
0.5 to 1.0 km	92,370	51.4	85,653	47.7
1.0 to 1.5 km	30,763	17.1	43,398	24.2
1.5 to 2.0 km	6,189	3.4	10,775	6.0
More than 2.0 km	251	0.1	576	0.3
Totals	179,583	100.0	179,583	100.0

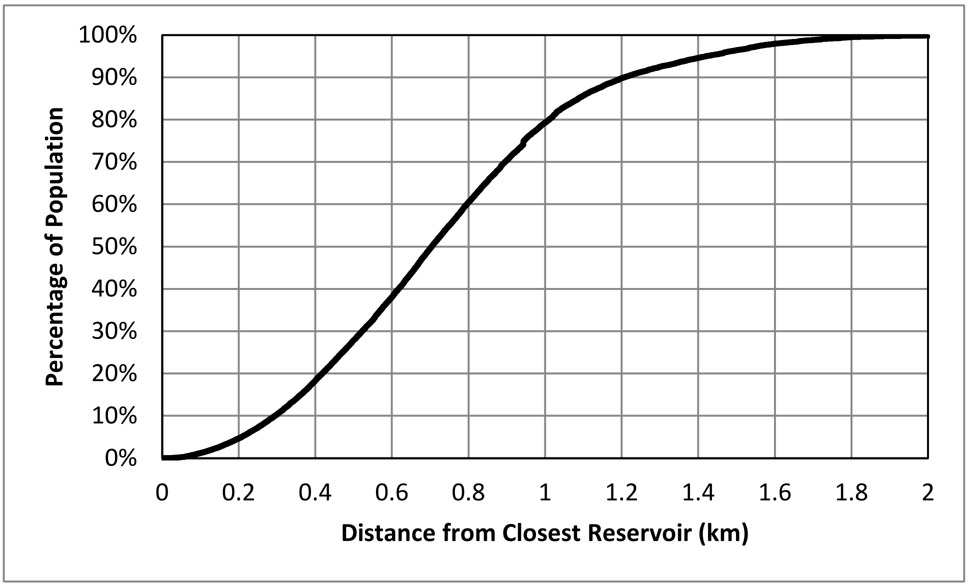

Figure 4.1 Percentages of Wellington's population within various radial distances of their nearest reservoir.

Table 4.4 Quantities of reservoir water available to people from their closest reservoirs.

Reservoir Water (litres)	Percent of Households	Percent of People
<200	0	0
200 - 300	32	32
300 - 600	31	31
600 - 1200	30	31
1200 - 3000	7	6
>3000	0	0

4.1.2 Personal Stored Water

Most households have a hot water cylinder, and many people store emergency water. Surveys in Wellington have given the results shown in Table 4.5 and Table 4.6 (Beban et al., 2012; Doody et al., 2013).

Table 4.5 Hot water cylinder statistics for households (litres per person values based on 2.6 people per household).

Cylinder Capacity (litres)	Percent of Households	Litres per Person
0	7	0
25	3	10
50	2	19
75	1	29
135	42	52
180	40	69
250	4	96
350	1	135

Table 4.6 Emergency water stored by households (litres per person values based on 2.6 people per household).

Stored Water (litres)	Percent of Households	Litres per Person
0	30	0
5	17	2
15	18	6
35	20	14
75	8	29
100	7	39

4.1.3 Water per Household

The first step in the modelling was to allocate water to households, as follows:

- Reservoir Water – Each building was allocated the litres per person (lpp) value belonging to its closest reservoir.
- Hot Water Cylinders – Each building with people in it at night was first divided into households, with 1 to 6 people being one household, 7 to 12 being two households, and so on. Each household was allocated cylinder water with the quantity following the probabilities of Table 4.5, and then the total allocated water was divided by the number of residents in the building to give the cylinder lpp value for the building.
- Stored water: As for hot water cylinder water, with the water quantities following the household percentages of Table 4.6.

Summing over all buildings in normal time, i.e. when there had been no earthquake, gave the results of Table 4.1.

4.2 CONSUMPTION OF STORED WATER

A scenario earthquake was created using the RiskScape model and applied to the buildings model so that building damage states and casualty numbers could be estimated. It was assumed that both hot water cylinder and stored water would be totally lost for buildings that had collapsed, there was a 50% probability of total loss in buildings that had been severely damaged, and no loss for less badly damaged buildings.

At the end of this process, each household was allocated a total amount of water for consumption, comprising its share of its nearest reservoir, its hot water cylinder contents, and its stored water. The allocated water was then consumed at one of two set rates, either 6 lpppd (litres per person per day), by all people in all suburbs, or 20 lpppd, by all people in all suburbs. Six lpppd is regarded as a minimum survival rate, and 20 lpppd a minimum recommended rate that allows for a degree of sanitation. In both cases, it was assumed that all people would consume their allocated water at the specified rate regardless of the distance between them and their closest reservoir.

The outcome of the modelling was a set of plots of the number of people with water as functions of time from the earthquake. For example Figure 4.2, which is for a large earthquake in which water is lost from all reservoirs not fitted with auto-shut valves, plus 50% loss of water from other reservoirs, shows that at a consumption rate of 20 lpppd the households with the least available water (i.e. small quantity of reservoir water, no hot water cylinder and no stored water) would run out of water after 8 days, and by 20 days nearly 85% households would have run out of water. The equivalent times for a rate of 6 lpppd were 20 days and 75 days. Figure 4.3 includes the equivalent results for 75% and 100% retention of reservoir water.

Note the implicit assumptions (a) that people would use their reservoir water first, then the water stored in their buildings, and (b) once their closest reservoir(s) ran dry they did not go to the next closest. Other assumptions could have been be made, e.g. household water used first, but are expected to make little substantive change to the depletion times.

Another import assumption is that no water will be available from sources other than reservoirs, hot water cylinders and personal stored water, the reason being that one of the purposes of the work is to estimate the additional quantities of water that might be required.

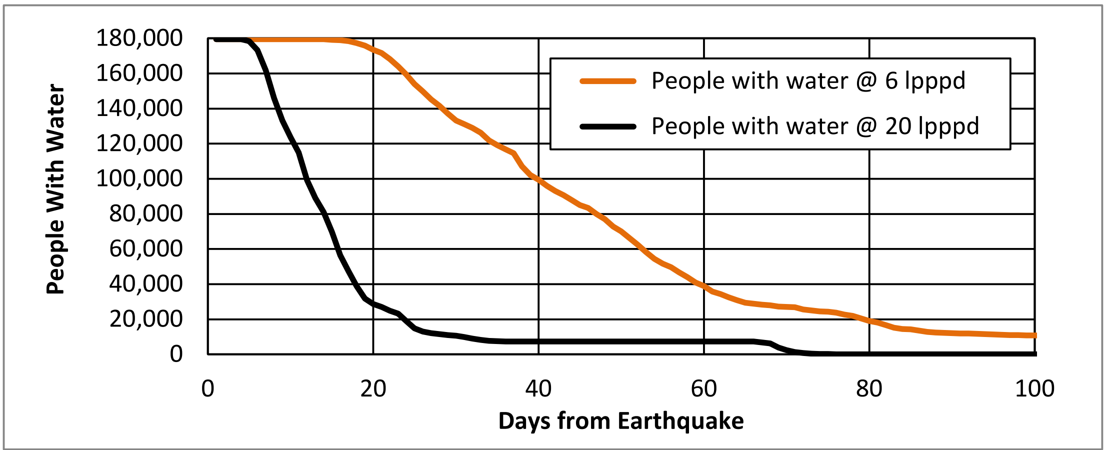

Figure 4.2 Depletion of stored water in Wellington following an earthquake large enough to halt bulk supply for a long time, assuming two rates of consumption of the stored water (6 and 20 lpppd) and 50% retention of water in reservoirs fitted with auto-shut valves.

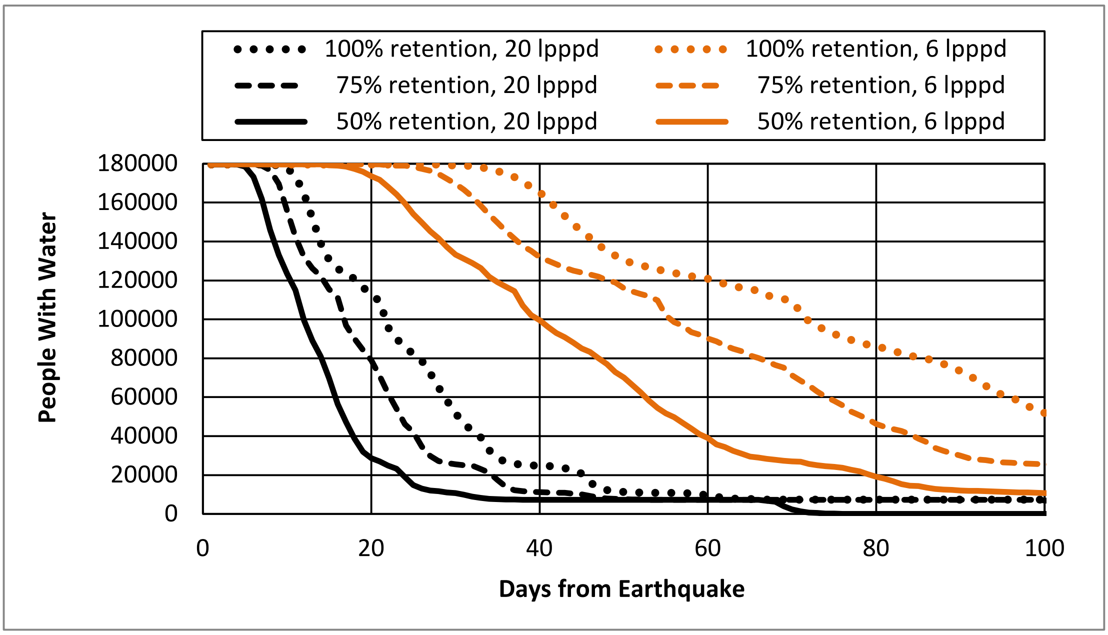

Figure 4.3 Depletion of stored water in Wellington following an earthquake large enough to halt bulk supply for a long time, assuming two rates of consumption of the stored water (6 and 20 lpppd) and three levels of retention of water in reservoirs fitted with auto-shut valves (100%, 75% and 50%).

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5.0 DAMAGE, RESTORATION TIMES, AND WATER SHORTFALLS

5.1 DAMAGE MODEL

Reports of damage to water-supply pipelines in twelve major earthquakes worldwide were reviewed for useful information, as were two extensive reviews of the topic and results of one detailed study. A great deal of anecdotal / descriptive information was found, but despite the quantity of words and data, the topic was fraught with incomplete and often inconsistent data, apparent high variability, and models with inadequate support. A few highly detailed damage models were noted, but they were unsuitable for the Wellington study because they required a level of detailed knowledge of the ground conditions that was not available for the Wellington networks. Salient information from the surveys is contained in Appendices 2 and 3, as follows:

- Appendix 2: Damage to bulk water systems in historical earthquakes
- Appendix 3: Modelling and analysis – Major reports

Complete water supply systems have experienced shaking levels comparable to those expected from a Wellington Fault earthquake in 5 historical earthquakes, viz. Hawke's Bay (New Zealand) 1931, Kobe (Japan) 1995, ChiChi (Taiwan) 1999, Kocaelli (Turkey) 1999, and Bhuj (India) 2001. In all cases, there was severe damage to water distribution systems, but the water source structures and bulk-supply pipelines appear to have performed much better.

Information from the reviews was extrapolated to a Wellington context, followed by development of models for damage to, and restoration of, bulk water supply throughout Wellington. Both topics are covered fully in appendices, as follows:

- Appendix 4: Damage and restoration modelling for Wellington
- Appendix 5: Results: numbers of breaks, and restoration times

5.2 RESTORATION OF EMERGENCY SUPPLY

The focus of the modelling was on restoring an emergency-level supply of water from the bulk-supply system. Neither the restoration of full bulk supply nor the restoration of partial or full reticulated supply to houses and workplaces were considered. For modelling purposes restoration was taken to mean restoration of bulk supply to reservoirs, or for a few cases to other collection points that were readily accessible to people and which could be provided with water more quickly than the associated reservoirs. As each reservoir or collection point acquired water, it was assumed that the people for whom it was the closest supply point could be counted as having emergency-level water restored. All reservoirs were assumed to be available for this process, not just those fitted with auto-shut valves. Modelling details are provided in Appendix 5.

Results are summarised in Figure 5.1 and Figure 5.2, for the Kaitoke and proposed Whakatikei sources. Two clear features of the results are (a) the Wellington Hutt Valley earthquake has longer restoration times than any of the other events modelled, and (b) the proposed Whakatikei source results in shorter restoration times than the Kaitoke source, for the Wellington Hutt Valley, Wairarapa 1855, MM9, Whitemans, Akatarawa-Otaki and Wellington Tararua East scenarios, but has little impact for the Ohariu South, MM8 and MM7 scenarios.

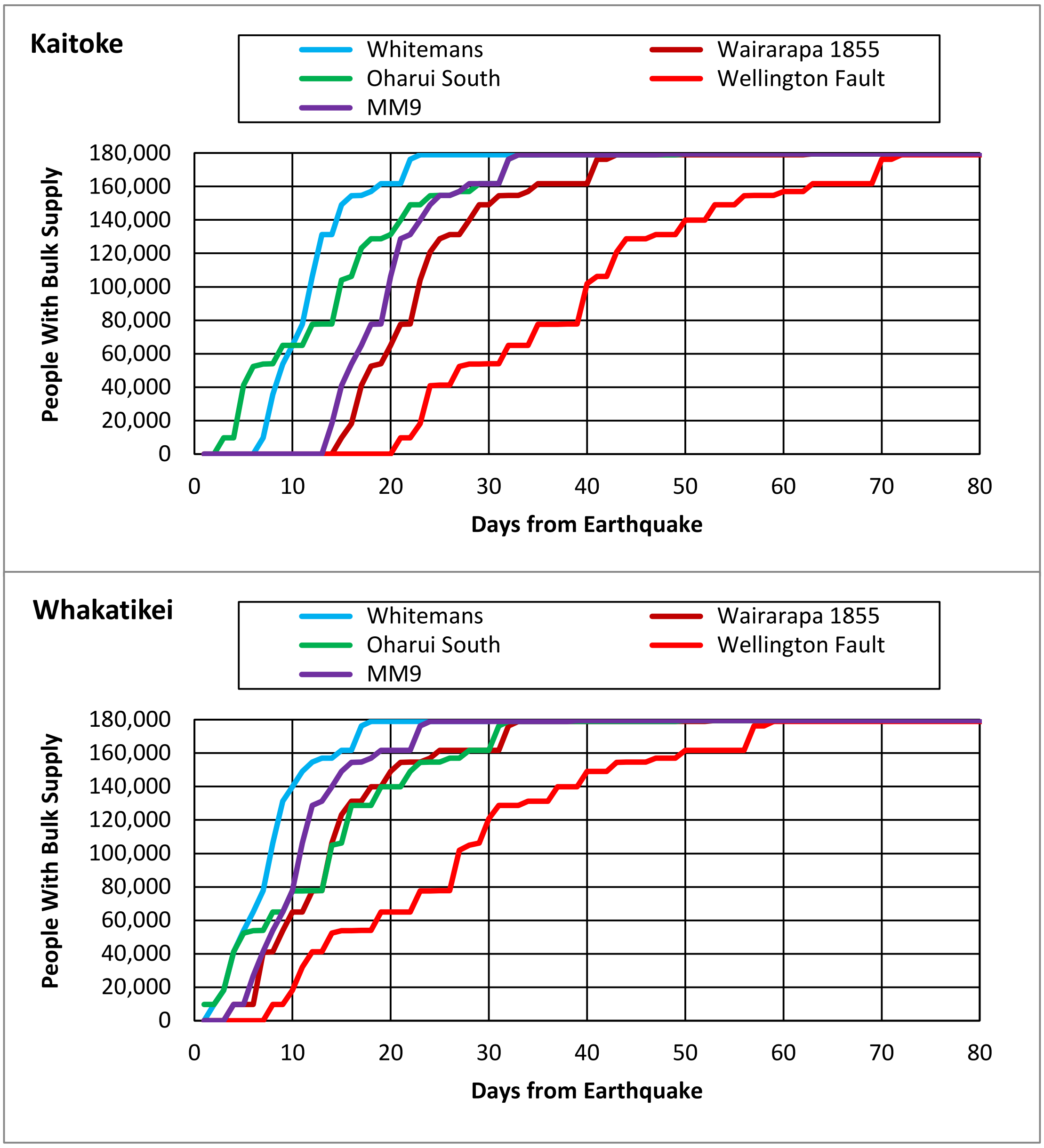

Figure 5.1 Restoration of bulk water supply to reservoirs in Wellington, from the Kaitoke and proposed Whakatikei sources, for the five largest of the earthquake scenarios modelled.

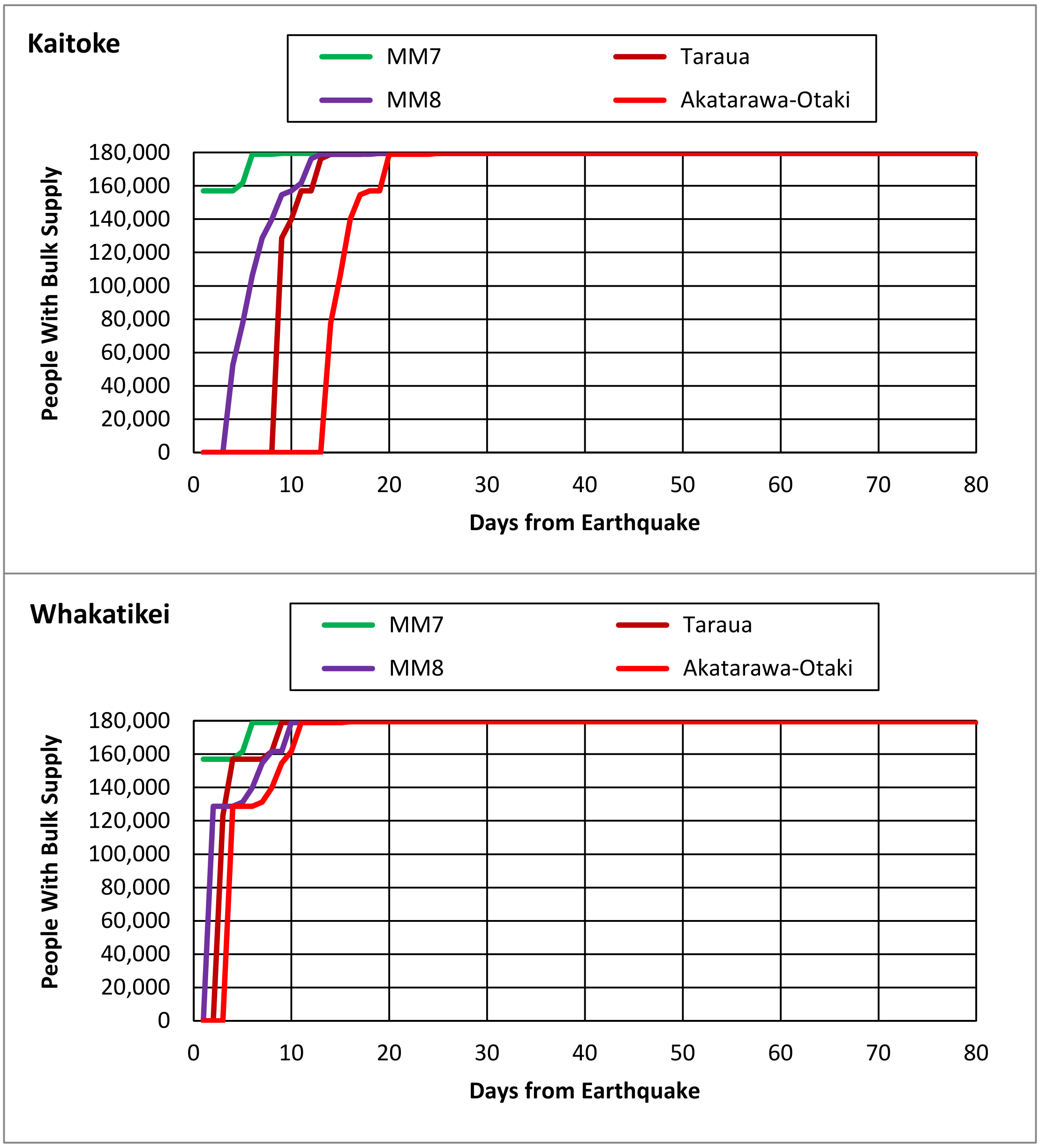

Figure 5.2 Restoration of bulk water supply to reservoirs in Wellington, from the Kaitoke and proposed Whakatikei sources, for the four smaller earthquake scenarios modelled.

5.3 SHORTFALL

Overlaying the water depletion (e.g. Figure 4.2) and restoration (e.g. Figure 5.1) curves from above indicates the potential for a serious shortfall in water supply, for a large earthquake affecting Wellington (Figure 5.3). Although a simple overlay as shown in the figure cannot be used to compute the numbers of people without water for various lengths of time, it does illustrate the root cause of the problem, i.e. that many people could lose all access to water within a few weeks of the earthquake, and then have to wait for a few weeks more before bulk water supply can be restored. Other large earthquakes affecting Wellington also could cause a water shortfall, Figure 5.4, but the situation is less serious than for the Wellington Fault rupture.

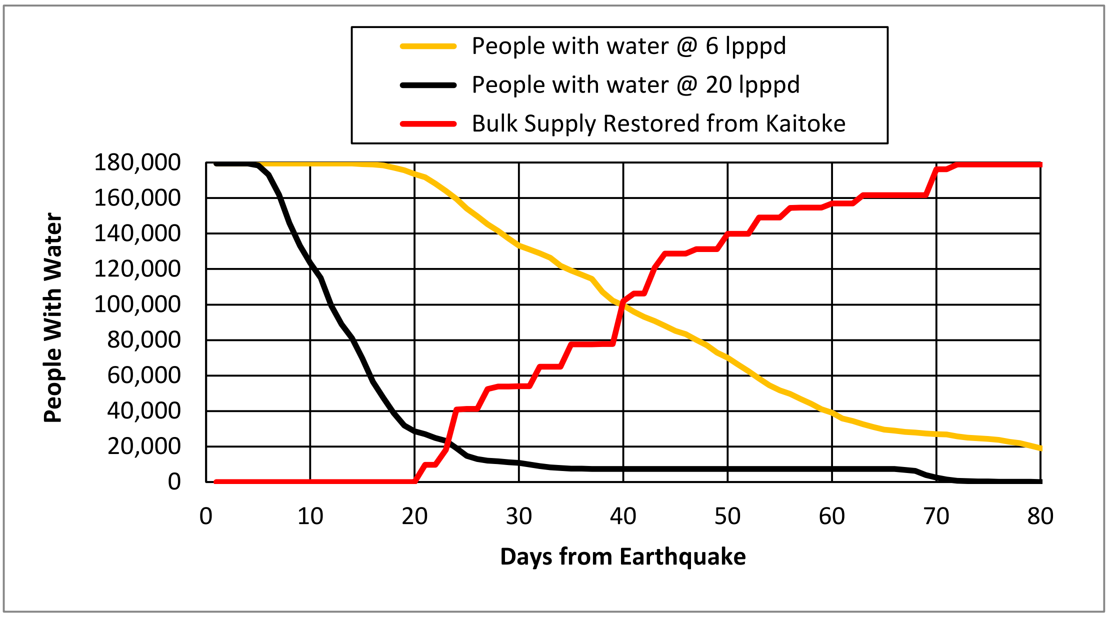

Figure 5.3 Overlay of depletion and restoration curves for the Wellington Fault scenario. For the 20 lpppd case, people below either the black line or the red line, have water, those above both lines do not. Similar logic applied to the 6 lpppd case (comparing the orange and red lines) indicates, unsurprisingly, that fewer people will be without water when it is consumed less rapidly.

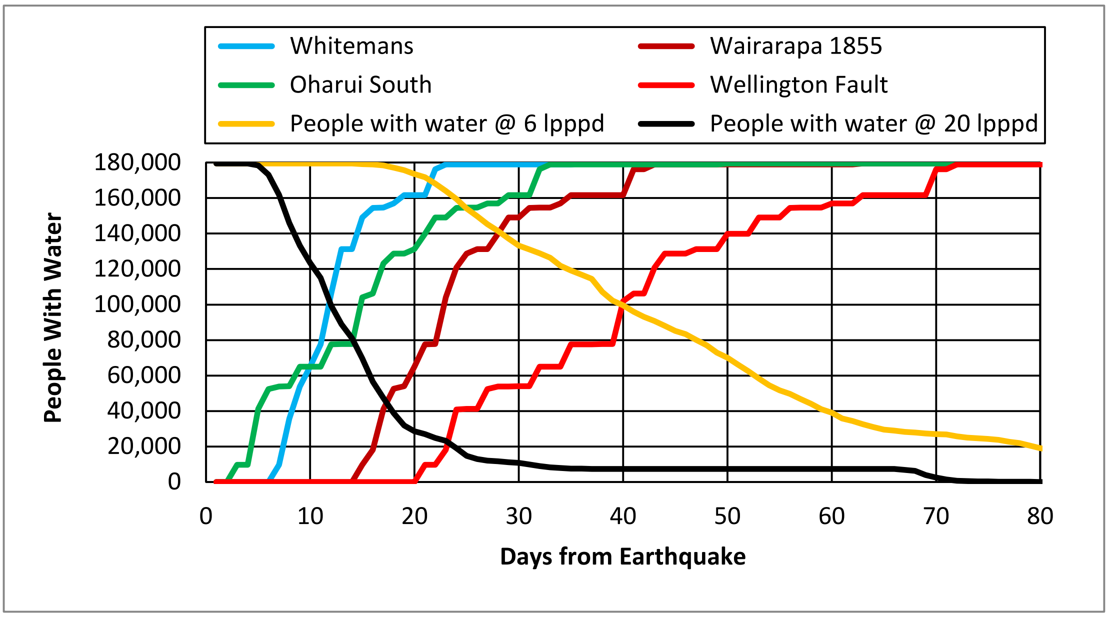

Figure 5.4 Overlay of depletion and restoration curves for four large Wellington-area earthquakes.

The numbers of people without water, for any particular day after the earthquake, were obtained by comparing the depletion and restoration times for each building in the assets model, multiplying the resultant time without water by the numbers of occupants, and summing over the whole city. This was done separately for each of the two consumption rates, 6 and 20 lpppd. Multiplying the numbers of people without water by the appropriate consumption rate gave the water shortfalls in litres per day. The results for the Wellington Fault scenario (Figure 5.5) indicate that, assuming stored water is depleted at a rate of 20 lpppd, 140,000 people could be without water for several days, 100,000 for twenty days, and 20,000 for more than 50 days. Even if stored water is consumed at a minimal rate of 6 lpppd, 40,000 people could be without water for several days, and 20,000 for about 40 days. The corresponding shortfalls of water are (a) for the 20 lpppd consumption rate, 2.8 million litres per day for several days, 2.0 million litres per day for twenty days, and 400,000 litres per day for more than 50 days, and (b) at the consumption rate of 6 lpppd, 800,000 litres/day for several days, and 400,000 litres/day for about 40 days.

The above example is severe, but is a probable worst-case scenario of a large earthquake on the Wellington-Hutt Valley segment of the Wellington Fault, exacerbated by loss of half of the water stored in reservoirs as a result of shaking damage to them.

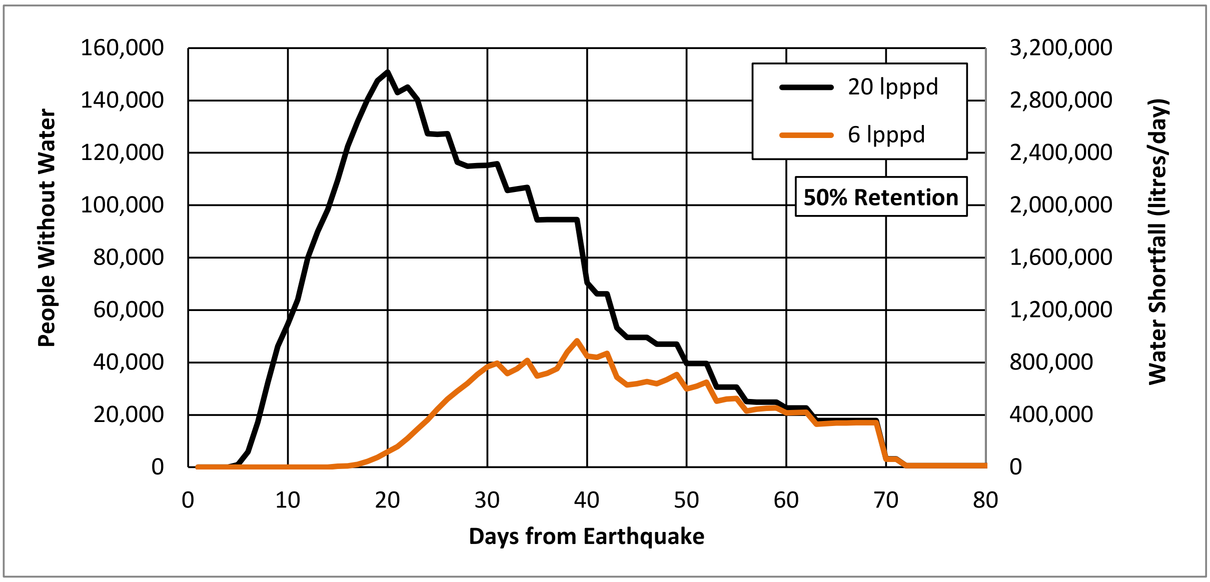

Figure 5.5 Numbers of people without water, and shortfall in supply, following a Wellington Fault earthquake.

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6.0 RESULTS

Section 6 applies the modelling to a variety of situations and attempts to provide answers to some important questions, like, for example, what happens of some if the reservoirs are damaged in the earthquake and lose part or all of their contents? A standard format is followed in most cases, comprising a brief introductory paragraph, a table of main modelling settings, plots of the results which usually display on the same plot both the numbers of people without water and the shortfall in supply, as functions of elapsed time (in days) from the earthquake, and lastly a brief summary paragraph. The topics covered are as follows:

- 6.1 Loss of Reservoir Contents
- 6.2 Size of Earthquake
- 6.3 Impact of the Whakatikei Source
- 6.4 Improvement of Pipes
- 6.5 Combination of Whakatikei Source and Improvement of Pipes
- 6.6 Inherent uncertainty in the modelling
- 6.7 Suburb-Level Results, and
- 6.8 Numbers of Repair Crews needed.

6.1 LOSS OF RESERVOIR CONTENTS

6.1.1 Wellington Fault Scenario

One of the big unknowns is how much water will be retained in the reservoirs after strong shaking. This was simulated by artificially lowering the amounts of water held in the reservoirs. Three cases are illustrated here, viz. loss of 0%, 25% and 50% of the original stored water. Note that because the shaking was stronger than MM9 it was assumed that all water had been lost from reservoirs not fitted with auto-shut valves before the above loss percentages were imposed on the other reservoirs. The main conditions of the modelling were:

- Event: Wellington Fault Earthquake (shaking level MM10+)
- Variable: % of water retained in reservoirs fitted with auto-shut valves
- Water source: Kaitoke
- Consumption rates: 20 and 6 lpppd

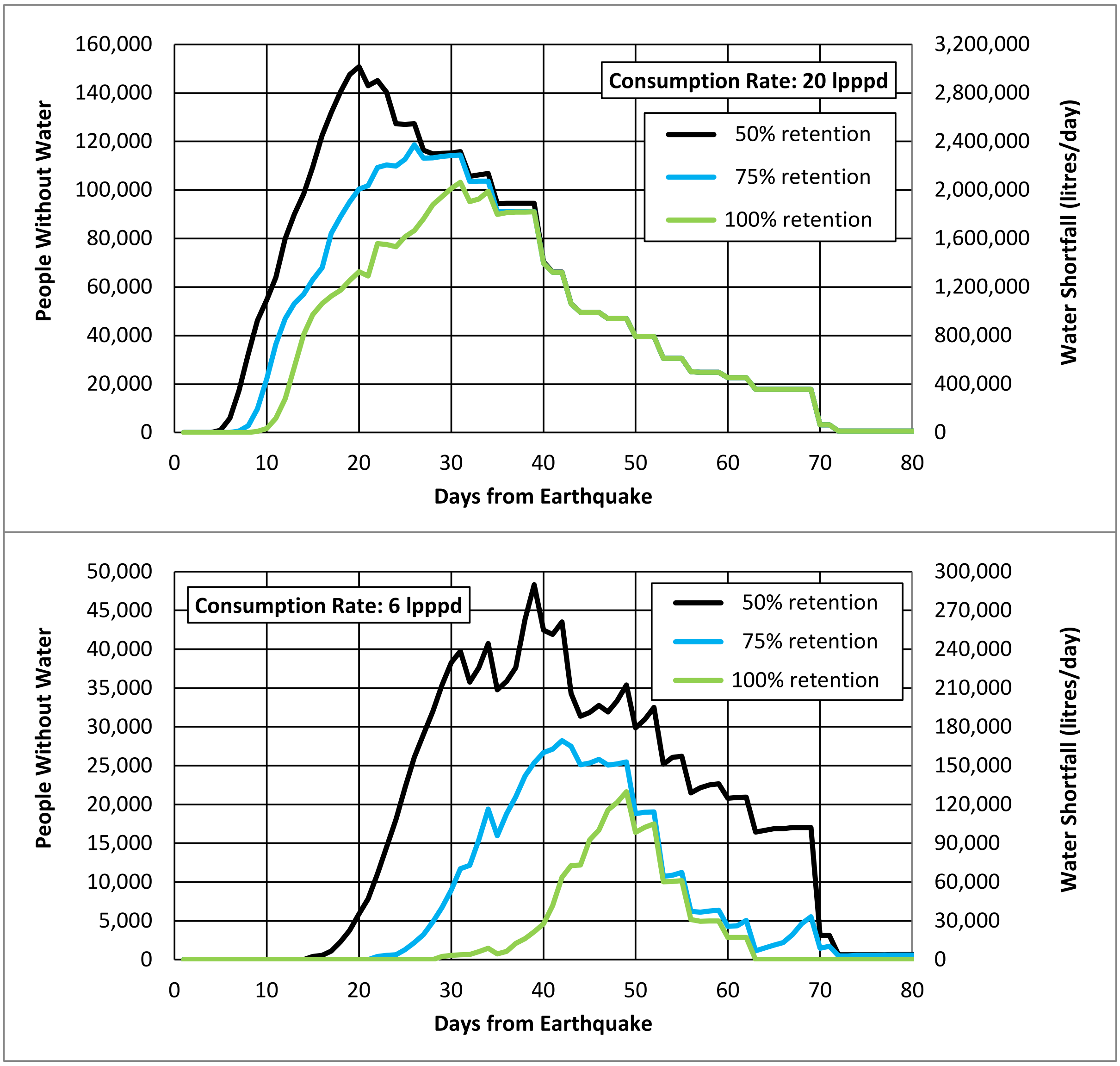

Figure 6.1 Numbers of people without water, and shortfalls in water supply, for consumption rates of 20 lpppd (top) and 6 lpppd (bottom), for a Wellington Fault scenario.

6.1.2 Wairarapa 1855 Scenario

The Wairarapa 1855 scenario is likely to be the second worst earthquake event for Wellington after the Wellington Fault scenario. It is expected to generate shaking intensities of MM9.5 over most of Wellington. For this scenario both the numbers of people without water, and the durations of the shortfalls, are significantly smaller than for the Wellington Fault scenario (Figure 6.2). The most likely reasons for the reductions are (a) there are no fault ruptures of the bulk-supply pipelines, and (b) shaking intensities over Wellington are lower than in the Wellington Fault scenario.

- Event: Wairarapa 1855 scenario (shaking level MM9+)
- Variable: % of water retained in reservoirs fitted with auto-shut valves
- Water source: Kaitoke
- Consumption rates: 20 and 6 lpppd

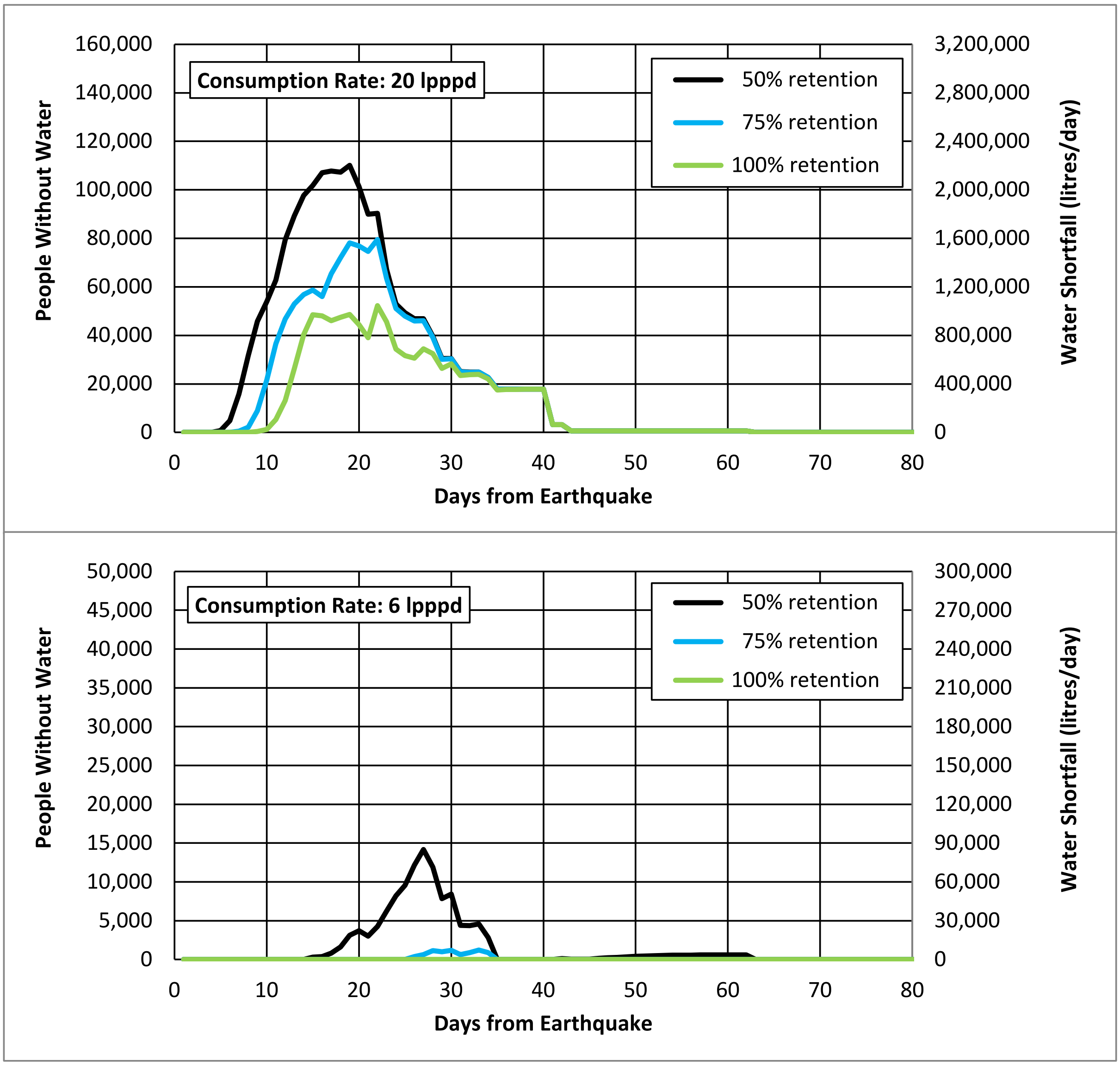

Figure 6.2 Numbers of people without water, and shortfalls in water supply, for a magnitude 8.1 earthquake on the Wairarapa Fault (the Wairarapa 1855 scenario).

6.1.3 MM9 Shaking Scenario

MM9 intensity shaking is about two times as likely to be experienced in Wellington as a Wellington Fault earthquake (Appendix 1, Table A 1.1). Numbers of people without water, and durations of shortfalls (Figure 6.3), are estimated to be much smaller than for the Wellington Fault scenario. For a consumption rate of 6 lpppd, and 75% or more retention of water in reservoirs fitted with auto-shut valves, the water shortfall is negligible.

- Event: MM9 scenario
- Variable: % of water retained in reservoirs fitted with auto-shut valves
- Water source: Kaitoke
- Consumption rates: 20 and 6 lpppd

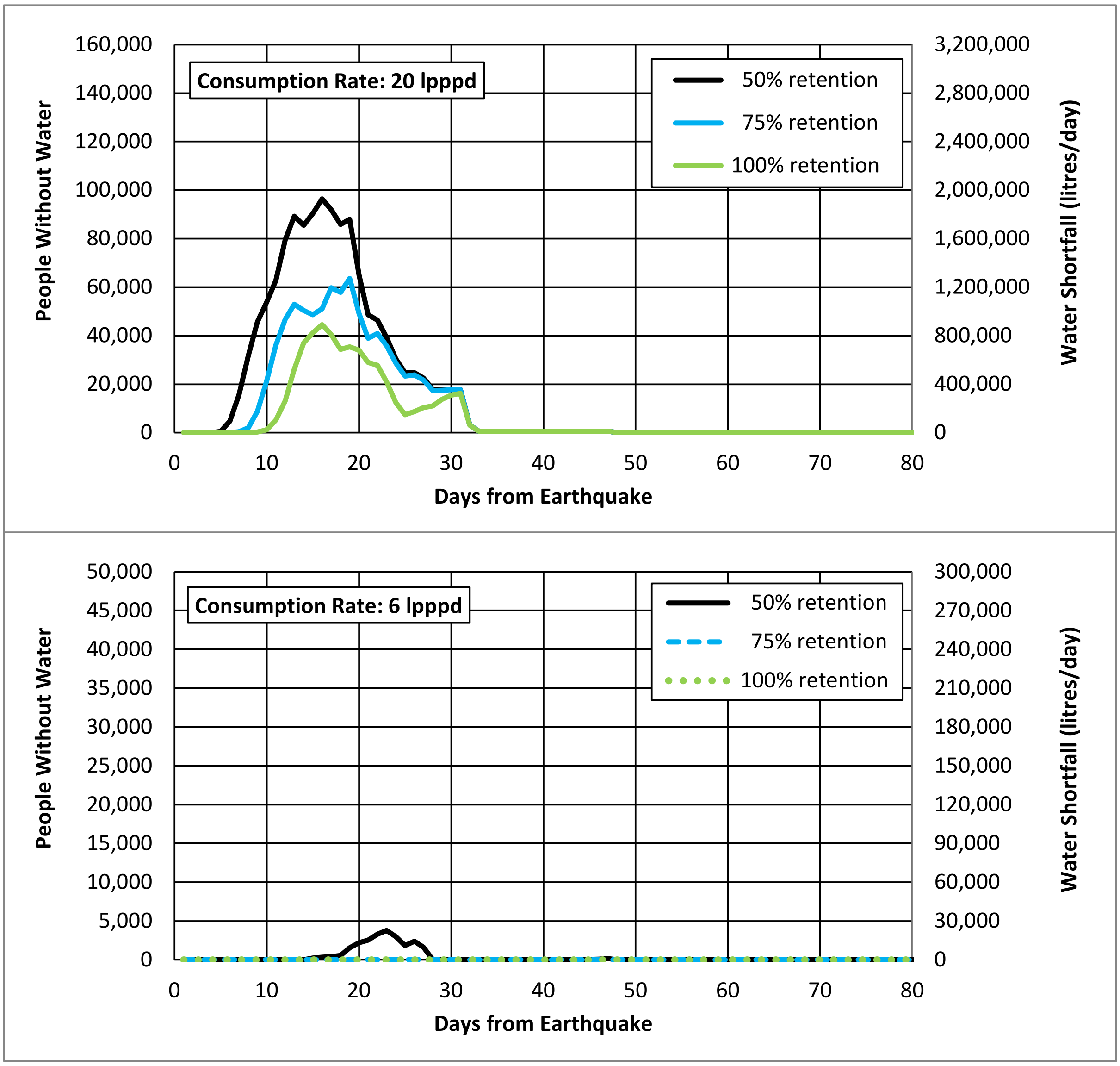

Figure 6.3 Numbers of people without water, and shortfalls in water supply, for an MM9 shaking scenario.

6.1.4 Ohariu South Scenario

The Ohariu South earthquake is expected to generate shaking stronger than MM9 over all of Wellington, MM10 over about 10% of the city, and MM8-9 over the northern part of the bulk supply system (Appendix 1, Figure A 1.5). Water shortfalls (Figure 6.4) are smaller than those of the MM9 scenario, despite the MM10 level of shaking over part of the city.

- Event: Ohariu South scenario (shaking level MM9+)
- Variable: % of water retained in reservoirs fitted with auto-shut valves
- Water source: Kaitoke
- Consumption rates: 20 and 6 lpppd

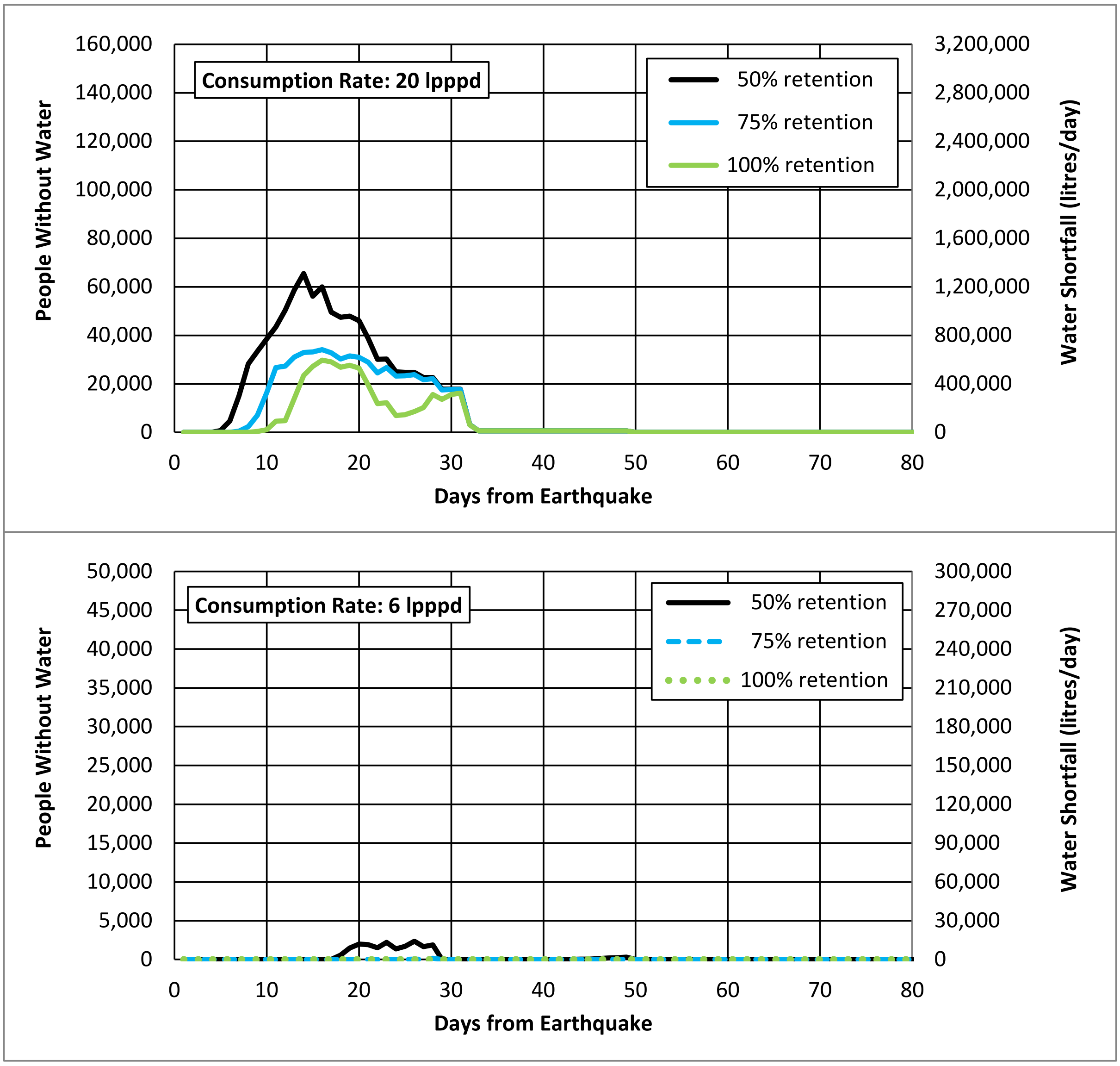

Figure 6.4 Numbers of people without water, and shortfalls in water supply, for a magnitude 7.4 earthquake on the Ohariu South scenario.

6.1.5 Whitemans Scenario

The Whitemans scenario results in shaking of MM9 over less than 20% of Wellington and the bulk supply system, and less than MM9 shaking over the remainder. Water shortfalls (Figure 6.5) are correspondingly low.

- Event: Whitemans scenario (shaking level MM8+)
- Variable: % of water retained in reservoirs fitted with auto-shut valves
- Water source: Kaitoke
- Consumption rates: 20 and 6 lpppd

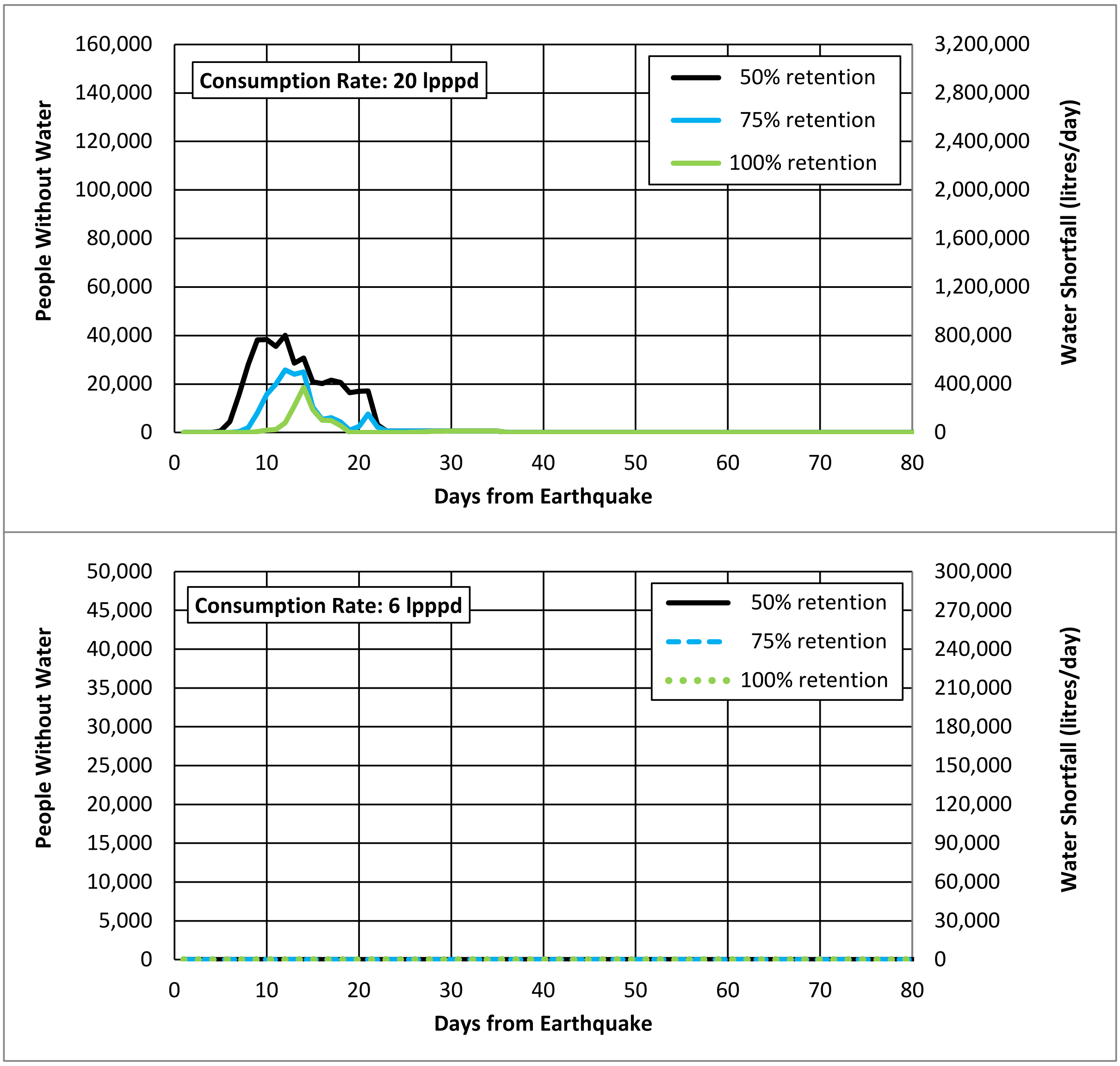

Figure 6.5 Numbers of people without water, and shortfalls in water supply, for a magnitude 7.0 earthquake on the Whitemans Fault.

6.2 SIZE OF EARTHQUAKE

Figure 6.6 and Figure 6.7 provide direct comparisons between the six most damaging of the nine earthquake scenarios considered. All events are defined in Appendix 1. Figure 6.6 compares scenario events tailored to give shaking levels of MM9 and MM8 over the bulk supply lines (noting that the MM7 event resulted in essentially zero water shortfall).

- Variable: Earthquake scenario (shaking level)
- Retention: 50 % (for all cases except MM8 Event), 75% (MM8 Event)
- Water Source: Kaitoke
- Consumption rates: 20 and 6 lpppd

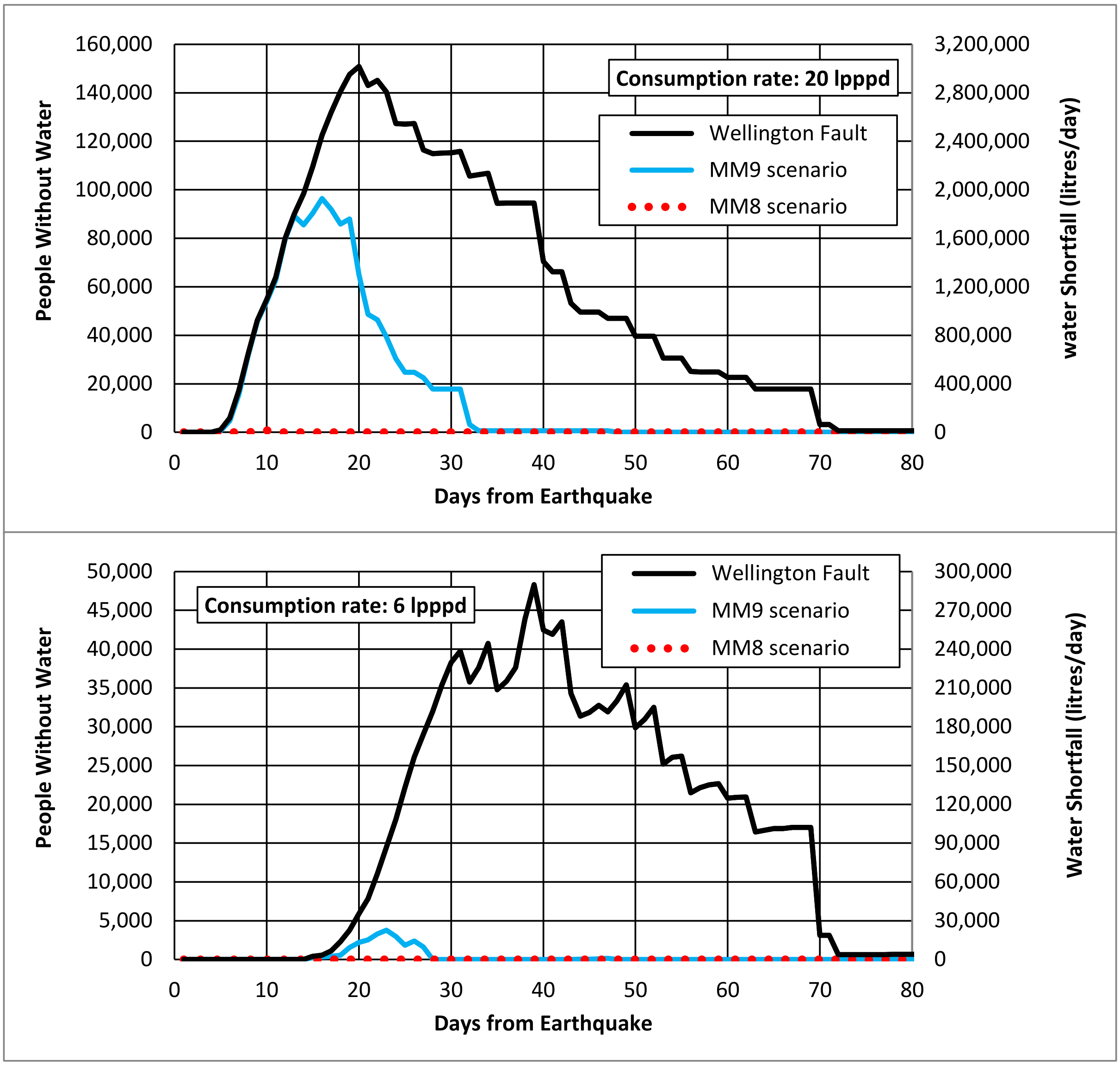

Figure 6.6 Numbers of people without water in Wellington City for three major events , (a) a magnitude 7.5 earthquake on the Wellington-Hutt Valley segment of the Wellington Fault (WnHV), giving shaking of MM9 to MM11 over the bulk supply lines, (b) a smaller earthquake giving MM9 shaking intensity over the Kaitoke – Karori part of the bulk supply line, and (c) an even smaller earthquake giving MM8 shaking.

Potential sources of the lesser shaking levels over Wellington are other active faults in the area, such as the Wairarapa, Ohariu (southern segment), Whitemans Valley, and Akatarawa-Otaki Faults, and the Tararua East Segment of the Wellington Fault. Estimated impacts of the three most damaging scenarios are shown in Figure 6.7. Water shortfalls from the other two scenarios were negligible or zero.

- Variable: Earthquake source
- Retention: 50 % of water retained in reservoirs fitted with auto-shut valves
- Water Source: Kaitoke
- Consumption rates: 20 and 6 lpppd

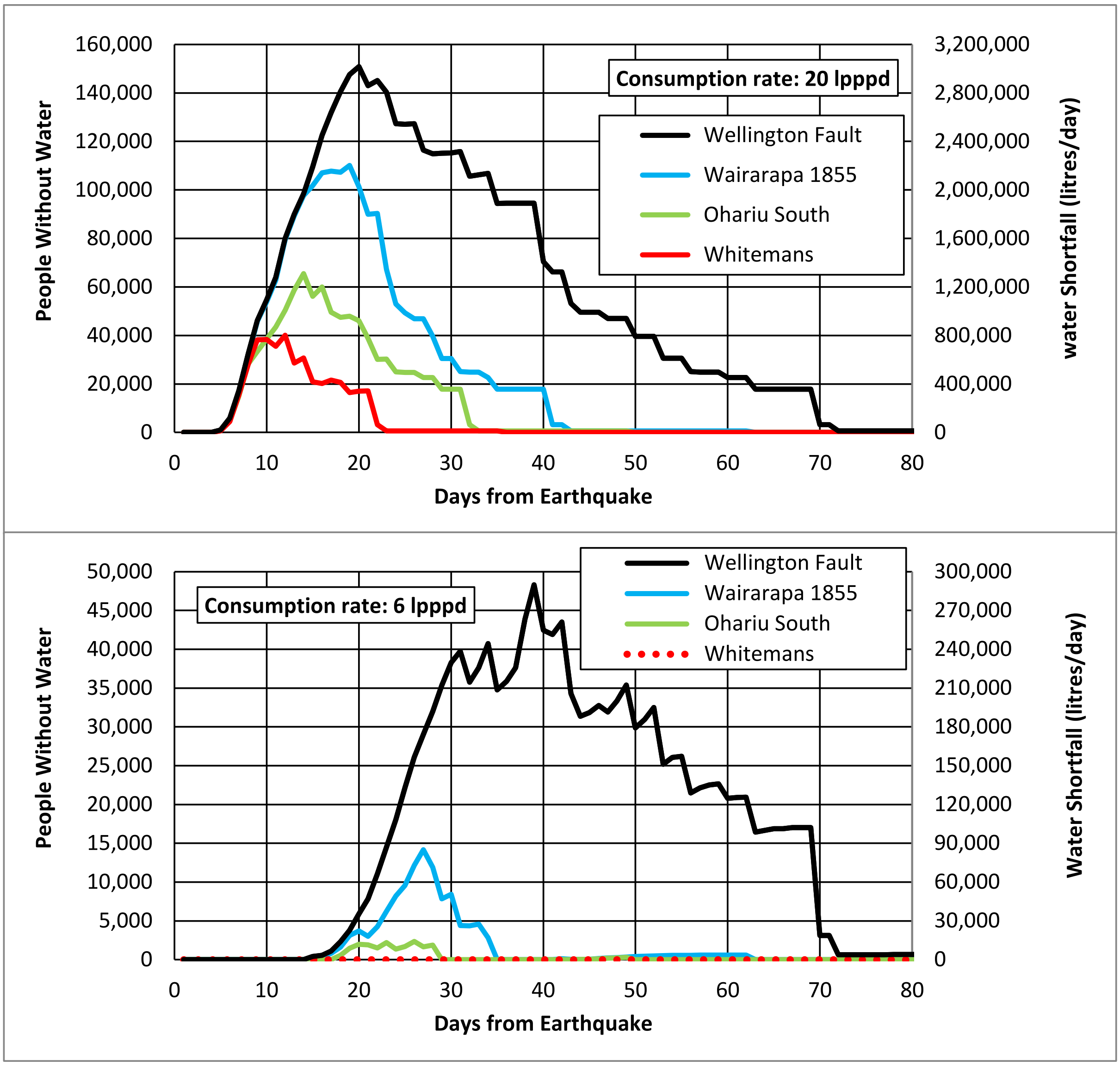

Figure 6.7 Numbers of people without water in Wellington City for earthquakes on the four closest and largest active faults , (a) a magnitude 7.5 earthquake on the Wellington-Hutt Valley segment of the Wellington Fault, (b) a repeat of the magnitude 8.2 Wairarapa earthquake of 1855, (c) a magnitude 7.4 earthquake on the southern segment of the Ohariu Fault, and (d) a magnitude 7.0 earthquake on the Whitemans Fault.

6.3 IMPACT OF THE WHAKATIKEI SOURCE

A new source of water for Wellington could be the Whakatikei River (Figure 1.2). Because it lies west of the Wellington Fault it has the big advantage over the Kaitoke source in that there are two fewer crossings of the Wellington Fault between the source and Wellington City. Assuming a consumption rate of 20 lpppd, having the Whakatikei source would mean that 40,000 fewer people would be without water from about day 18 to day 43, and about 20,000 fewer thereafter (Figure 6.8). Restoration times would be lowered by about two weeks for all reservoirs. At a consumption rate of 6 lpppd, about 15,000 fewer people would be without water from day 30 onwards.

- Event: Wellington Fault scenario
- Retention: 50 % of water retained in reservoirs fitted with auto-shut valves
- Variable: Water source, Kaitoke or Whakatikei
- Consumption rates: 20 and 6 lpppd

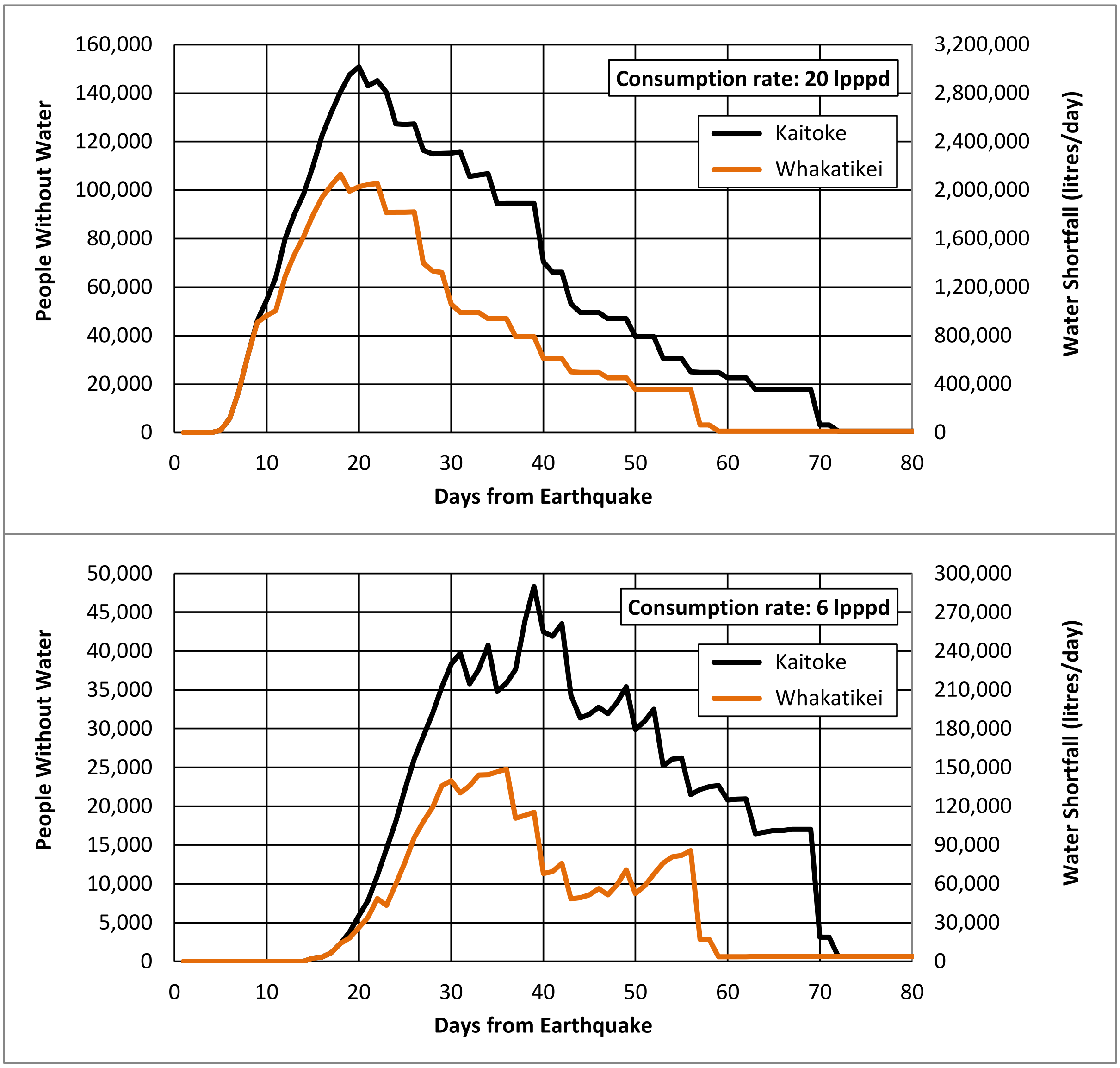

Figure 6.8 Numbers of people without water and shortfalls in supply, for two sources of supply, following a Wellington Fault earthquake.

Equivalent results, assuming that 75% of water in reservoirs (fitted with auto-shut valves) is retained after the earthquake, are shown in Figure 6.9.

- Event: Wellington Fault Earthquake
- Retention: 75 % of water retained in reservoirs fitted with auto-shut valves
- Variable: Water source, Kaitoke or Whakatikei
- Consumption rates: 20 and 6 lpppd

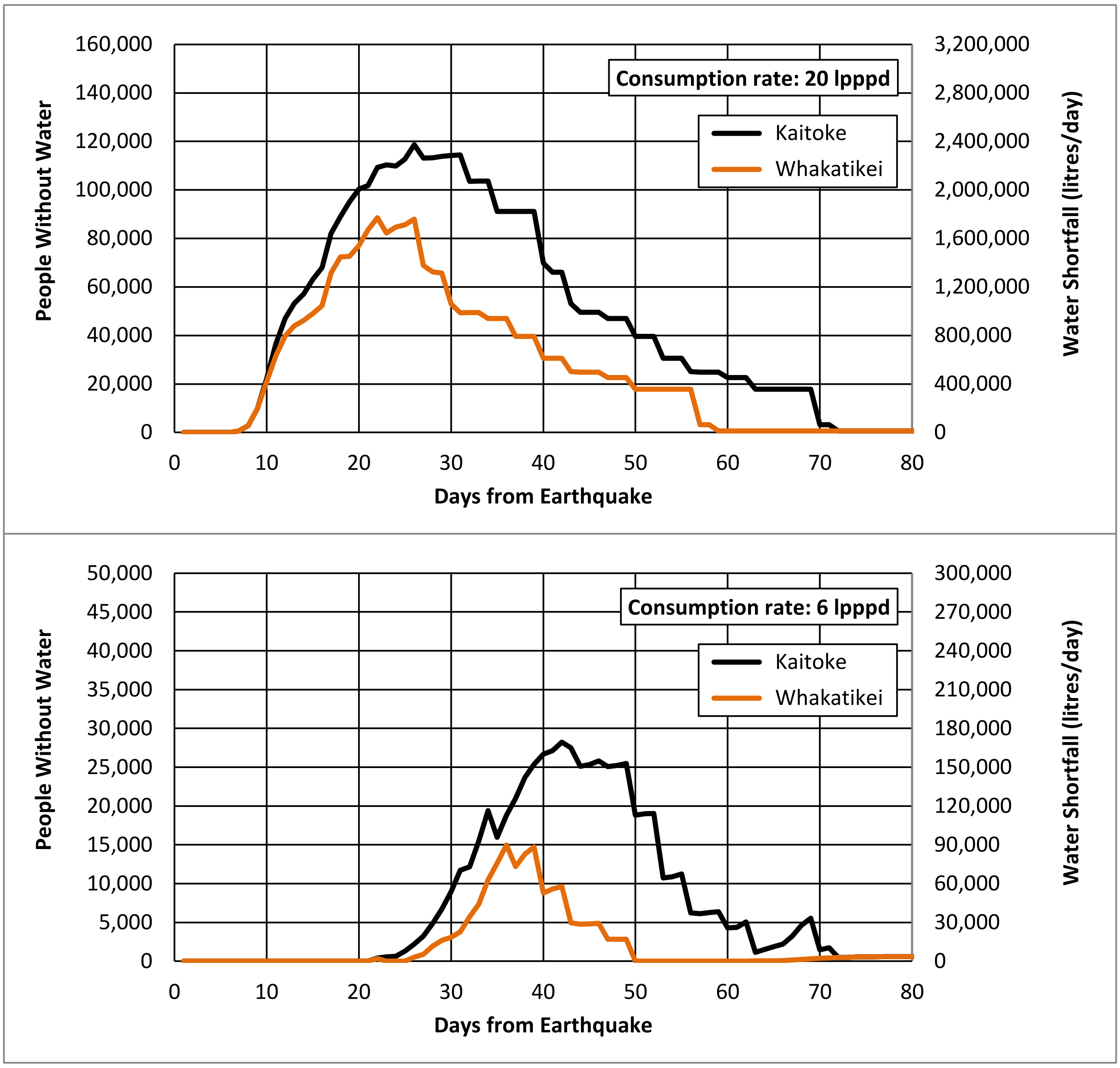

Figure 6.9 Numbers of people without water and shortfalls in supply, for two sources of supply, following a Wellington Fault earthquake.

6.4 IMPROVEMENT OF PIPES

Another way of lowering the restoration times could be to increase the resilience of the bulk-supply network by upgrading all of the weak pipes to the best available materials. This has been simulated by replacing all old (pre-1960) and jointed parts of the network with modern pipes having welded joints. Doing this results in large reductions in the restoration times beyond about day 20 (Figure 6.10). Reasons for the lack of effect up to day 20 were (a) more than half of the restoration time was governed by the repair of damage at fault crossings, and (b) 70 percent of the pipe from the Kaitoke intake to Tawa was already of welded steel construction. Note that welded steel is a representative of a modern, resilient, pipe material.

- Event: Wellington Fault earthquake
- Retention: 50 % of water retained in reservoirs fitted with auto-shut valves
- Source: Kaitoke
- Variable: Pipe construction (current or all welded steel)
- Consumption rates: 20 and 6 lpppd

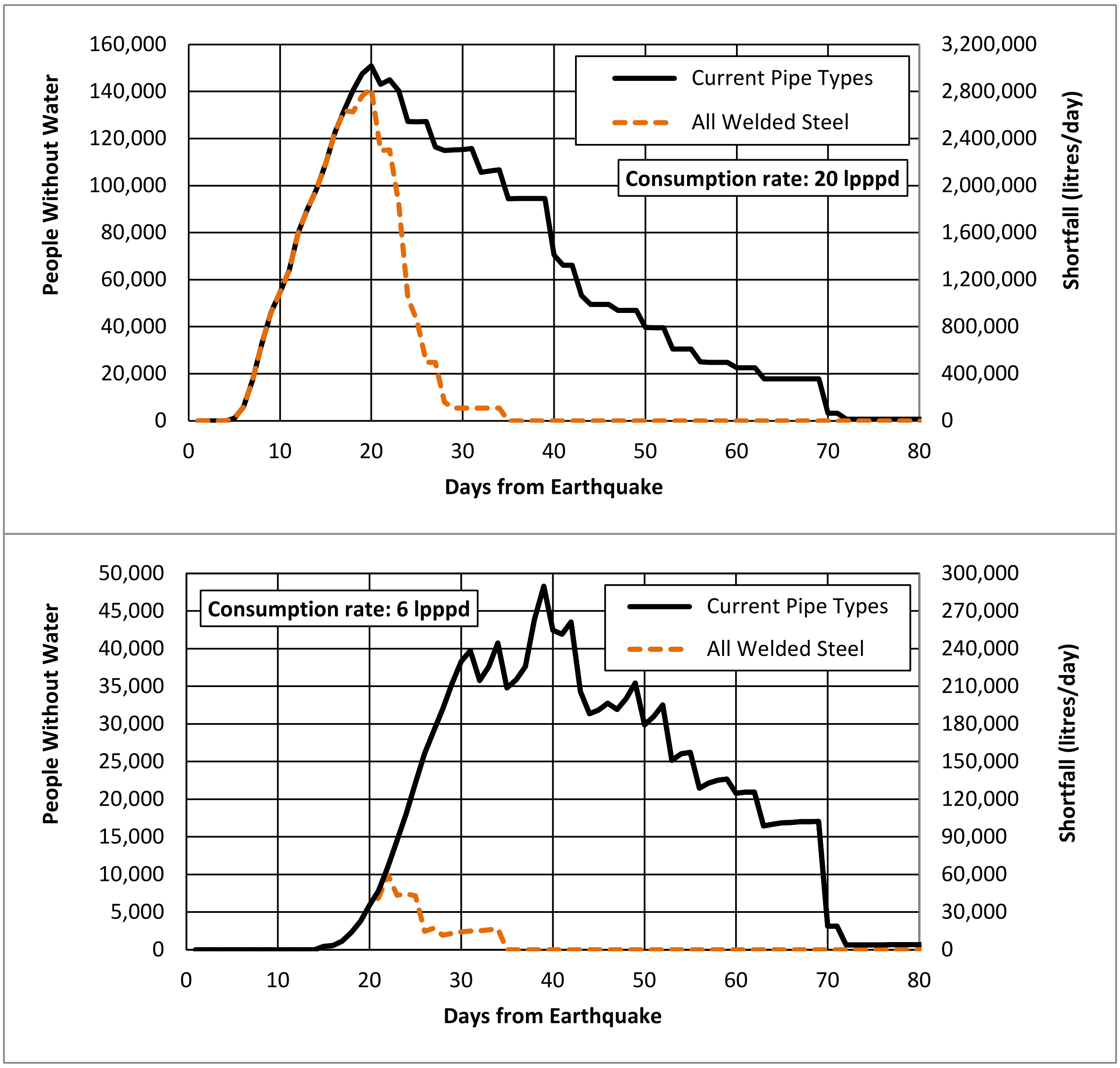

Figure 6.10 Estimated water shortfalls for (a) the current bulk supply network, and (b) an improved network made entirely of modern welded-steel pipe (dashed line), following a Wellington Fault earthquake - 50 % of water retained in reservoirs fitted with auto-shut valves.

Equivalent results, assuming that 75% of water in reservoirs (fitted with auto-shut valves) is retained after the earthquake, are shown in Figure 6.11.

- Event: Wellington Fault earthquake
- Retention: 75 % of water retained in reservoirs fitted with auto-shut valves
- Source: Kaitoke
- Variable: Pipe construction (current or all welded steel)
- Consumption rates: 20 and 6 lpppd

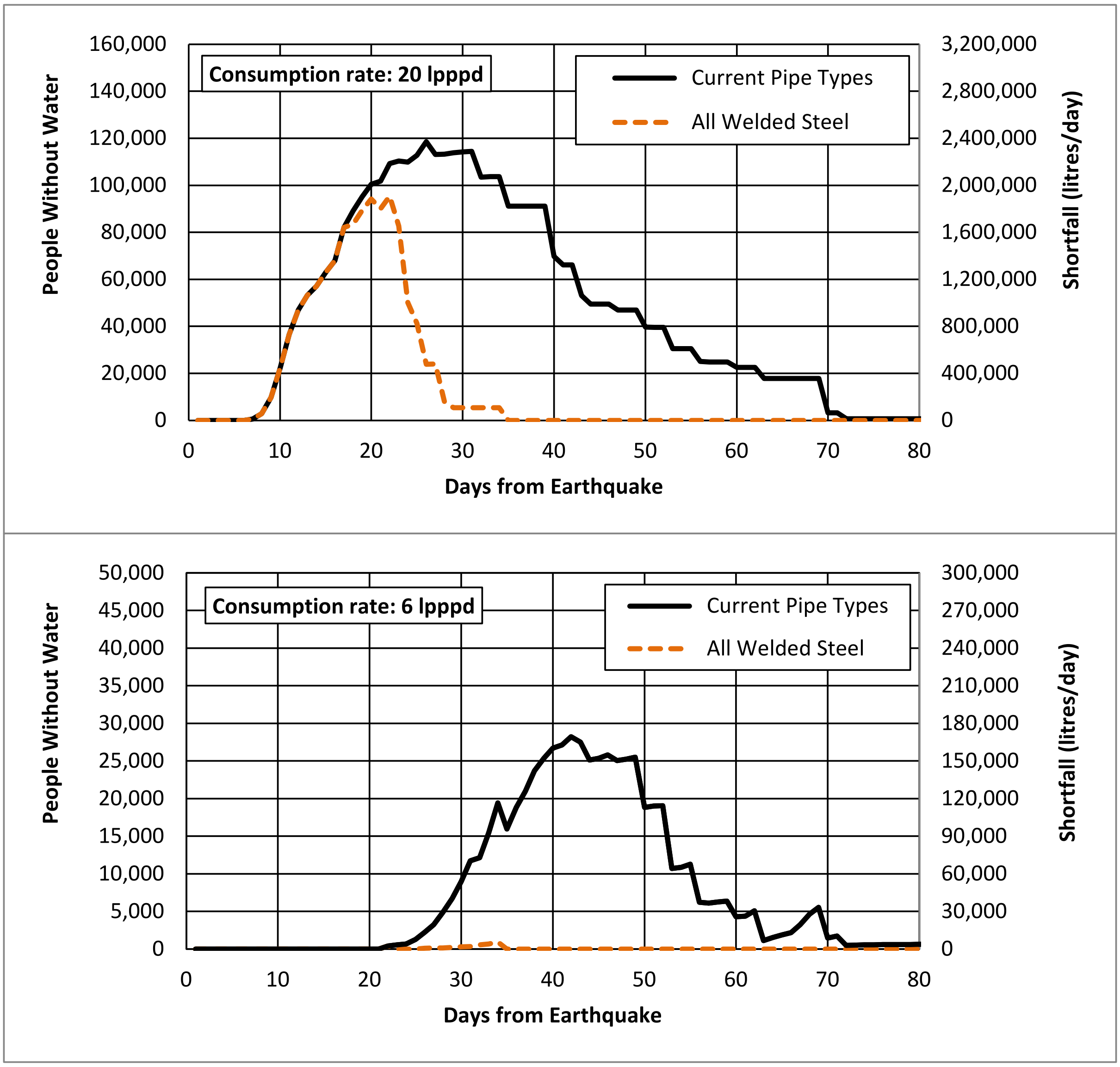

Figure 6.11 Estimated water shortfalls for (a) the current bulk supply network, and (b) an improved network made entirely of modern welded-steel pipe (dashed line), following a Wellington Fault earthquake - 75 % of water retained in reservoirs fitted with auto-shut valves.

6.5 WHAKATIKEI SOURCE AND IMPROVEMENT OF PIPES

A combination of both measures, i.e. a new water source at Whakatikei and improvement of pipes to modern welded steel quality, has the potential to lower the shortfalls to low levels (Figure 6.12 and Figure 6.13).

- Event: Wellington Fault earthquake
- Retention: 50 % of water retained in reservoirs fitted with auto-shut valves
- Variable 1: Water source (Kaitoke or Whakatikei)
- Variable 2: Pipe construction (current or all welded steel)
- Consumption rates: 20 and 6 lpppd

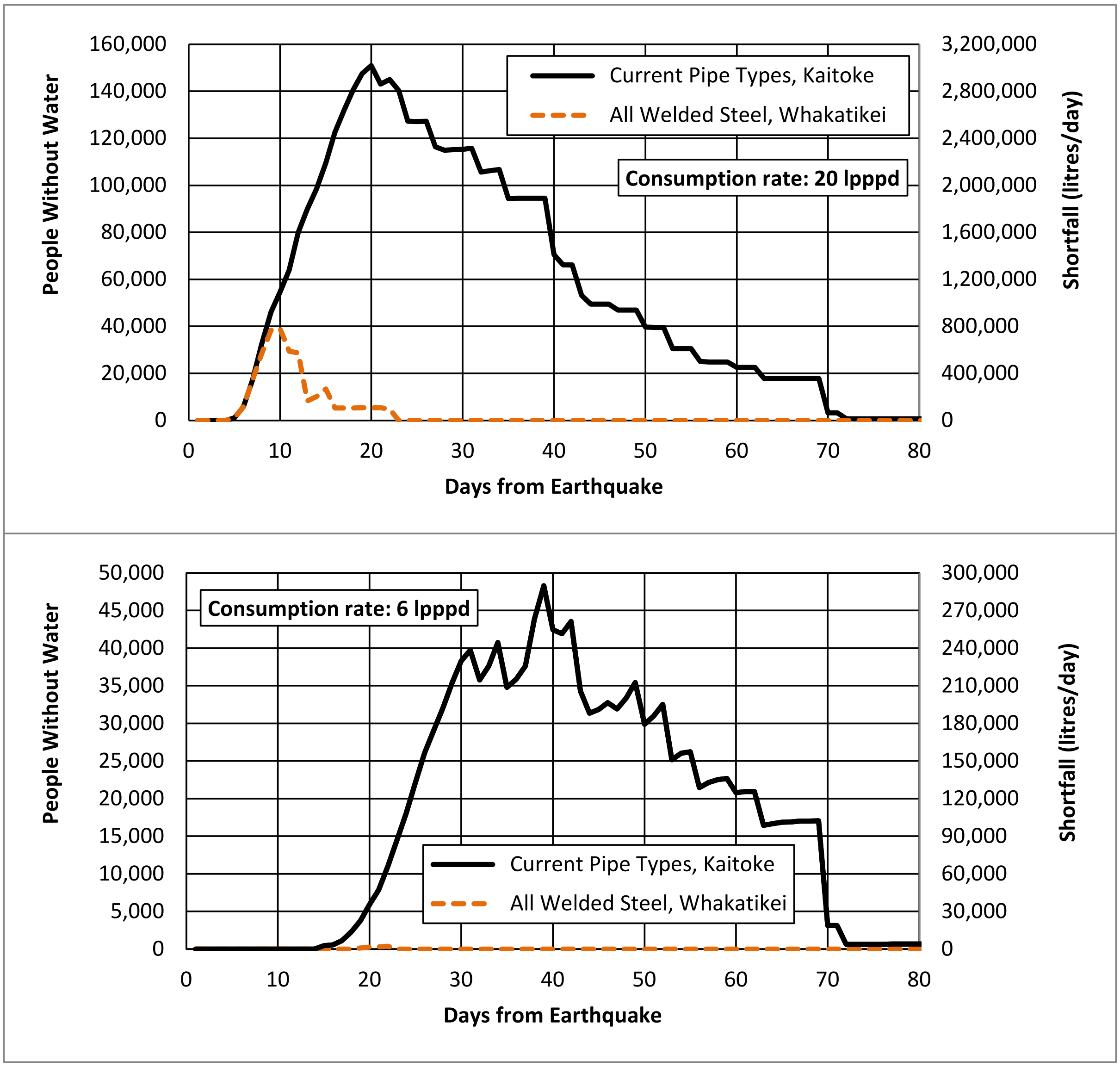

Figure 6.12 People without water, and daily shortfall of water for (a) the current bulk supply network and Kaitoke source and (b) a hypothetical network made entirely of modern welded-steel pipe (dashed line) and drawing water from the proposed Whakatikei source, following a Wellington Fault earthquake - 50 % of water retained in reservoirs fitted with auto-shut valves.

Equivalent results, assuming that 75% of water in reservoirs (fitted with auto-shut valves) is retained after the earthquake, are shown in Figure 6.13.

- Event: Wellington Fault earthquake
- Retention: 75 % of water retained in reservoirs fitted with auto-shut valves
- Variable 1: Water source (Kaitoke or Whakatikei)
- Variable 2: Pipe construction (current or all welded steel)
- Consumption rates: 20 and 6 lpppd

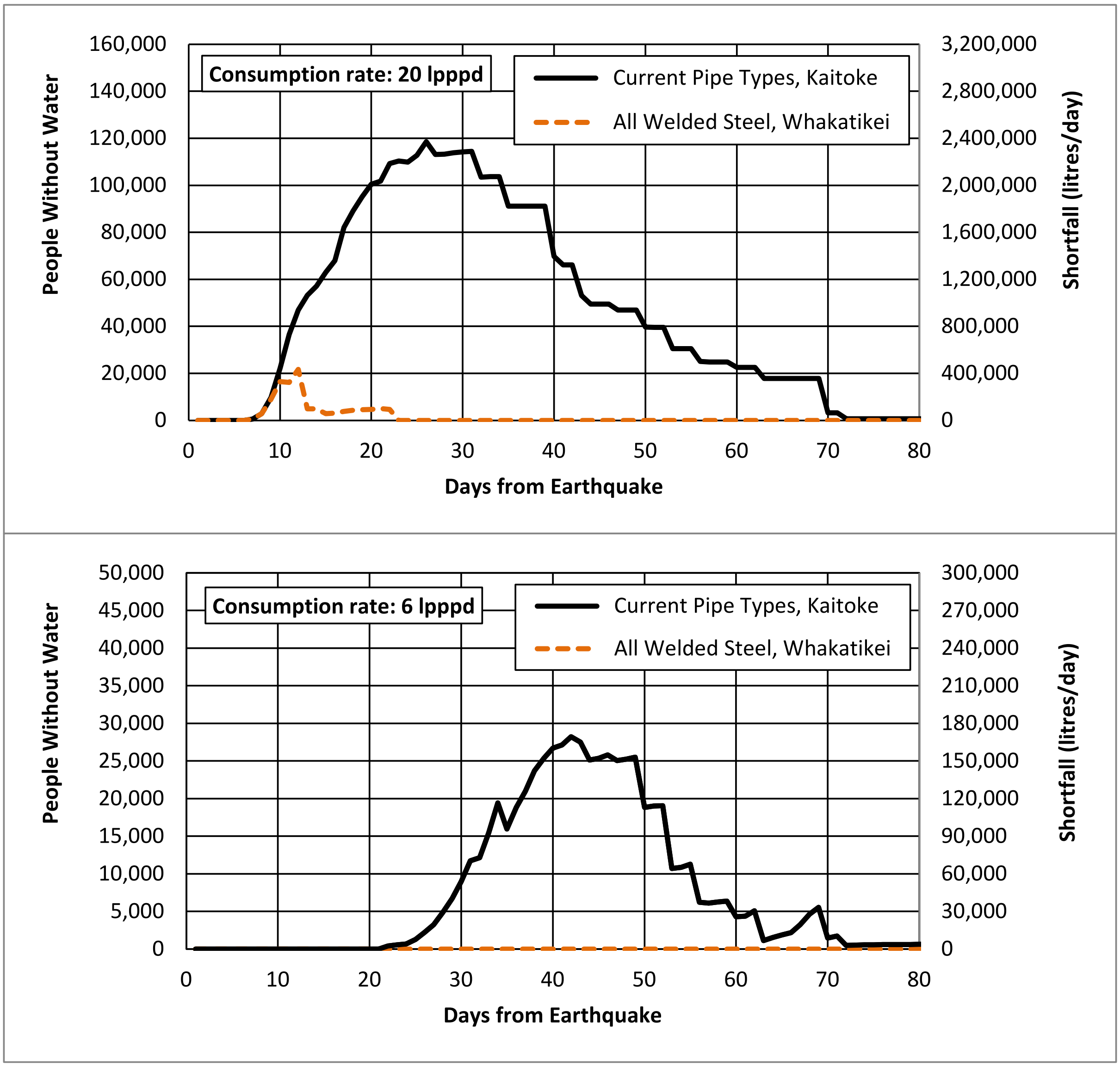

Figure 6.13 People without water, and daily shortfall of water, for (a) the current bulk supply network and Kaitoke source and (b) a hypothetical network made entirely of modern welded-steel pipe (dashed line) and drawing water from the proposed Whakatikei source, following a Wellington Fault earthquake - 75 % of water retained in reservoirs fitted with auto-shut valves.

6.6 NATURAL VARIABILITY – WELLINGTON FAULT SCENARIO

There are many sources of uncertainty in risk modelling, including natural variability in the processes being modelled, sometimes inherent randomness, and uncertainty in the models being used. The impacts of two pervasive forms of variability are considered here, (a) the inherent variability in the shaking intensity from point to point, and (b) randomness in the occurrence and placement of breaks in the pipes. Both are built-in to the modelling, with the result being that the outputs vary a little from one run of the model to another even when all of the basic inputs remain constant. The model is therefore run many (5000) times so that median and other percentile results can be extracted. Figure 6.14 is an example of the median and ±1 standard deviation results.

- Event: Wellington Fault Earthquake (shaking level MM10+)
- Retention: 50 % of water retained in reservoirs fitted with auto-shut valves
- Water source: Kaitoke
- Consumption rates: 20 and 6 lpppd
- Variable: percentile of modelled results (16th, 50th (median), 84th)

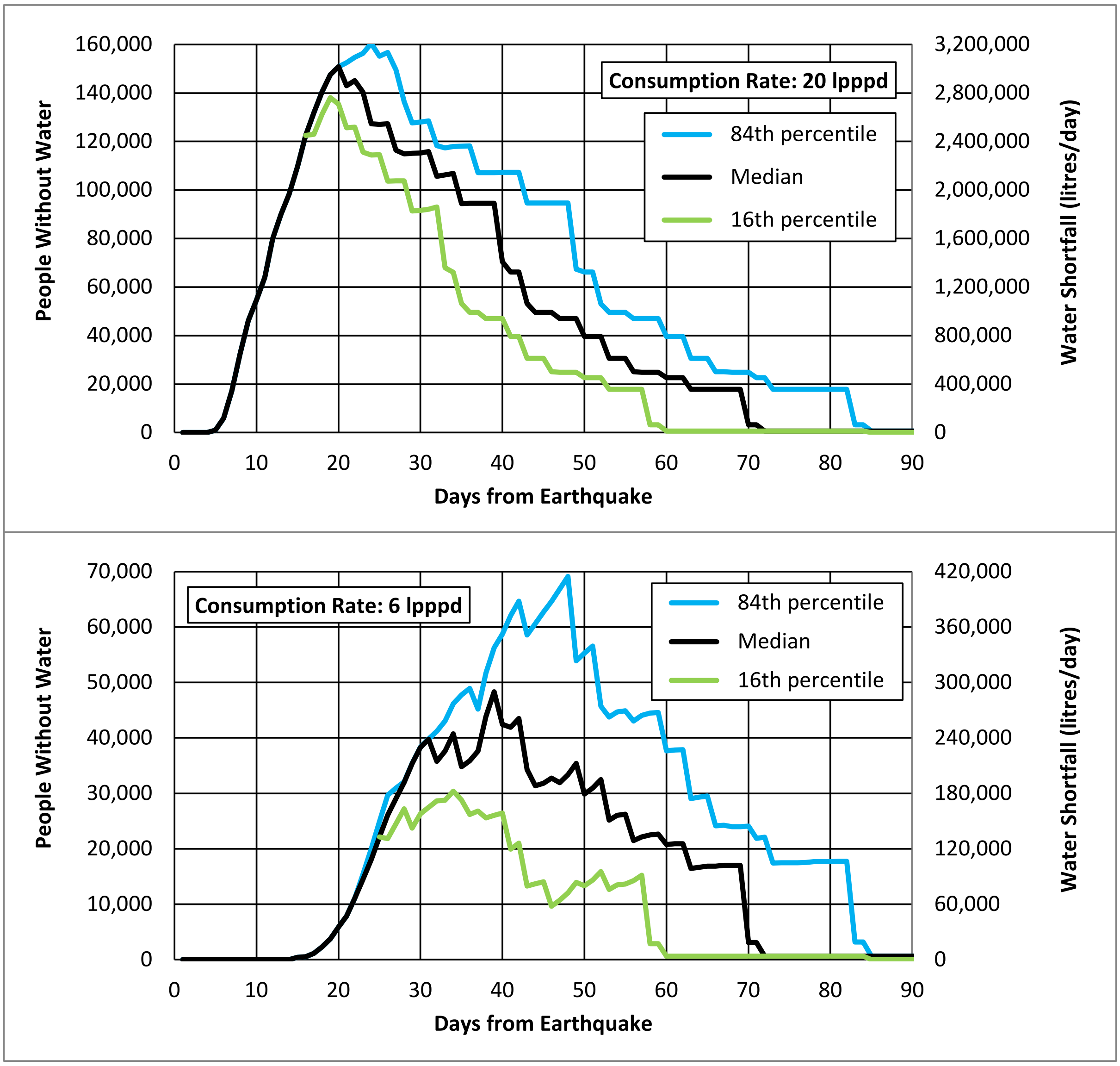

Figure 6.14 Numbers of people without water, and shortfalls in water supply, for consumption rates of 20 lpppd (top) and 6 lpppd (bottom) following a Wellington Fault earthquake.

6.7 SUBURB-LEVEL RESULTS

Results can also be accumulated and viewed at a suburb level. As an illustration, the suburbs of Wellington have been aggregated into eight groups according to distance from water source, with the Tawa area being the closest to source (Group 1) and the Miramar area being the farthest (Group 8) (Figure 6.15). The group-level restoration of bulk water supply is presented for three earthquake scenarios in Figure 6.16 to Figure 6.21. For reader convenience the groups have been given names indicative of the suburbs included (Table 6.1).

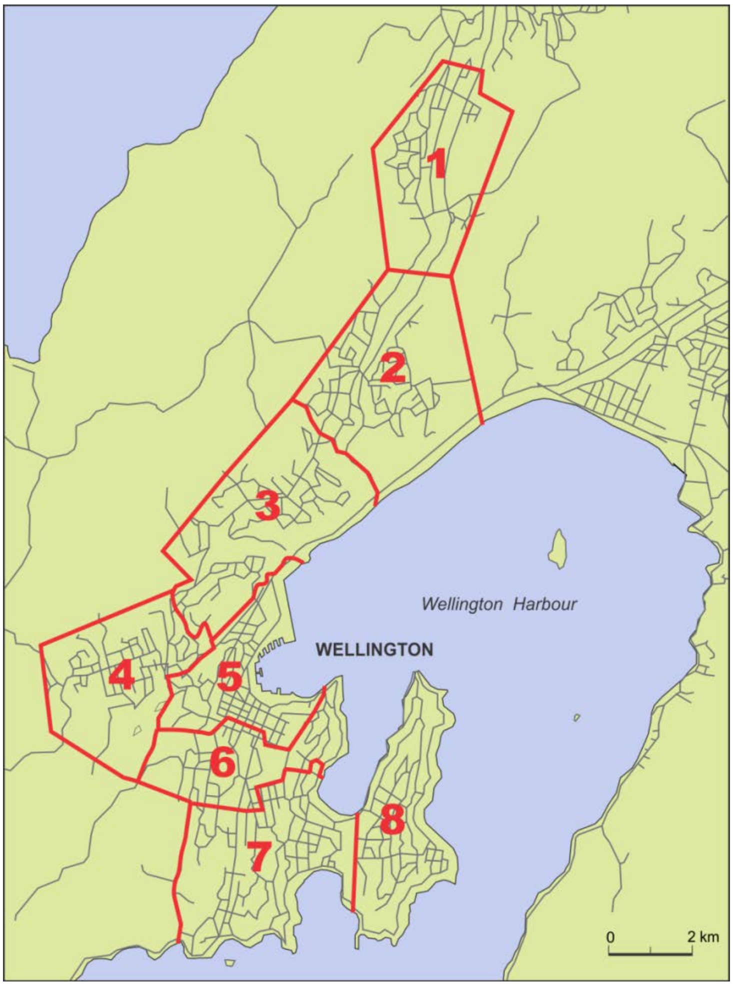

Figure 6.15 Wellington suburbs aggregated according to increasing distance from water source and, therefore, increasing time to restoration of bulk water supply following large earthquakes.

Table 6.1 Names and populations of the suburb groups.

Group	Group Title	Population
1	Tawa	15,315
2	Johsonville, Newlands	25,019
3	Ngaio, Khandallah, Wadestown	27,020
4	Karori, Northland	18,139
5	Kelburn, CBD	24,619
6	Brooklyn, MtCook, Hataitai	25,622
7	Newtown, Lyall, Kilbirnie	25,521
8	Miramar Peninsular	18,328

6.7.1 Wellington Fault Scenario

Two consumption rates are plotted, 20 and 6 lpppd. For a rate of 20 lpppd there are two main points to be taken from the plots. First, for the two groups closest to source, bulk supply is restored before stored water is fully consumed, whereas for the five groups farthest from source, the number of people without water reaches plateaus at or near the total populations of the groups (see Table 6.1 for the population numbers). Second, the durations of the plateaus are long, from 15 to 50 days.

- Event: Wellington Fault Earthquake
- Retention: 50 % of water retained in reservoirs fitted with auto-shut valves
- Water Source: Kaitoke
- Consumption rates: 20 lpppd (Figure 6.16) and 6 lpppd (Figure 6.17)

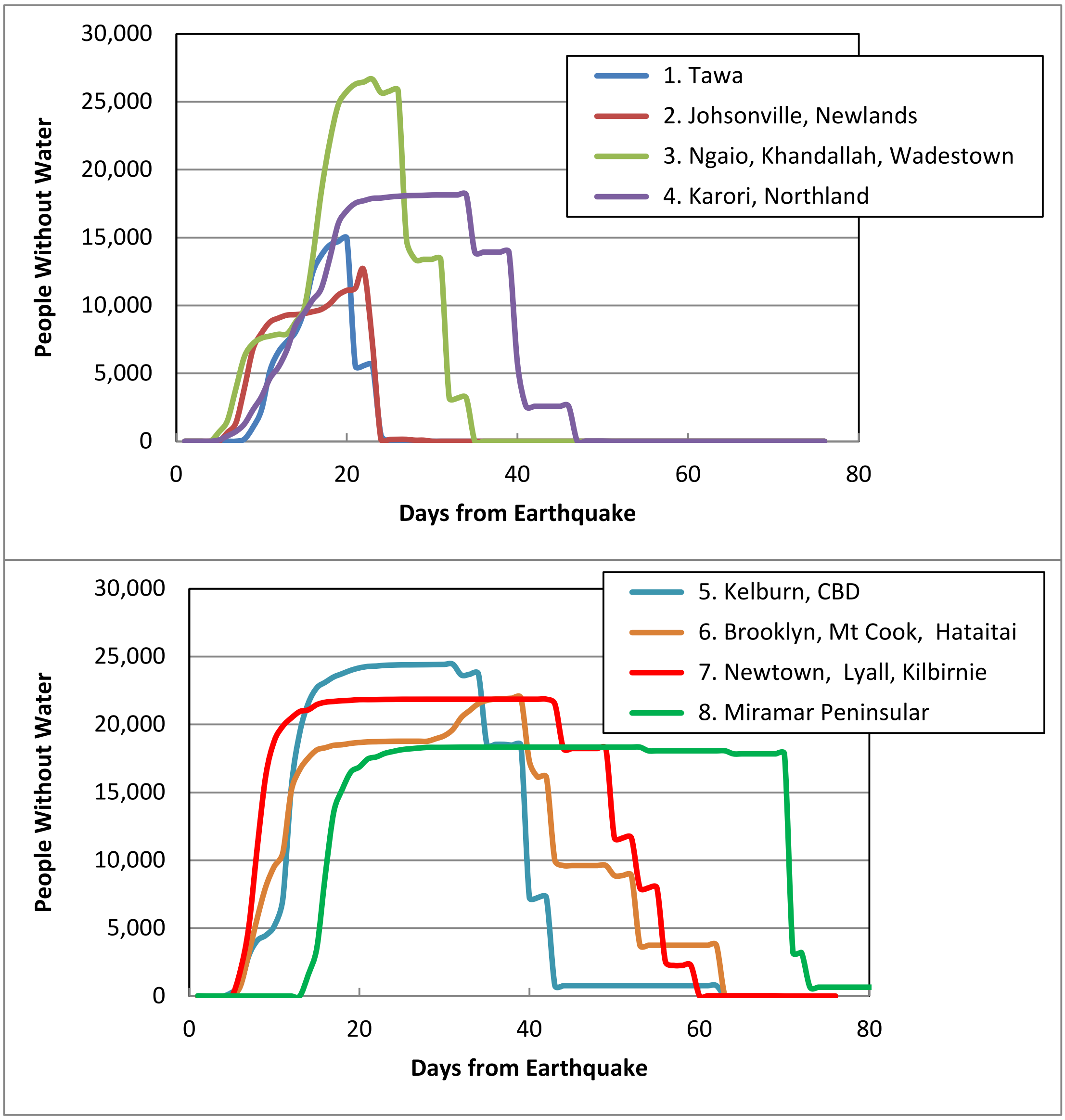

Figure 6.16 People without water by suburb group, for a consumption rate of 20 lpppd, following a Wellington Fault earthquake. The highest, flat portions, present in some of the curves indicate that all or nearly all residents in the group are without water from conventional sources (i.e. stored water has been consumed, and bulk supply has not been restored). For the Miramar group, the period during which all or nearly all residents will need water from alternative sources lasts for more than 50 days.

For a consumption rate of 6 lpppd, bulk water supply is restored to the first two groups almost before any people are without stored water, and it is only in the three most distant groups that large numbers of people are without water for long periods of time.

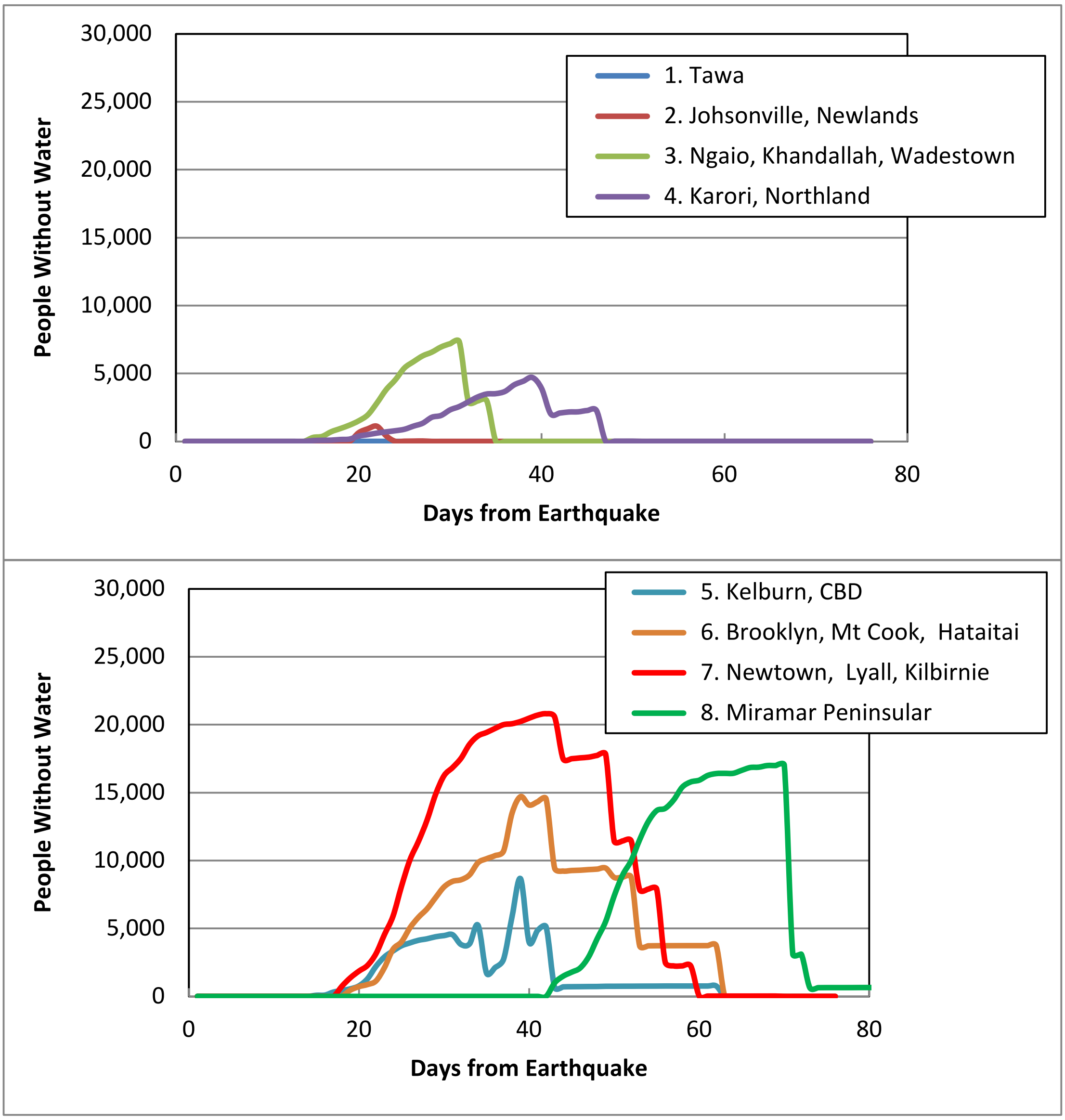

Figure 6.17 People without water by suburb group, for a consumption rate of 6 lpppd, following a Wellington Fault earthquake. The numbers of people without water, and in particular the durations of the water shortfalls, are much smaller than for the 20 lpppd case.

6.7.2 MM9 Scenario

Because the Wairarapa fault last ruptured only 150 years ago, the likelihood that it will rupture again in the next few decades is relatively low. This leaves the MM9 and Ohariu South events as the most likely strongest scenarios after the Wellington Fault earthquake. For the MM9 scenario the suburb-group water deficits are much smaller than those of the Wellington Fault event, assuming a consumption rate of 20 lpppd (Figure 6.18), and are almost insignificant for a consumption rate of 6 lpppd (Figure 6.19).

- Event: MM9 shaking scenario
- Retention: 50 % of water retained in reservoirs fitted with auto-shut valves
- Water Source: Kaitoke
- Consumption rates: 20 lpppd (Figure 6.18) and 6 lpppd (Figure 6.19)

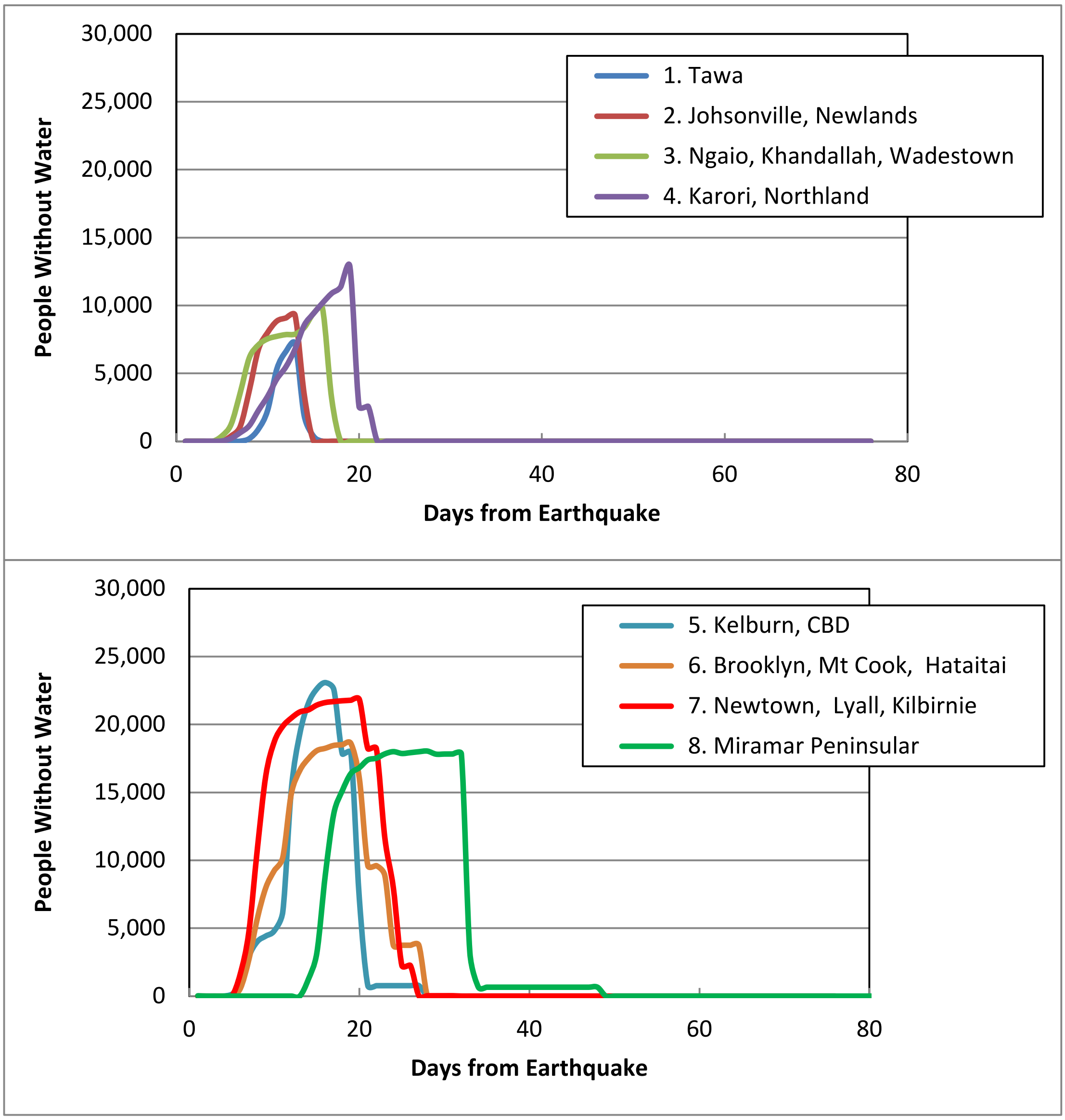

Figure 6.18 People without water by suburb group, for a consumption rate of 20 lpppd, following an MM9 earthquake scenario. Bulk water is restored before stored water is exhausted for the four suburb groups closest to source, but for the four most distant groups large proportions of the population are without water for 5 to 15 days.

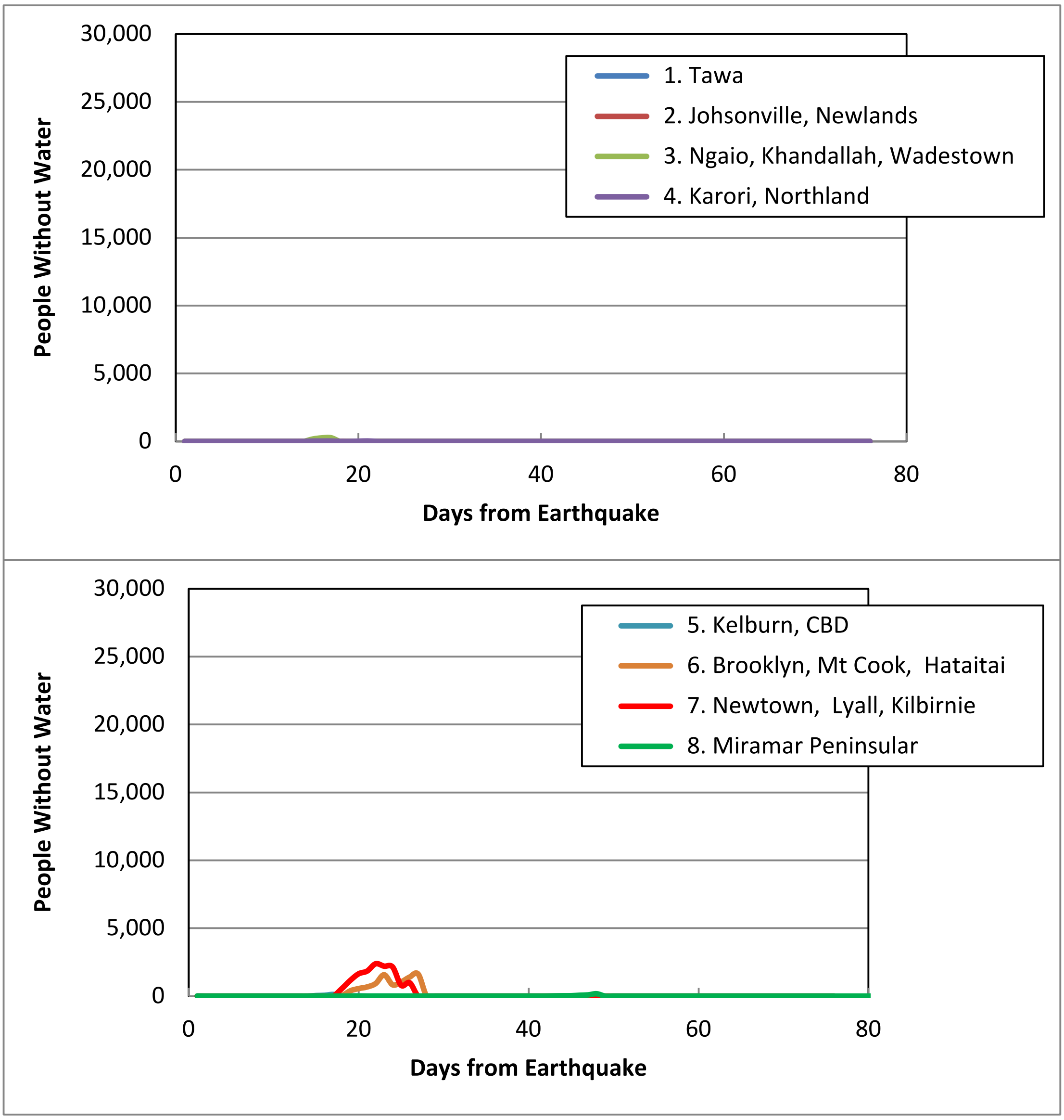

Figure 6.19 People without water by suburb group, for a consumption rate of 6 lpppd, following an MM9 earthquake scenario. The water deficits are small enough that they probably can be filled with water from alternative sources without difficulty.

6.7.3 Ohariu South Scenario

For the Ohariu South scenario the suburb-group water deficits are mostly smaller than those of the MM9 scenario (Figure 6.20 and Figure 6.21). The exceptions are the two groups farthest from source, groups 7 and 8, for which the deficits are similar in size and duration to those of the MM9 event.

- Event: Ohariu South Fault rupture
- Retention: 50 % of water retained in reservoirs fitted with auto-shut valves
- Water Source: Kaitoke
- Consumption rates: 20 lpppd (Figure 6.20) and 6 lpppd (Figure 6.21)

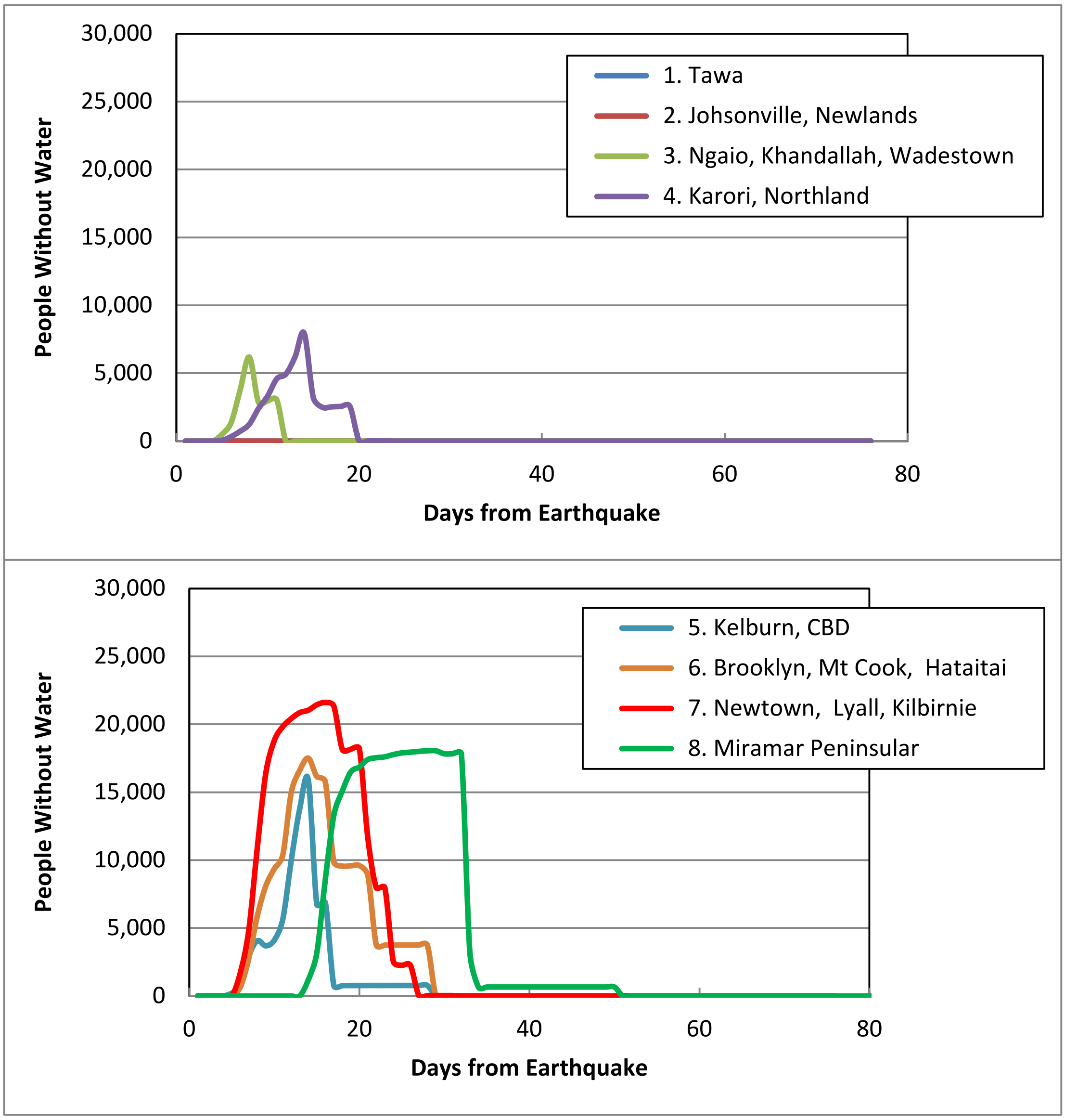

Figure 6.20 People without water by suburb group, for a consumption rate of 20 lpppd, following an Ohario South earthquake. Bulk water is restored before stored water is exhausted for the six suburb groups closest to source, but for the two most distant groups large proportions of the population are without water for 5 to 15 days.

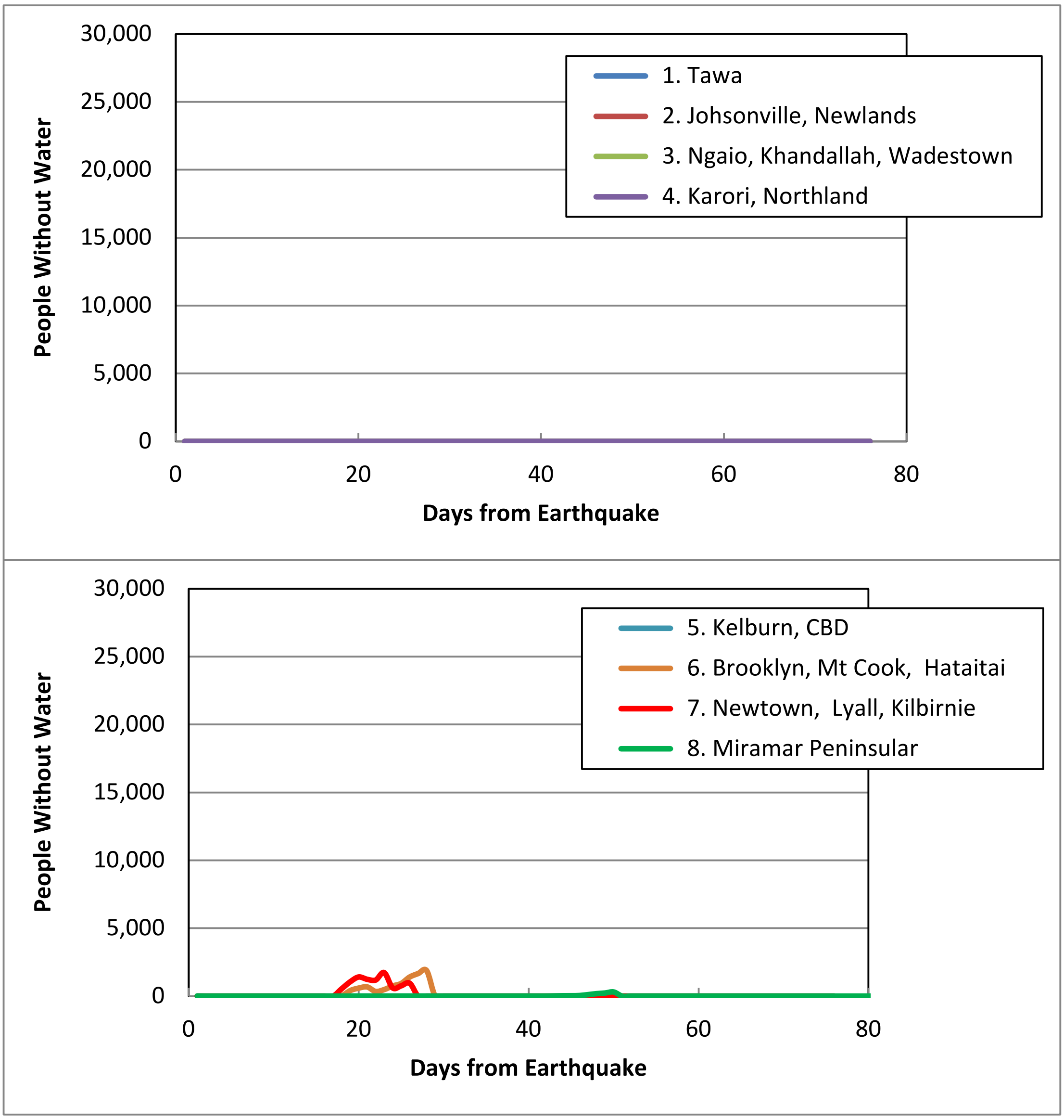

Figure 6.21 People without water by suburb group, for a consumption rate of 6 lpppd, following an Oharui South earthquake. The water deficits are small enough that they probably can be filled with water from alternative sources without difficulty.

6.8 NUMBERS OF CREWS NEEDED FOR REPAIRS TO PIPELINES

A typical repair crew is expected to consist of 4 to 5 people, equipped with a mobile welder, a large digger, at least one truck and ancillary equipment such as power saws (McCarthy 2009). For practical reasons there are limits to the number of repair crews that can usefully be employed at any given time on any particular task (Table 6.2) (McCarthy 2009).

Table 6.2 Numbers of repair crews employed for various tasks.

Repair Type	Number
Fault crossing at Te Marua	1
Fault crossing at Silverstream	2
Fault crossing at Karori	1
Leak in trunk main	2
Leak in branch main	1

The repair of a potable water pipeline, which in normal operation is a pressurised pipeline, is a sequential process from intake to reservoir (Appendix 4). This means that where there is a single pipeline there is no benefit in using more than one or two crews at any one time; one crew for a branch main and two for a trunk (large diameter) main. For the first phase of repair for the Wellington bulk supply, which is repair of the single trunk pipeline from the Kaitoke intake up to the point where the first branch main to a reservoir is encountered (i.e. to the Tawa Reservoir, Figure 1.2), just two repair crews will be required at any one time. From there on, however, it is assumed that repairs to the trunk main and branch main(s) to reservoirs, will be made simultaneously, so that multiple repair crews can be usefully employed. Figure 6.22 provides median estimates of the numbers of repair crews needed, for four large earthquakes, as functions of time. Up to eight may be required. Note that the starting point for the simulations is the junction, at Judgeford, where the trunk main from the Kaitoke joins with the trunk main from the proposed Whakatikei intake.

Repair-crew plots for individual earthquakes are provided in Appendix 7. Note that 100 simulations were run for each earthquake, with natural variability and uncertainty allowed for in the modelling (Section A4.8), so that median and 84th percentile estimates of the crew numbers could be made.

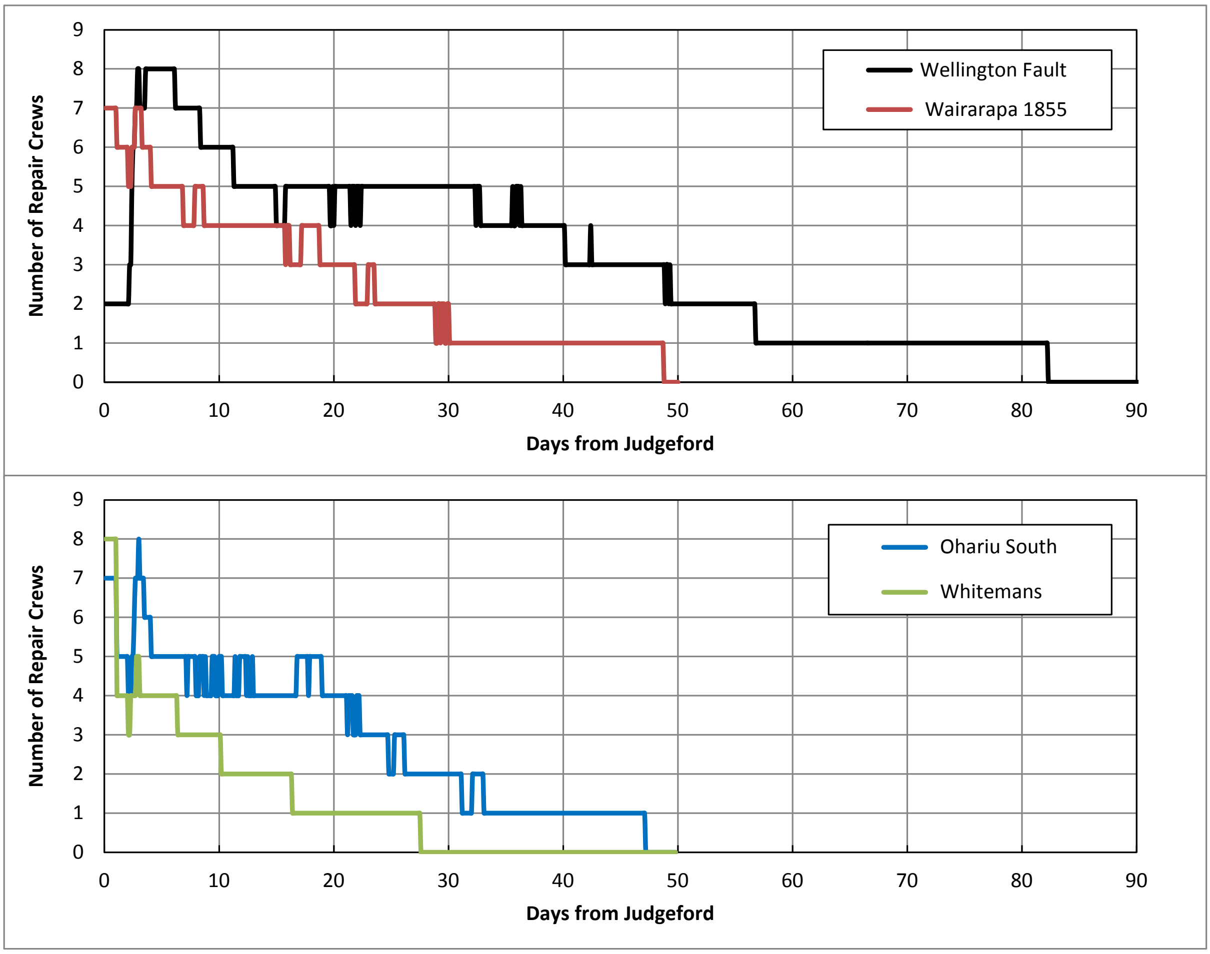

Figure 6.22 Numbers of repair crews needed at various stages of the restoration process, for the four most damaging earthquake scenarios.

7.0 DISCUSSION

A Wellington Fault Earthquake has the potential to become one of New Zealand's greatest disasters, not so much from damage and immediate casualties, as from shortfalls of water in Wellington. Assuming a recommended minimum consumption rate of 20 lpppd (which in reality may be unachievable for the 50,000 people more than 1 km from their nearest reservoirs) and assuming that half of the reservoir water is lost as a result of shaking and other damage to the reservoirs, the estimated gap between depletion of stored water and restoration of emergency supply from the bulk supply system is large (Figure 6.1). Some representative details on the size of the shortfall are:

- 3 million litres/day, at day 20 from the earthquake (a peak of 1 day duration) needed to supply 150,000 people,
- 2 million or more litres/day from days 14 to 34 (20 days duration) needed to supply 100,000 or more people, and
- 1 million or more litres/day from days 10 to 45 (35 days) for 50,000 or more people.

Lowering the consumption rate to 6 lpppd, which is regarded as an absolute minimum for survival, still leaves a significant shortfall (Figure 6.1), as follows:

- 300,000 litres/day, at day 39 from the earthquake (a peak of 1 day duration), to supply almost 50,000 people,
- 180,000 or more litres/day from days 27 to 53 (26 days) needed to supply 30,000 or more people, and
- 90,000 or more litres/day from days 23 to 69 (46 days) for 15,000 or more people.

It must also be remembered that the water problem would not be in isolation (e.g. CAE, 1991; Sanderson and Norman, 2010, Mowll, 2012). It would accompanied by other shortages including food, power and fuel. Road access, needed for resupply could well be cut for months. Both the port and airport are likely to be heavily damaged. This situation is clearly serious, and so ways of reducing the size of the water shortfall need to be found.

Two engineering-based mitigation possibilities were modelled. One involved constructing a new water intake closer to the city than the present Kaitoke intake, and the other replacing old weak pipes in the network with more robust modern pipes. Providing water from a new intake at Whakatikei, west of the Wellington Fault and about 20 km closer to Wellington than Kaitoke, was found to lower the restoration times by about two weeks, reducing the shortfalls (at 20 lpppd consumption and 50% loss of water from the reservoirs) to

- 2.1 million litres/day, at day 18 from the earthquake (a peak of 1 day duration) for just over 100,000 people (Figure 6.8),
- 1 million or more litres/day, for 20 days, to supply 50,000 or more people.

Lowering the consumption rate to the survival level of 6 lpppd would leave

- a peak shortfall of 150,000 litres/day to supply 25,000 people for 1 day, and
- 60,000 or more litres/day, for about 33 days, for 10,000 or more people (Figure 6.8).

The Whakatikei intake achieved the reductions in water shortfalls largely through avoidance of the two crossings of the Wellington Fault in Upper Hutt. This can determined by comparing

the numbers of breaks in Table A 5.3 and Table A 5.4 (respectively for the Kaitoke and Whakatikei intakes), and restoration times in Table A 5.5 and Table A 5.6.

Improving the pipeline quality was the second mitigation option studied. Improvement could be achieved by replacing old pipes that have coupled joints with pipes of modern robust construction, probably a combination of steel with welded joints for large diameters and high performing plastic materials for small diameters, assuming of course that plastic pipelines will meet the welded steel criterion that only one failure in five will leak sufficiently badly as to need immediate repair. Improving the pipeline appeared to make little difference to either the size or the timing of the peak shortfall, but more than halved the times without water (Figure 6.10). Assuming 20 lpppd consumption and 50% loss of water from the reservoirs, the shortfalls became:

- a peak of 2.8 million litres/d for 140,000 people at day 20 (previously 3 million litres/d),
- 2 million or more litres/d for 9 days (previously 20 days) for 100,000 people, and
- 1 million or more litres/d for 14 days (previously 35 days) for 50,000 people.

At a consumption rate of 6 lpppd the shortfalls dropped to:

- a peak of 60,000 litres/day (to supply 10,000 people), and
- 30,000 litres/day for 5 days (for 5000 people).

Combining both of the above mitigation measures (and assuming, as previously, 20 lpppd consumption rate and 50% loss of water from the reservoirs) lowered the estimated shortfalls (Figure 6.10) to

- a peak of 800,000 litres/day for 40,000 people at day 9, and
- 400,000 litres/day or more for 5 days (20,000 or more people).

At a consumption rate of 6 lpppd the shortfalls were almost zero.

Thus, while neither of the two mitigation measures on its own appeared to make the post-earthquake situation acceptable, combining the two had the potential to lower the shortfalls to levels that probably would be acceptable, in that the necessary quantities of additional water should be able to be provided from non-conventional sources without undue difficulty.

The Wellington Fault scenario was a clear worst-case event. Eight other large earthquake scenarios were also modelled with the results for the worst five being presented separately in Figure 6.2 to 6.5 and compared in Figure 6.6 and Figure 6.7. The recurrence interval for a magnitude 7.5 earthquake on the Wellington Fault is 1000 years (10-15% probability in 100 years, Rhoades et al. 2011). Shaking intensities in the central business district of Wellington are expected to be MM10 or greater. Lower levels of shaking, MM9 or MM8, have higher probabilities of occurrence, i.e. return periods of 400 years for MM9 and 120 years for MM8. Consequences of the lower levels of shaking are much less severe than for the Wellington Fault event, as follows:

- MM9 shaking: 40,000 people without water for about 15 days, another 40,000 for 8 days.
- MM8 shaking: Loss of supply in some areas, with restoration of supply being completed before stored water has been consumed.
- MM7 shaking: Minor loss of supply in some areas, with restoration of supply being completed before stored water has been consumed.

Scenarios with shaking in the range MM9 to MM10 include Wairarapa1855 and MM9, with the Hikurangi Subduction Zone possibly being a source of MM9-level shaking. Scenarios with shaking in the range MM8 to MM9 include the Ohariu South and Whitemans. Sources falling in the range MM7 to MM8 include the Akatarawa-Otaki and Tararua.

Sources that clearly are capable of generating serious levels of damage to the water supply system are, therefore, the Wellington-Hutt Valley segment of the Wellington Fault, the Wairarapa Fault (which last ruptured in 1855 and so is unlikely to rupture again in the near future), the southern segment of the Ohariu Fault, and probably the Hikurangi Subduction Zone. In all cases it would be necessary to find ways of providing large quantities of emergency water, hundreds of thousands to millions of litres per day, to sustain tens of thousands, possibly as high as 150,000, people for one to several weeks.

Unconventional sources of water were not included in the above modelling, because one purpose of the modelling was to determine what quantities of water might be required from such sources. Some have the potential to make big impacts. Possibilities discussed by MWH (2012) include the following:

- Tunnel drainage. Water flow from the Tawa rail tunnel, about 1.3 million litres/d, could meet the shortfalls for all events apart from the three worst, i.e. earthquakes on the Wellington Fault, the Wairarapa Fault and the Subduction Zone (a likely “MM9” event).
- Rainwater harvesting. The mean summer rainfall in Wellington is about 60 mm/month, hence an average-sized house, with roof area 125 m^2, could collect on average about 200 litres/day, enough for 10 people at 20 lpppd. For a family of four, a 1000-litre storage tank would last 12.5 days between refills, and a 2000-litre tank 25 days. Hence a 2000-litre tank is definitely large enough, and a 1000-litre one probably large enough. The potential impacts of rainwater have also been considered by Abbott et al. (2012) and Shaw (2012).
- Desalination. Assuming power could be found to run them, 3 desalination plants producing 1 million litres/day each would suffice. Disadvantages include cost, at about $2 million each, power requirements, at about 200 kW each and, most serious, procurement time, about 3 months.

The water shortfalls estimated above are not necessarily the maximum values that could occur. Two potential causes of higher losses could be (a) natural variability and uncertainty in both the natural processes involved and the modelling of them, and (b) an assumption that two major elements of the water supply network will not fail under strong earthquake shaking, with the two elements being a flume bridge that carries the water across the Hutt River at Kaitoke (Figure 7.1) and a road bridge that carries the bulk main across the Hutt River at Silverstream (Figure 7.2).

Two forms of variability were incorporated in the modelling. They were the inherent variability in the shaking intensity from point to point, and randomness in the occurrence and placement of breaks in the pipes. Multiple runs of the Wellington Fault scenario indicated that, for a consumption rate of 20 lpppd, the standard deviation in the peak water shortage, arising from the two sources of variability, was about 10% of the median peak value, and that the standard deviation in the water restoration time was about 20% of the median value (Figure 6.14). Two other, major, uncertainties were the amount of water retained in reservoirs following strong shaking, and the rate of consumption of water under post-earthquake conditions. Both were modelled specifically.

Figure 7.1 Kaitoke flume bridge, carrying water across the Hutt River between the intake weir and the treatment plant at Kaitoke (original photo by Marnee Ackerman, 2008). Earthquake strengthening of the central support pier is visible.

Figure 7.2 Road and rail bridges across the Hutt River at Silverstream. The bulk supply pipeline can be seen on the upstream (left) side of the road bridge. Although the exact line is not known, the Wellington Fault runs approximately parallel to the nearer bank of the river, between the nearer bank and the bottom of the photo. (Original photograph by Graeme Hancox.)

The Kaitoke flume bridge was constructed in the early 1950s (GWRC, 2007). In the early 1990s the supporting structure was assessed as having 25% of the strength required by the then current standard, and shortly after was strengthened to full seismic standard (Brunsdon, 2000). Despite the strengthening, however, there is still a possibility that it could fail in strong shaking. Reinstatement of even a temporary structure could take from days to weeks. The reinstatement time, however, would not necessarily increase the overall times needed for water resupply, because the work could be handled as a separate work-stream in the same way as was done for repair of pipe breaks caused directly by rupture of the Wellington Fault.

Reinstatement of the river crossing at the Silverstream Bridge also could take days to weeks, but, as was noted for repair of damage to the flume bridge, also could be handled as a separate work-stream and would not necessarily increase the overall system repair times.

The work reported above has covered many aspects of the post-earthquake water situation in Wellington, including impacts of several large earthquake scenarios, variation in water retention in reservoirs post-earthqukae, variation in water consumption rates, and impacts of two potential engineered mitigation measures (a new water source located west of the Wellington Fault, and improvements to pipe quality). Much remains to be done, however, and areas for future development of the water deficit modelling could include:

- Incorporating a model for rainwater harvesting, because rainwater has the potential to provide large quantities of water, already distributed to users, over long time periods.
- Validation of the pipe fragility functions, a critical but not well-evidenced component of the modelling. Data from the recent Canterbury earthquakes (e.g. O'Rourke et al., 2012) should provide valuable guidance.
- Incorporation of Porirua into the modelling because it, like Wellington, is critically dependent on conventional sources of water.
- Apply method to another city, perhaps Palmerston North, which will almost certainly show that the Wellington/Porirua vulnerability does not apply (a) because reinstating road access will be easier than for Wellington, and (b) there is a large river nearby.

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8.0 ACKNOWLEDGEMENTS

Many contributors to the work have either been acknowledged in the text or included in the references, but special mention is due (a) to Graham Hancox, Nick Perrin and Biljana Lukovic of GNS for creation of the geotechnical hazard model, and freely given advice on other topics (b) to Alistair McCarthy, Tony Shaw and Mike McMenamin of the Greater Wellington Regional Council for advice on repair times, personnel requirements, and repair procedures for various components of the bulk supply network, (c) staff of the Regional Council and Capacity Ltd for provision of pipe network data, and (d) to Dave Brunsdon of Kestrel Group, and Russ Van Dissen, Rob Buxton, Peter Barker, Graeme McVerry and Maureen Commer of GNS, for helpful reviews of the current and earlier reports on the topic. The project was supported by public research funding from the Government of New Zealand, Greater Wellington Regional Council, and the Earthquake Commission and other local and government bodies through the "It's Our Fault" project.

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APPENDICES

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APPENDIX 1: HAZARD MODELS

A1.1 EARTHQUAKE MODELS

Nine earthquake scenarios were considered. The scenario considered in most depth was one that can almost be considered a standard worst-case event for New Zealand, i.e. a magnitude 7.5 earthquake generated by rupture of the Wellington-Hutt Valley segment of the Wellington Fault, with the epicentre approximately in the centre of the rupture (Figure A 1.1). Note that this location was chosen because it gives the highest loss estimate, and that in a real earthquake the epicentre could be located elsewhere along the fault.

Three more distant hypothetical events, with locations and magnitudes chosen arbitrarily so as to give shaking intensities of about MM9, MM8 and MM7 over the key parts of the water network, were created so that the impacts of shaking levels less severe but more probable than those from the Wellington Fault event could be assessed (Figure A 1.2 to A 1.4), and finally large earthquakes generated by five known active faults in the Wellington area were modelled (Figure A 1.5 to A 1.9). Fault data were taken from recent studies (by scenario name: Wellington Fault – Rhoades et al., 2011; Ohariu South and Wairarapa 1855 – Van Dissen et al., 2013; Whitemans – Begg and Van Dissen, 1998; Tararua – Langridge et al., 2005; Akatarawa-Otaki – Stirling et al., 2012).

Table A 1.1 Earthquake parameters for a worst case scenario based on rupture of the Wellington Hutt Valley segment of the Wellington Fault, and three arbitrary scenarios chosen to give the specified shaking intensities over central Wellington and key parts of the bulk supply pipelines.

Earthquake scenario Name	Wellington Fault	MM9	MM8	MM7
Epicentre easting (nzmg)	2661000	2682000	2684500	2687000
Epicentre northing (nzmg)	5992500	5984500	5981500	5980500
Magnitude	7.50	7.85	7.10	6.30
Fault Centroid Depth (km)	10.0	7.5	7.5	7.5
Fault Top Depth (km)	0.0	0.0	0.0	0.0
Fault Strike (Degrees East)	52	42	42	42
Focal Mechanism	Strike-slip	Strike-slip	Strike-slip	Strike-slip
Recurrence Interval (y) (1)	840 (1000)	400 (2)	120 (2)	30 (2)

Table A 1.2 Earthquake parameters for scenarios based on five Wellington-area active faults.

Earthquake scenario Name	Ohariu South	Wairarapa (1855)	Whitemans	Akatarawa-Otaki	Tararua East
Epicentre easting (nzmg)	2648589	2690000	2674483	2698146	2711913
Epicentre northing (nzmg)	5986781	5993500	5992216	6031808	6029801
Magnitude	7.40	8.20	7.00	7.50	7.30
Fault Centroid Depth (km)	10.0	17.5	10.0	10.0	10.0
Fault Top Depth (km)	0.0	0.0	0.0	0.0	0.0
Fault Strike (Degrees East)	42	47	29	36	36
Focal Mechanism	Strike-slip	Strike-slip	Reverse	Strike-slip	Strike-slip
Recurrence Interval (y) (1)	2500 (2100)	1200 (5300)	20,000	6800	710

Note 1: Two values of recurrence interval are given for some faults, (a) the long-term average, and (b) in brackets, a "conditional" value that takes into account the geologically recent rupture history of the fault in question and that of its neighbours, and which is the better of the two values to use for near-future impact modelling (Rhoades et al., 2011; Van Dissen et al., 2013).

Note 2: Return periods for the specified shaking intensities.

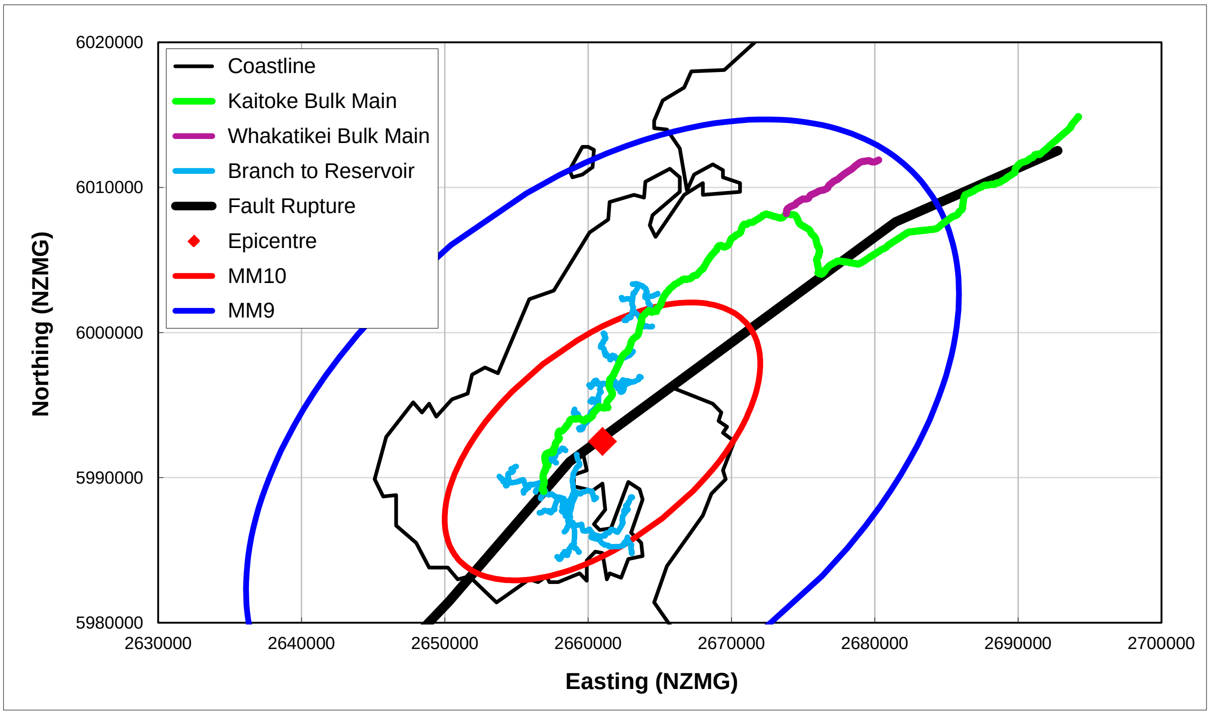

Figure A 1.1 Isoseismal map for the maximum event - a magnitude 7.5 earthquake resulting from rupture of the Wellington-Hutt Valley segment of the Wellington Fault. (Scale: each grid square is 10 km x 10 km in size.)

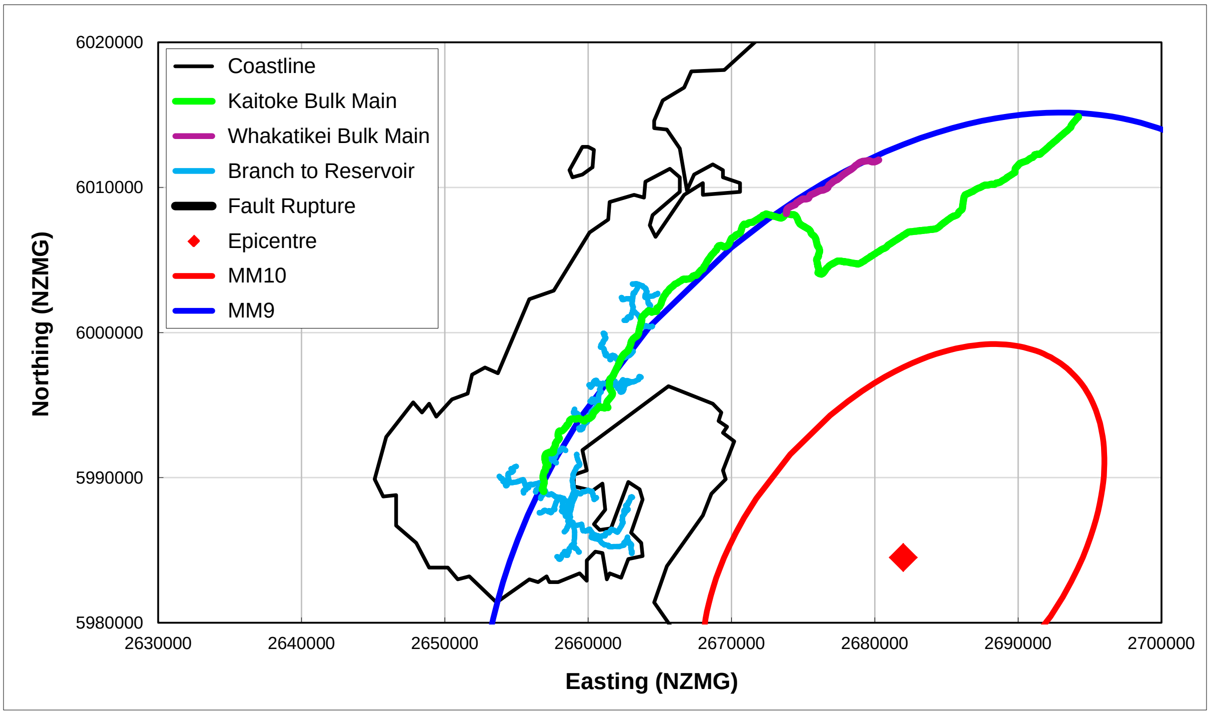

Figure A 1.2 MM9 event - a hypothetical magnitude 7.85 earthquake positioned so as to give MM9 intensity shaking over central Wellington and much of the bulk supply network.

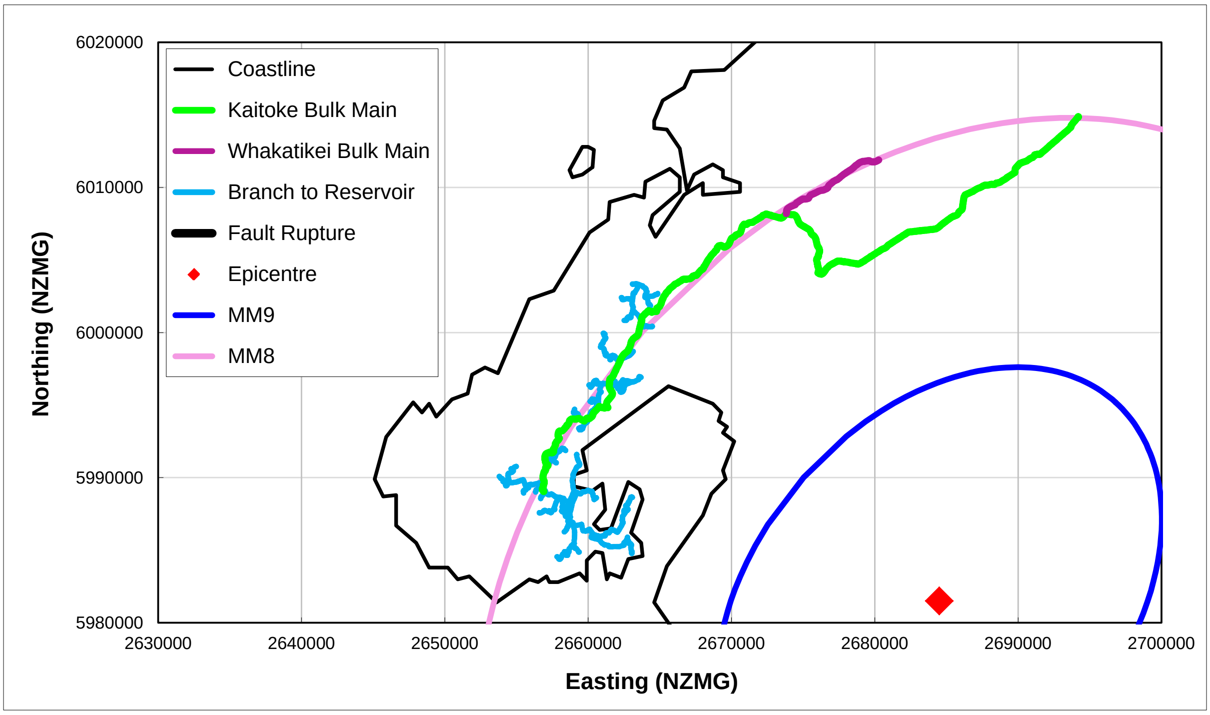

Figure A 1.3 MM8 event - a hypothetical magnitude 7.1 earthquake positioned so as to give MM8 intensity shaking over central Wellington and much of the bulk supply network.

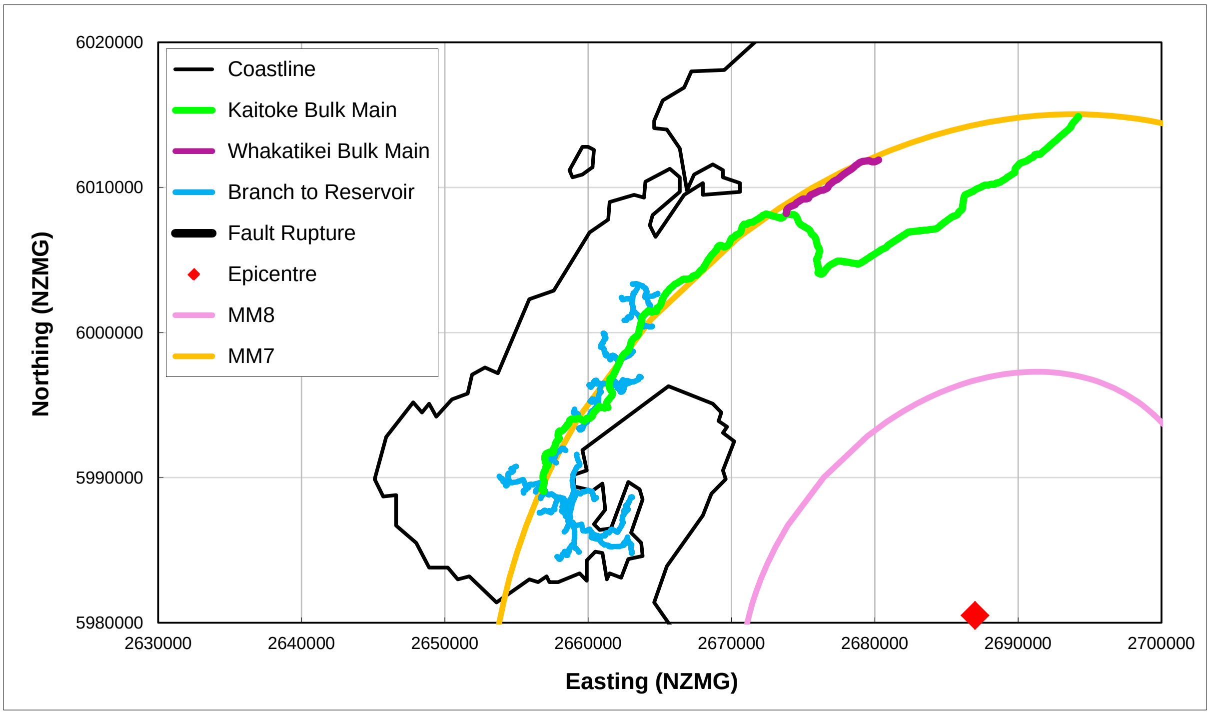

Figure A 1.4 MM7 event - a hypothetical magnitude 6.3 earthquake positioned so as to give MM8 intensity shaking over central Wellington and much of the bulk supply network.

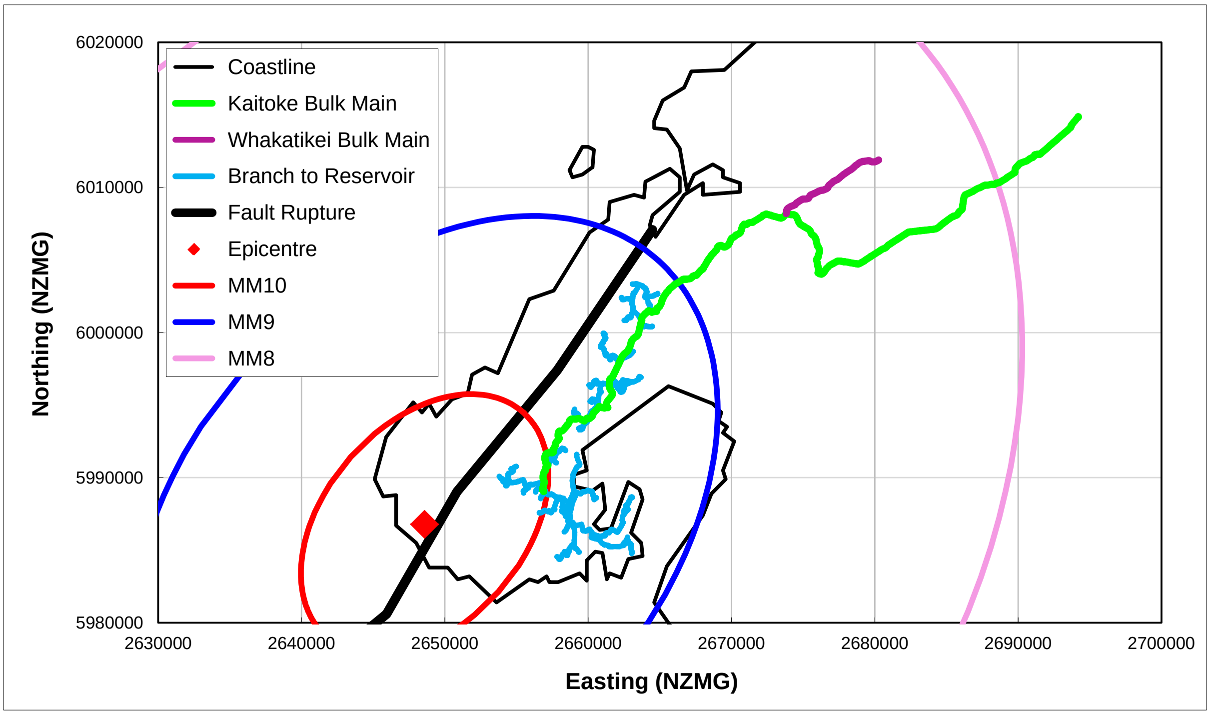

Figure A 1.5 Isoseismal map for a magnitude 7.4 earthquake resulting from rupture of the Ohariu South Fault. A feature of this event is that it gives very strong shaking over southern parts of Wellington, but only moderately strong shaking around the Kaitoke intake.

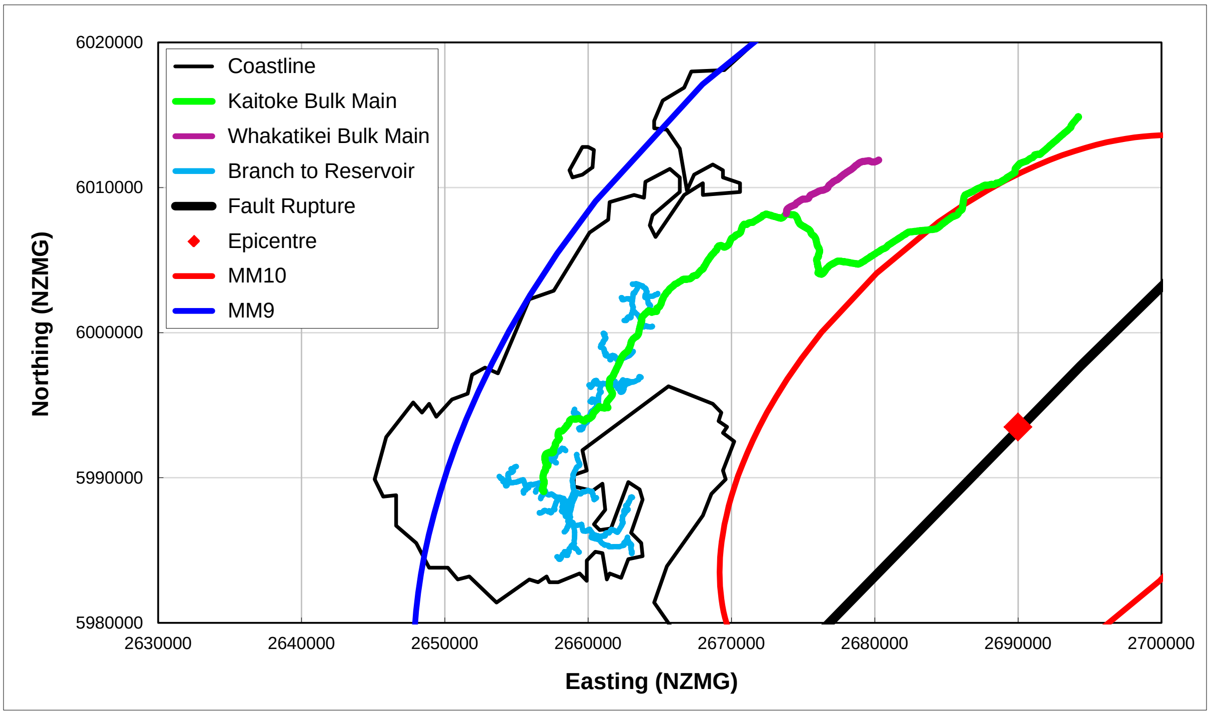

Figure A 1.6 Isoseismal map for a magnitude 8.2 earthquake resulting from rupture of the Wairarapa Fault (which last ruptured in 1855). Note that this event gives very strong shaking near the Kaitoke intake, stronger than any of the other events modelled.

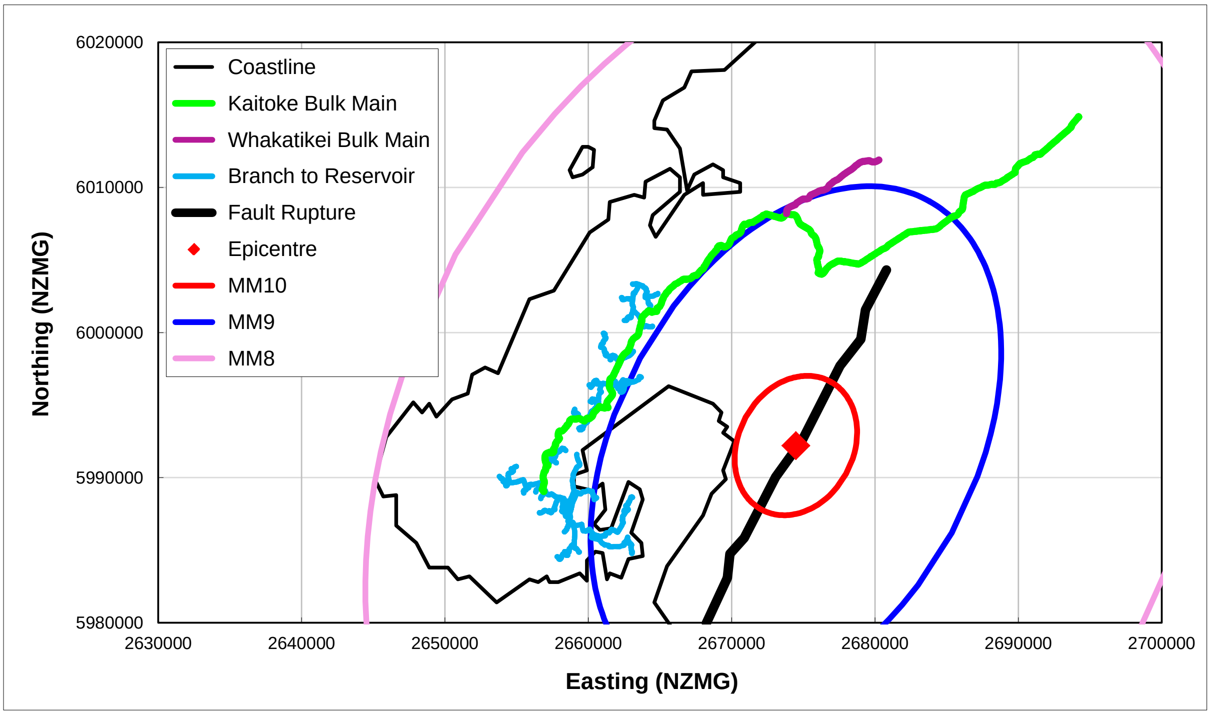

Figure A 1.7 Isoseismal map for a magnitude 7.0 earthquake resulting from rupture of the Whitemans Fault.

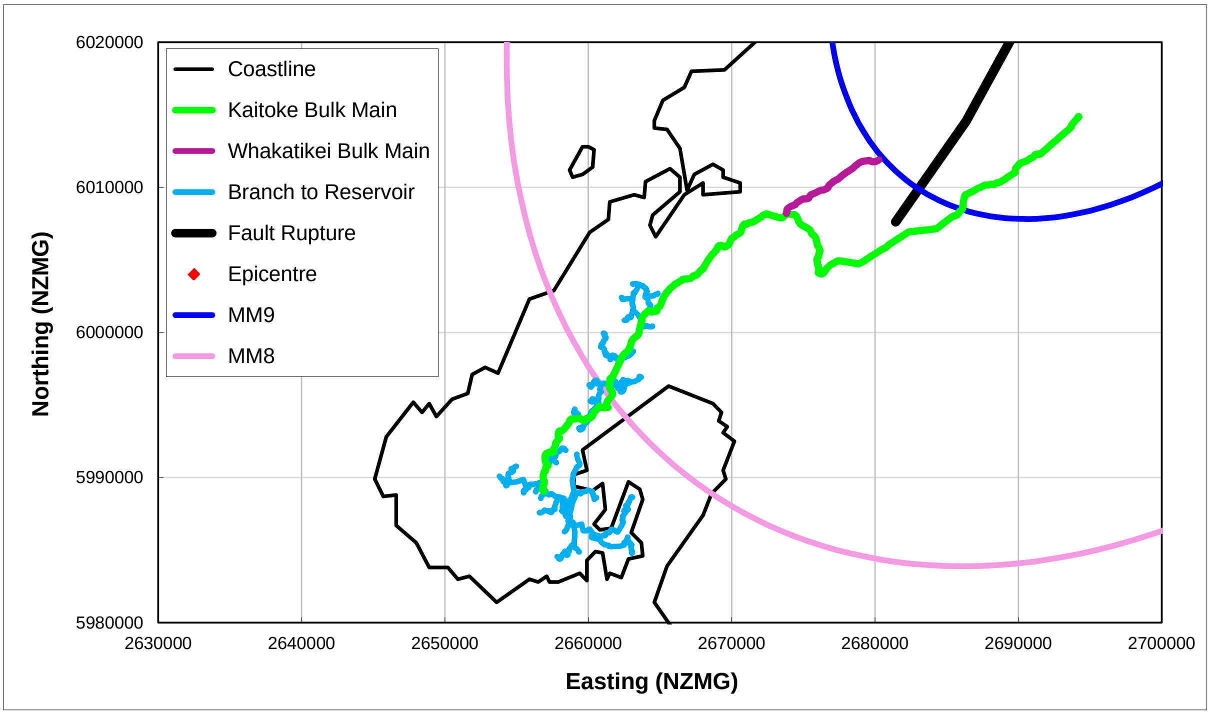

Figure A 1.8 Isoseismal map for a magnitude 7.5 earthquake resulting from rupture of the Akatarawa-Otaki Fault. Shaking is strong over both the Kaitoke and proposed Whakatikei intakes, but only moderately strong over Wellington.

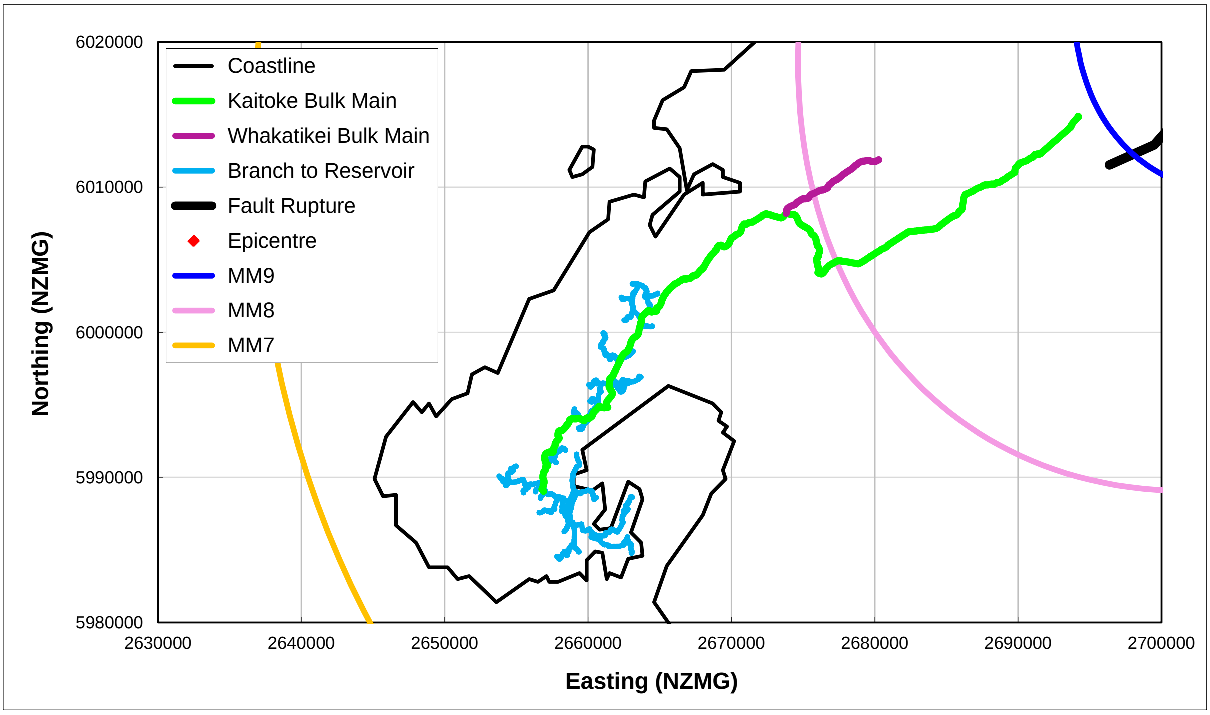

Figure A 1.9 Isoseismal map for a magnitude 7.0 earthquake resulting from rupture of the Tararua East segment of the Wellington Fault.

A1.2 SHAKING AND MICROZONATION

In all cases the earthquake shaking fields around the epicentres were modelled using the MMI attenuation model of Dowrick and Rhoades (2005). An important point about the Dowrick and Rhoades model is that it is based on New Zealand-wide intensity data from eighty-nine large earthquakes, with no specific allowance being made for the impact of the class of the ground on the perceived strength of the shaking. Hence the Dowrick and Rhoades model is commonly assumed to predict the shaking intensity for an average class of ground, which we take to be Subsoil Class C shallow soil as defined by the New Zealand Standard NZS1170.5: 2004 (Standards New Zealand, 2004). Effective intensities for non-average ground, i.e. soft soil or rock, can be higher or lower than the average-ground case as a result of microzonation. Various factors can be involved, including amplification of shaking by soft soils and some topographic forms, both of which directly affect the perceived strength of the shaking, and liquefaction and landsliding, which contribute to increased damage through permanent ground movement. Amplification by soft soils is important at low intensities of shaking, MM7 and below. The remaining three phenomena are important at high intensities, MM8 and above. They are discussed below.

Amplification of seismic shaking by soft soils is a complex topic. In some circumstances soft soils can amplify relatively innocuous input rock motions until they become damaging, while in others there is evidence that when the input motions are strong, i.e. MM8 and above, soft soils can isolate some structures from the strong shaking.

Amplification is most obvious when the input rock motions are relatively weak and caused by large, distant earthquakes. An extreme example occurred in Mexico City in 1985. The earthquake causing the damage was a magnitude 8.1 event centred about 400 km away from the City. On firm ground adjacent to the city the shaking was quite weak, about MM5, but on certain soft soils within the city was strong enough to seriously damage many modern high-rise buildings and kill more than 10,000 people. One reason for this was a double

resonance effect. Areas of soft soils that had resonant periods of about 2 seconds were preferentially set in motion by the incoming seismic waves, and buildings that had the same resonant frequency, i.e. those 8-16 stories high, swayed particularly strongly. Many collapsed. Nearby buildings of weak stone construction were undamaged because their resonant periods did not match the resonant period of the soft soils (Munich Re, 1986; Butcher et al. 1988).

A second example occurred in San Francisco during the 1989 Loma Prieta earthquake. Downtown San Francisco was nearly 100 km from the epicentre of the magnitude 6.9 earthquake. On firm soils and rocky areas of the city the prevailing intensity was MM6, increasing to MM7 on some adjacent softer soils and to MM9 in some small pockets of very soft soils (Benuska, 1990). Note that liquefaction effects also contributed to the damage associated with the very soft soils.

In both Mexico City and San Francisco the soft soils have repeatedly shown the same amplification effects, e.g. in Mexico City in 1957, 1979 and 1985, and in San Francisco in 1906 and 1989 (Borcherdt and Gibbs, 1976; Butcher et al. 1988; Benuska, 1990).

Amplification of weak seismic shaking by soft soils has been seen many times in recordings made by arrays of seismological instruments in Wellington, Lower Hutt and Porirua and is included in some attenuation models (e.g. McVerry et al., 2006).

What happens when the ground motion is very strong is not at all clear. For instance, Napier suffered a direct hit from a magnitude 7.8 earthquake in 1931 and was severely shaken. Houses on ground classified as rock were, on average, more badly damaged than houses on ground classified as firm soils and gravels, which in turn were more badly damaged than most houses on ground classified as soft soil (Dowrick et al., 1995). Of course an exception to this was that houses on soft soil that suffered *lateral spreading*, about 10% of all houses on soft soil, were the most badly damaged of all.

A second example of the protective effect of soft soil at high levels of shaking was noted in Los Angeles after the magnitude 6.7 Northridge earthquake of 1994. Over a considerable area there was an anti-correlation between house damage and pipe damage, i.e. where houses were highly damaged underground pipes were not and vice versa. It seemed that where there were large dynamic strains in the soil (excluding regions of permanent ground deformations such as differential settlement and lateral spreading) the soil absorbed enough seismic energy to significantly protect the houses on it, the downside being that the large dynamic strains resulted in increased levels of damage to underground pipelines (Trifunac and Todorovska. 1997, 1998).

To summarise, amplification of seismic shaking intensity in soft soils can occur, but is not general at all levels of shaking. It occurs (a) for all frequencies of vibration if the amplitudes are small, i.e. for intensities up to about MM8, and (b) for longer periods of vibration, approximately 0.6 seconds and above, for intensities up to MM10. Conversely, peak ground accelerations and short-period vibrations appear to be attenuated on soft soils for intensities greater than about MM8 to MM9. The most important point to be made here, though, is that underground pipes are long-period structures, and so will likely suffer from soft-soil amplification effects at all intensities.

On the other hand, and remembering that the baseline is the Dowrick and Rhoades model for average intensity, shaking intensities can be attenuated for structures on or in weak and strong rock.

For the pipeline work being described here, amplification was modelled by applying increments to the Dowrick and Rhoades intensity as shown in Figure A 1.10. Subsoil classes A to E are as defined in the New Zealand Loadings Standard NZS1170.5:2004 (Standards New Zealand, 2004). There are some data to support the increments but much judgement also is involved.

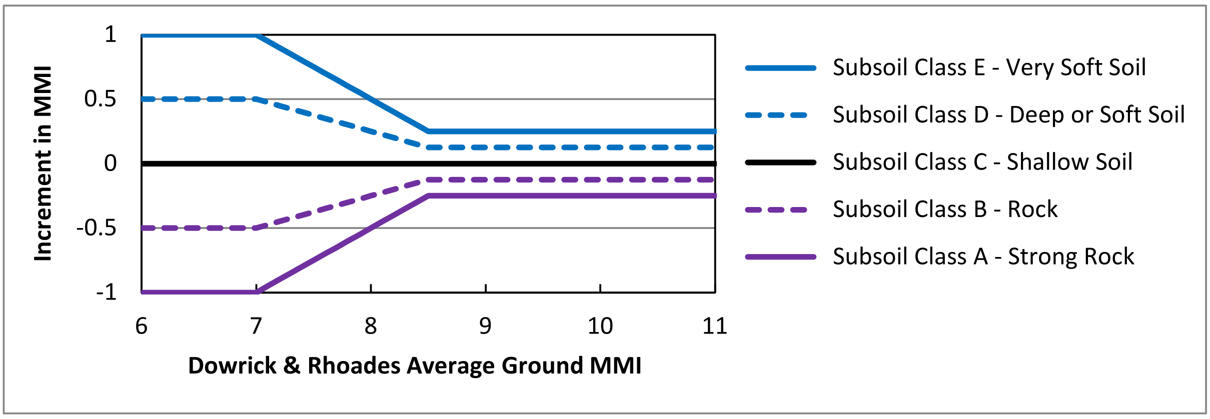

Figure A 1.10 Increments applied to the Dowrick and Rhoades (2005) average MMI estimates to allow for amplification and attenuation of shaking on non-average ground. The increments are suitable for long-period structures like underground pipelines and high-rise buildings.

Liquefaction is the loss of bearing strength experienced when uniformly graded, saturated, sand and silt are subjected to dynamic shaking. Its effects can range from harmless sand boils to serious ground damage such as subsidence, lateral spreading and loss of bearing strength. At intensities of MM6 to MM7 the effects of liquefaction are nearly always small and rarely cause significant damage to pipelines or buildings. At higher intensities, MM8 and above, ground damage (settlement, spreading or displacement) often occurs and can result in substantial damage to assets in or on the ground. Some urban areas of New Zealand have extensive areas of soils with very high liquefaction potential, notably Christchurch, Kaiapoi, Napier and Gisborne. However, little of the Wellington bulk supply system, 2.5%, is in ground that is very highly susceptible to liquefaction, with a further 10% being in ground that is highly susceptible (Table 3.3).

Strong shaking in earthquakes is a major cause of landslides in New Zealand. Factors that are important in determining the stability of sloping ground include the slope angle, the slope height, slope modification, the underlying geology, existing landslides, and groundwater content. Assets below and above areas of high landslide susceptibility also are at risk should landsliding occur, from burial and undermining respectively. As for liquefaction, little of the Wellington bulk supply system, 1.6%, is in ground that is very highly susceptible to landslide, with a further 10% being in ground that is highly susceptible (Table 3.3).

The impacts of liquefaction and landsliding were accommodated in the modelling of damage to the bulk supply system by applying multiplicative factors to the initial estimates of damage that were based on shaking intensity and pipe properties alone. This is discussed in Appendix 4).

Amplification of shaking can also occur at the crests of ridges and hills, the effect being somewhat analogous to the increase of height in water waves approaching the edge of a beach. This is called topographic enhancement. Increased damage to structures can occur as a result. It is not modelled (a) because little of the bulk supply system is in ridge-crest areas, and (b) we have neither suitable models nor data to support modelling.

Earthquakes are sometimes accompanied by tectonic movements, which are the subsidence or uplift of large blocks of land. Areas of hundreds to thousands of square kilometres can be affected, and changes in elevation of several metres have been observed. During the 1987 Edgecumbe earthquake, for example, there was 1 to 2 m subsidence of about 30% of the Rangitaiki Plains. The cost of countering the effects of the subsidence, i.e. increasing the heights of stopbanks, additional pumping, and re-grading drains, was approximately equal to the cost of repairing shaking damage to the flood protection structures.

Other New Zealand examples of earthquakes which have caused tectonic movements include the 1855 Wairarapa Earthquake in which the western half of Wellington Region was tilted upwards, by more than 5 m in the vicinity of the Rimutaka Range about 15 km east of Wellington, the 1931 Hawkes Bay Earthquake in which Napier and surrounding low ground were uplifted by about 1 m, and the 2010-2011 earthquake sequence in Canterbury which has resulted in subsidence in and around the Christchurch estuary.

Wellington and the Hutt Valley could be affected by tectonic movements caused by future large earthquakes in the Region. Compared with earthquake shaking, however, the tectonic movements are very gentle, and unless there is flooding following tectonic subsidence are unlikely to have significant impact on pipelines. The bulk supply system from Kaitoke is mostly well away from coastal locations and is unlikely to be affected by tectonic movements.

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APPENDIX 2: DAMAGE TO BULK WATER SYSTEMS IN HISTORICAL EARTHQUAKES

Appendix 2 contains brief summaries of reports on damage to bulk water supply systems in twelve large earthquakes. Its purpose is to provide guidance as to the fragility of the main components of such systems, in particular intakes, artesian wells, tunnels and pipelines.

A2.1 HAWKE'S BAY, NEW ZEALAND, 1931

References

Callaghan (1933), Conly (1980), McGregor (1989), Wright (2001), Dowrick (1998).

Earthquake Details

- Magnitude 7.8, epicentre 15 km NE of Napier, 15 km deep, fault upper edge 3 km deep.
- Shaking Intensity: MM10 in Napier and Hastings.

Damage to Bulk Water Facilities

- "Fortunately, there were in existence a number of artesian wells which were not destroyed by the earthquake, and from these the residents were furnished with supplies of water at specified points." [Napier] (Callaghan 1933, p26)
- "Those [in Napier] who had wells were fortunate, although those on the hill went dry" (McGregor 1989, p 32)
- "Water had to be fetched, usually from artesian wells in the town area, such as that at the Sunshine Brewery." (Conly 1980, p66)
- "Bell tents were erected for 2500 people …. and a pipeline run from the artesian well in the park to the kitchen [in Napier]." (Conly 1980, p89)
- "Artesian well water was freely available in Napier (as throughout the Heretaunga Plains), but because it had to be carried to distribution points, the Health Department decided that all water should be chlorinated." (Conly 1980, p91)
- "Borough engineer W.D. Corbett organised water for them in barrels filled from 400-gallon tanks on lorries, themselves topped up from broken but still serviceable wells in McLean Park [Napier]." (Wright 2001, p84).
- "The four wells supplying the system from the aquifer under Hastings were still available, but – again as in Napier – power failure rendered the pumps inoperative." (Wright 2001, p66).

Summary Comments

- The level of shaking was as strong as that expected in Wellington and Hutt Cities for a Wellington Fault earthquake.
- Bulk water supply, from artesian wells located in the zone of strongest shaking, appears not to have been a problem. The wells certainly continued to provide water, though some were damaged.
- The distribution network, however, was heavily damaged, so that there was insufficient water for fire fighting.

A2.2 MEXICO, 1985

References

Butcher et al. (1988), Munich Re (1986), O'Rourke & Deyoe (2004).

Earthquake Details

- Magnitude 8.1, epicentre c. 400 km SW of Mexico City, subduction thrust.
- Shaking Intensities: c. MM5 on weak rock around the City ("Hill Zone"), but greatly amplified by the soft lake sediments underlying the City ("Lake Zone"), possibly to MM9 in the worst areas.

Damage to Bulk Water Facilities in Mexico City

- About two thirds of the bulk supply was derived from wells, and the remainder was brought into the city through a concrete aqueduct system. Four branches of the aqueduct were severely damaged.
- Damage rates to large diameter pipes were lowest in the hill zone, and highest in the soft lake soils, Table A 2.1.

Table A 2.1 Repair rates to bulk supply pipelines on various soil types in Mexico City. The pipes were a mixture of asbestos cement, cast iron and concrete. Jointing methods were not specified.

Zone	Pipe Diameter (mm)	Pipeline Length (km)	Repair Rate (repairs/km)
Hill	508 and 1220	≥ 55	0.01
Transition	508 and 1220	≥ 200	0.17
Lake	508 and 1220	312	0.45

Summary Comments

- The level of shaking, MM5 to perhaps MM9, is less severe than the MM9 to MM10+ expected close to a rupturing Wellington Fault.
- The variation in repair rate is likely to arise from combined variations in shaking strength and ground type, from low MM Intensity with good soil (Hill Zone) to amplified shaking and poor soil (Lake Zone).

A2.3 EDGECUMBE, NEW ZEALAND, 1987

References

Butcher et al. (1998).

Earthquake Details

- Magnitude 6.5, epicentre in Rangitaiki Plain, normal faulting (Stirling et al., 2012).
- Shaking Intensities: c. MM9 in the centre of the Rangitaiki Plain, MM8 at Whakatane and edges of the Plain.

Damage to Bulk Water Supplies

- "The water intake, treatment plant, pumping stations, reservoirs and reticulation system in Whakatane all suffered some damage, most of it minor, but the supply to customers was not interrupted". (c. MM8).
- Supplies for the small towns of Edgecumbe, Te Teko, Kawerau and Matata were from springs. The supply to Matata was not affected, but the other supplies became contaminated with sand (c. MM9).
- Asbestos-cement mains pipes, all small diameter (< 400 mm), were heavily damaged.
- Some water bores (irrigation water for farms and orchards) were damaged, worst affected being those to high pressure sources at depths of more than 300 m. Steel casings to several were damaged by ground movements (MM8 – 9), allowing entry of sand and pumice that blocked filters, irrigation lines and sprinklers. Contamination by iron minerals was a problem for some shallower wells.
- Matahina Dam, a large earth hydro-power dam, was structurally damaged by the shaking (c. MM8.5) and was later reconstructed. It had some significant design flaws.

Summary Comments

- The level of shaking, MM8 to MM9, is less severe than the MM9 to MM10 expected close to a rupturing Wellington Fault.
- Ground in the Rangitaiki is deep and soft, and is classified as having moderate – high liquefaction hazard over most of its extent.
- The performance of water bores was mixed, with ground movement and contamination being issues. It was not clear whether the term "movement" referred to ground shaking or to permanent ground deformation.

A2.4 LOMA PRIETA EARTHQUAKE, SAN FRANCISCO, 1989

Reference

Benuska (Editor) (1990).

Earthquake Details

- Magnitude 6.9, epicentre c. 100 km SE of San Francisco, 18 km deep, fault upper edge 6 km deep.
- Shaking Intensities: MM8 in epicentral area, MM6 – MM7 over San Francisco with a few spot intensities of MM9 in the MM7 zone.

Damage to Bulk Water Facilities

Central Bay Area

- No damage to aqueducts or large storage reservoirs. Minimal damage to distribution mains (c. 350 leaks) mostly in soft ground in the Marina and South of Market Districts, and bay shore areas in Oakland, Berkeley and Alameda. Most were thought to be due to differential settlement, especially in areas of liquefaction. All were in the MM7 zone, but probably associated with the "spot" intensities of MM9. Two leaks in large pipes (508 & 760 mm diameter). One break in a prestressed concrete pipe at a treatment plant (1520 mm diameter) (MMI unknown).
- No reported damage to water treatment plants.

South Bay Area

- Pipelines (MM7 – MM8): One minor leak at a rubber gasket in a joint in a 1600 mm diameter prestressed concrete pipe. 120 leaks in distribution mains of 100 – 940 mm (steel, cast iron, asbestos cement, ductile iron).
- Rinconada Water Treatment Plant (MM8): One clarifier damaged – out of action for few (?) days until repaired. Plant capacity down to 50%.
- Montevina Water Treatment Plant (MM8?): Water sloshing damage to baffles, break in 760 mm pipe (1 day to repair).
- Penitencia and Santa Teresa Water Treatment Plants (MM7): No reported damage.

Monterey Bay Area

- 60 leaks in distribution mains (100 – 200 mm), plus many more in area of liquefaction.

Santa Cruz Area

- (MM7 – 8) Approx 240 leaks in distribution mains.

Throughout whole area

- Damage to some above-ground tanks, often rupture of associated pipe-work by differential movements.

Summary Comments

- The general level of shaking, MM6 to MM8 with localised instances of MM9 (rare), is much less severe than the MM9 to MM10 expected close to a rupturing Wellington Fault.
- Roads were largely undamaged (apart from some notable collapses of bridges and elevated freeway structures) so that access for repair appeared not to be a problem.
- The overall level of damage to buildings and infrastructure was relatively low, which meant that there was not a high level of competition for resources needed for repair.

A2.5 NORTHRIDGE EARTHQUAKE, LOS ANGELES, 1994

Reference

Hall (Editor) (1995).

Earthquake Details

- Magnitude 6.7, epicentre beneath Northridge, 19 km deep, Fault top about 7 km deep
- Shaking Intensity: MM8 and patches of MM9 in epicentral area, MM6 – MM7 over Los Angeles.

Damage to Bulk Water Facilities

Bulk Pipelines

Major failures of bulk pipelines were as follows:

- Balboa Inlet: one complete break in a steel pipe, with about 75mm of offset.
- Aqueduct #1: one circumferential crack, 1.5 m long, in a steel section, and 2 complete breaks in a concrete section.
- Aqueduct #2: damage to two couplings, some circumferential bulging (that did not leak), and one circumferential tear, in steel sections.
- Castaic Conduit: 35 leaks in Modified Prestressed Concrete Cylinder Pipe (MPCCP), breaks at some bends, and pulled-apart rubber gasket joints.
- North Branch Feeder: 15 – 20 major pulled joints, and c. 500 cracks requiring mortaring.
- Calleguas Conduit: Minor damage to corroded components.
- Balboa Boulevard: A 200 m wide strip of ground moved about 300 mm, rupturing 1200 and 1700 mm pipes at the zone of tension, and also causing tension and compression failures at welded bell & spigot joints. There were approximately 12 other failures in large-diameter pipelines.
- Repair times are given in Table A 2.2. Repair times per failure (d/flr) are our (GNS) estimates based on data from Hall.

Table A 2.2 Repair times for damage to large pipelines. MM intensities were based on small-scale maps and are not highly reliable.

Pipeline	Diameter (mm)	Material	Repair Time (days)	Permanent Repair
Balboa Inlet (MM9)	2160	Steel (21 mm)	2 (2 d/flr[(1)])	-
Aqueduct #1 (MM8)	3050	Steel (10 mm) and Concrete	58 (19 d/flr)	c. 6 months
Aqueduct #2 (MM9)	1960	Steel	12 (4 d/flr)	c. 6 months
Castaic Conduit (MM7)	840 -1370	MPCCP	67 (< 2 d/flr)	-
North Branch Feeder (MM7)	1980	Prestres. conc.	46 (< 1 d/flr?)	-
Calleguas Conduit (MM7)	1300	Prestres. conc.	-	c. 6 months
Balboa Blvd. (MM8-9)	1200	Steel	12 (< 6 d/flr)	-
Balboa Blvd. (MM8-9)	1700	Steel	56 (< 28 d/flr)	-

Note 1: d/flr is days per failure

Water Treatment Plants

- Minor damage only (ground settlement, leaks in expansion joints, sloshing damage to gratings & baffles, overturned filing cabinets & bookcases, fallen ceiling tiles. Castaic - MM7, Jensen – MM9, Los Angeles – MM9.

Pumping Stations

- No reported damage, but many were non-functional because of power loss.

Groundwater Wells

- No reported damage.

Storage Tanks

- Mostly steel, riveted, welded and bolted construction types, MM7 – MM8. Twenty-one failed or were non-functional for a variety of reasons. Nearly all were pre-1970.

Summary Comments

- The general level of shaking, MM6 to MM9, was less severe than the MM9 to MM10 expected close to a rupturing Wellington Fault.
- Repair times for large diameter steel pipes ranged from 2 to < 28 days per failure, but note that (a) roads were largely undamaged (apart from collapse of five major bridges and severe damage to a few others) so that access for repair appears not to have been a problem, and (b) the overall level of damage to buildings and infrastructure was relatively low, which meant that there was not a high level of competition for resources needed for repair.

A2.6 KOBE EARTHQUAKE, JAPAN, 1995

References

- ALA (2001), Park et al. (1995), WELG (1995).

Earthquake Details

- Magnitude 7.2, epicentre c. 15 km SW of central Kobe, the fault rupture passed beneath Kobe City but did not quite reach the surface.
- Shaking Intensities: MM8 – MM10 over Kobe City.

Damage to Bulk Water Facilities

General and treatment plants

- About 75% of potable water for Kobe and the adjacent cities of Ashiya, Nishinomiya, Itama and Amagasaki was supplied from the Yoda River (about 25 km NE of central Kobe) via two main pipelines. Both were severed close to the source during the earthquake, leaving more than 1.5 million households without water. Twenty-three failures were found in one of the main pipelines (1.25 m diameter, apparently concrete pipe), while a pump station and treatment plant failed on the other line. Damage to the treatment plant occurred in the slow sand filter, the rapid sedimentation basin, the wash water tank, and the wastewater facility. The edge of another large treatment plant was partly undermined by a large landslide, but it is not known to what extent function was lost at this plant. There was minor damage to one other purification plant, but apparently none to the remaining four plants.

Pipelines

- Most of the bulk pipelines were in variable alluvial soils broadly similar to those found in Upper Hutt and Lower Hutt. Very little length was in the zone of liquefaction (Park et al., 1995). Also, most of it was outside of the zone of heaviest damage, and so the predominant shaking intensity was probably about MM9.
- Estimated failure rates showed some variation, with one early report (WELG, 1995) indicating a surprisingly high level of damage to large diameter pipes (Table A 2.3).

Table A 2.3 Large pipeline failures – Kobe earthquake (WELG 1995, p1.11).

Diameter (mm)	Length (km)	No. of failures	No. per km	Location of Failure		
				Pipe	Joint	Fitting
500	89	28	0.32	3	8	17
600	45	16	0.35	1	3	12
700	47	29	0.62	1	6	22
800	10	9	0.88	1	7	1
900	26	26	0.99	3	11	12
1000	0.5	1	2.0	0	0	1
Overall	217.5	109	0.5	9	35	65

- Later reports indicated somewhat lower repair rates, for pipelines not affected by liquefaction. Overall repair rates given for large diameter (≥ 500 mm) cast-iron and ductile-iron types were 0.3 and 0.06 repairs/km respectively (ALA 2001, p44). Repair rates for a wider range of pipe types, but with sizes unspecified, are given in Table A 2.4 (ALA 2001, p38). This suggests that repair rates for welded steel pipelines are somewhat lower than those of ductile iron pipelines with push-on joints.

Table A 2.4 Pipeline failure rates – Kobe earthquake.

Pipe Material	Length (km)	Repairs/km	Repair Rate Ratio
Ductile Iron (push-on joint)	3,180	0.25	1.7
Ductile iron (special joint)	237	0?	-
Steel (welded, high-pressure)	103	0.15	1
Cast Iron (mechanical joints)	309	1.3	9
PVC (push-on joint)	126	0.2	1.3

Wells

- Water supply to the city of Akashi was from an aquifer via 60 wells drilled to 180 m. Although Akashi was very close to the epicentre there were no problems with any of the wells, or with the four associated purification plants.
- Kobe City had one well under the Municipal building. It continued to supply satisfactorily after the earthquake even though it was in the zone of greatest damage.

Summary Comments

- The level of shaking was as strong as that expected in Wellington and Hutt Cities for a Wellington Fault earthquake, but a higher proportion of the Wellington bulk mains are likely to be in the MM10 intensity zone than was the case in Kobe.
- Bulk water supply, from artesian wells located in the zone of strongest shaking, appears not to have been a problem. The wells certainly continued to provide water.

A2.7 KOCAELI EARTHQUAKE, TURKEY, 17 AUGUST 1999

References

Durukal (2002), Eidinger et al. (2002), RMS (2000a), Scawthorn (1999), Sharpe et al. (2000), Youd et al. (2000).

Earthquake Details

- Magnitude 7.4, epicentre 7 km W of Kocaeli, surface fault rupture.
- Shaking Intensity: MM9-10 near fault.

Damage to Bulk Water Facilities

- Three major water supply systems, supplying 2.5 million people, were located within the zone of strong shaking. Main points about the damage to the bulk systems follow.

Izmit Water Project

- Construction date: 1990s.
- Reservoir: 6 km from fault, c. MM9, 60 million m^3, earth dam, no significant damage.
- Treatment Plant: 3 km from fault, c. MM10, light damage, minor damage to some plant and equipment.
- Main Pipeline: 2.2 m diameter spiral-welded steel, crossed fault, c. 2 m offset, pipe did not break (*"This location was inspected and found to have approximately a 2 m right lateral offset but, while some water flowing to the surface was observed (it was raining at the time, however), the pipe was reportedly undamaged at this location"*. Scawthorn, 1999). The soil at the site was Holocene alluvium (Eidinger et al., 2002)
- Other Bulk Pipelines: Butt-welded steel, some damage, especially where they crossed the fault zone or areas of severe ground movement, some minor seepage at flange fittings.

Yalova-Goluck System

- Construction date: "modern".
- Reservoir: c. 12 km from fault, c. MM9, earth dam, no significant damage.
- Treatment Plant: c. 12 km from fault, c. MM9, minor damage.
- Main Pipeline: 80 km long welded steel, parallel to fault at c. 10 km distance (MM9 – 10), *"The line was damaged in a number of locations leaving about 1 million people without water for seven days. During reconstruction, new damage occurred during aftershocks, requiring another two weeks for full restoration of water service."*

Adapazari

- Construction date: mostly “modern”, treatment plant 1997.
- Reservoir: Natural lake.
- Treatment Plant: c. 5 km from fault, MM9-10, minor damage.
- Pipelines (3) lake to chlorination plant: 2-5 km from fault, 1 of 700 mm diameter, 2 of 1200 mm; only one 1200 mm pipe remained operational. Fault rupture might have been an issue, close to intake structures in the lake.
- Pipelines (2) chlorination plant to filtration plant: c. 5 km from fault, 1 of 700 mm diameter asbestos cement, 1 of 1200 mm welded steel. There were breaks in both lines, and repairs took 5 days.

Summary Comments

- The general level of shaking, MM9 to MM10, is similar to that expected close to a rupturing Wellington Fault.
- Damage to dams, treatment plants, pump stations and steel bulk pipelines appears to have been light, apart from one location where fault rupture might have been involved. Most were of modern construction.
- Loss of power, and lack of backup generators, caused significant problems at treatment plants and pumping stations.
- Distribution pipelines were heavily damaged, especially in areas of soft ground. In Adapazari, where there was a combination of liquefiable ground and brittle asbestos cement pipes, virtually the whole distribution system was expected to need replacement.

A2.8 DUZCE-BOLU EARTHQUAKE, TURKEY, 12 NOVEMBER 1999

Reference

Aydan et al. (2000).

Earthquake Details

- Magnitude 7.2, epicentre 4 km S of Duzce, surface fault rupture.
- Shaking Intensity: MM9-10 near fault.

Damage to Bulk Water Facilities

- No damage to the wells, pipes and pumps of the bulk water system was reported. The main water pipes had a diameter of 1000 mm and were made of ductile iron. No damage information was provided.

Summary Comment

- Damage appears to have been light, but shaking intensities at the bulk water facilities were not reported.

A2.9 CHI-CHI EARTHQUAKE, TAIWAN, 1999

References

Brunsdon et al. (2000), RMS (2000b), Shih and Chang (2006), Tsai et al. (2000), Uruzaki and Arnold (2001).

Earthquake Details

- Magnitude 7.6, surface fault rupture (83 km long), c. 1 m horizontal and vertical movements over southern two thirds of the fault, increasing to c. 10 and 8 m at the northern end (Brunsdon et al., 2000).
- Shaking intensities were not reported, but, based on recorded ground accelerations, will have been MM9 to MM10 close to the fault rupture.

Damage to Bulk Water Facilities

- The Shih-kang (Shigun) Dam, which supplied about 50% of the water needs for 5 million people, and crossed the fault, was rendered virtually inoperable by an 8 m vertical offset in the dam close to one end (it was near the northern end of the fault). This terminated the water supply for the supplied area for at least 2 days. The dam was essentially a series of about 20 floodgates, of which only the few in the immediate vicinity of the fault offset were severely damaged, with the remainder experiencing zero to light damage.
- A treatment plant that was bisected by the fault was heavily damaged (it was near the northern end of the fault). Four of its steel pipelines, with diameters ranging from 400 to 2000 mm, were ruptured by the fault (Brunsdon et al., 2000). At least 4 other pipelines of 500 to 2000 mm diameter were broken.
- There were 22 treatment plants within 25 km of the surface rupture. Eight suffered slight to light damage, 5 moderate damage, 8 great damage, and 1 unknown. There was strong directionality in the effects, with plants towards the south (epicentre) end of the fault suffering light-moderate damage, and plants to the north end suffering mostly great damage (Shih and Chang, 2006). Exactly what constituted “great” damage was not specified. Pipelines were included in the “great” damage category.
- Thirty-three treatment plants were totally shut down by the earthquake. Restoration times were not reported. (Tsai et al., 2000).
- Several wells and intake structures were heavily damaged. Actual numbers and proportions were not given.
- In the city of Taichung, there was a strong inverse relationship between the pipe diameter and the number of “damage instances” per km of pipe, Figure A 2.1, (Tsai et al., 2000).

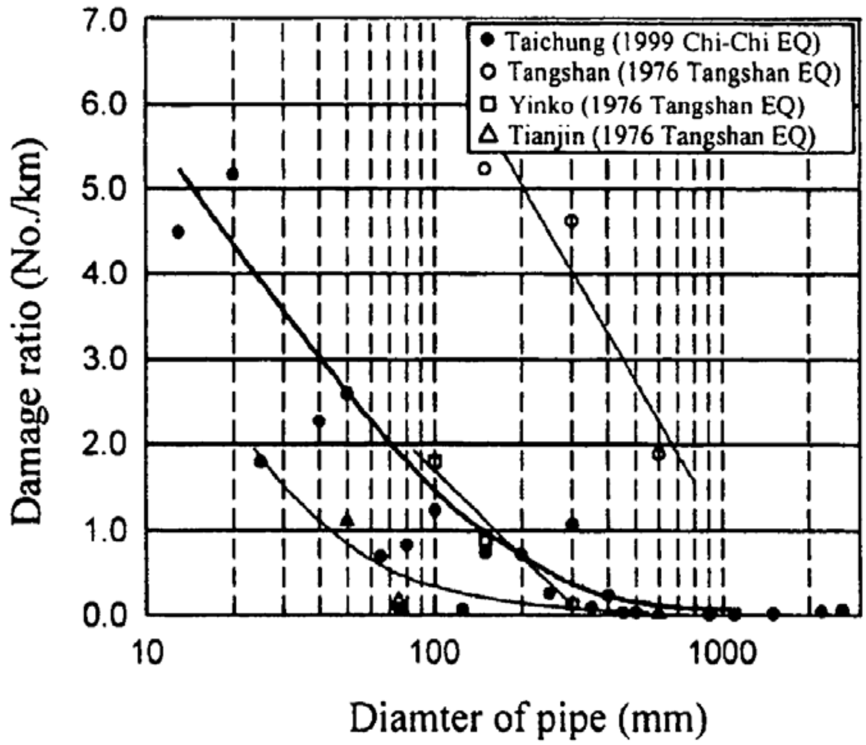

Figure A 2.1 Relationship between damage ratios and pipe diameters (from Tsai et al., 2000). Taichung was about 5 km from the fault rupture (Brunsdon et al., 2000) and so is likely to have experienced shaking intensities greater than MM9.

Summary Comments

- The general level of shaking near the fault that ruptured was similar to that expected close to a rupturing Wellington Fault.
- Damage to wells, dams and treatment plants varied from “slight” to “great”, but details were largely absent from the reports seen.
- Large diameter pipelines (> 500 mm) in Taichung appear to have experienced failure rates well below 0.1 / km (MM >9).

A2.10 BHUJ EARTHQUAKE, INDIA, 2001

Reference

Jain et al. (2002).

Earthquake Details

- Magnitude 7.7, epicentre 18 km deep, no surface fault rupture.
- Shaking Intensity: MM9 – MM10 in epicentral area (the MM10 zone covered nearly 2000 km^2).

Damage to Bulk Water Facilities

- Most of the water supply was groundwater from wells. Well casings were 250 mm diameter steel with 5 mm thick walls, and were typically 150 – 180 m deep. Approximately 106 out of 406 wells were not usable after the earthquake (intensity MM9). The main reasons for failure were bent well casings and lowered water quality.
- One supply from a dam passed through 26 km of 600 mm diameter pipe, made of cast iron, reinforced concrete and asbestos cement. After the earthquake, about 40% of the flow was being lost due to leakage, which seemed mostly to be at river/stream crossings.
- In Bhuj, six of 16 well casings collapsed. Ten of the 16 were not working because of electrical failure, building structural damage, and damage to pump-room piping.
- Bulk pipelines to the most distant villages were 250-300 km long.
- Some bulk systems in the area used welded-steel pipes in diameters greater than 400 mm, and ductile iron in diameters of 250 – 400 mm, but no damage information was given.

Summary Comments

- The area of strong (MM10) shaking was much greater than that expected from a Wellington Fault Earthquake.
- The performance of the wells may be relevant to the Hutt Artesian supply, which is likely to experience MM9 or greater shaking during the earthquake.

A2.11 PISCO EARTHQUAKE, PERU, 2007

Reference

Hopkins et al. (2008).

Earthquake Details

- Magnitude 8.0, subduction thrust, epicentre 40 km deep, no surface fault rupture.
- Maximum intensity: MM7 in epicentral area, including the towns of Pisco and Ica.

Damage to Bulk Water Facilities

- Pisco: "The almost zero rainfall on these coastal areas means that water supply must come from reservoirs well inland, and the main supply pipelines were functioning."
- Ica: "There was very little damage to the water supply network."

Summary Comment

- The shaking intensity was much lower than that expected from a Wellington Fault Earthquake.

A2.12 CANTERBURY EARTHQUAKE SEQUENCE, NEW ZEALAND, 2010-2011

References

O'Rourke et al. (2012), Gledhill et al. (2010), Kaiser et al. (2012), Eidinger et al. (2010), Christison (2013).

Earthquake Details

- Date, 4th September 2010
- M_W 7.1, reverse and strike-slip, depth 11 km, c. 30 km of surface fault rupture.
- Closest part of the rupture, 22 km from central Christchurch.
- Maximum intensity: about MM7 – MM8 in central Christchurch.

- Date, 22nd February 2011
- M_W 6.2, oblique-reverse, depth c. 10 km, no surface fault rupture.
- Closest part of the rupture, 3 km from central Christchurch.
- Maximum intensity: about MM8 – MM9 in central Christchurch.

- Date, 13th June 2011
- M_W 6.0, oblique-reverse, shallow depth, no surface fault rupture.
- Epicentral distance, 6 km from central Christchurch.
- Maximum intensity: about MM8 in central Christchurch.

Damage to Bulk Water Facilities

- The shaking intensity and duration in central Christchurch were generally lower than those expected from a Wellington Fault Earthquake, although very high peak accelerations (c. 2g) were recorded in a few locations.
- The potable water supply for Christchurch was drawn from an aquifer beneath the city through approximately 170 wells. The main supply system consisted of 1710 km of pipes of mostly small diameter, 100 to 200 mm, of which 75% were asbestos cement and 11% were of cast iron.
- Many of the wells were damaged during the earthquakes, but most continued to function.
- Damage to buried pipelines was largely due to severe and widespread liquefaction.
- O'Rourke et al. (2012) developed fragility functions for brittle water-supply pipes, using repair statistics gathered during repairs carried out after the main events in the Canterbury sequence, namely the three earthquakes listed above. For two brittle pipe types there were sufficient data to support robust models for repair rate as a function of peak ground velocity (geometric mean of horizontal components), for pipes in ground not affected by liquefaction (Figure A 4.2). In deriving Figure A 4.2 the O'Rourke et al. velocities were converted to MMIs using the model of Atkinson and Kaka (2007). The

Christchurch data were consistent with similar data from United States earthquakes. There were been insufficient data to support similar models for ductile pipe types.

- The highest damage rates for pipes in ground that liquefied were about 9 repairs/km for asbestos cement pipes, 6 repairs/km for cast iron, and 4 repairs per km for PVC.

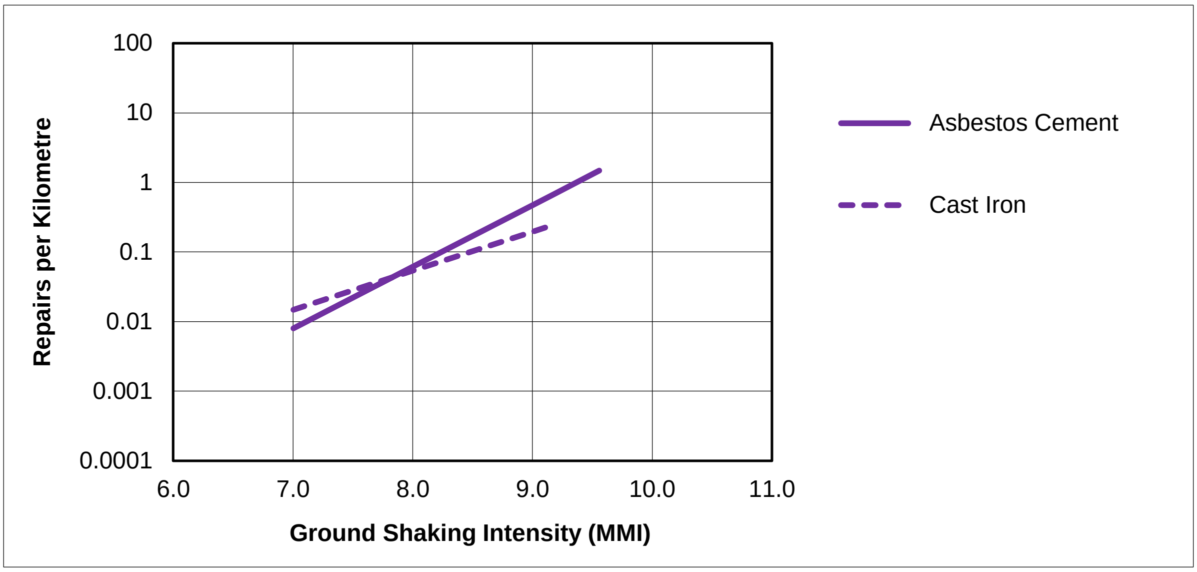

Figure A 2.2 Observed fragility functions for brittle water supply pipes in Christchurch, in ground not affected by liquefaction.

APPENDIX 3: MODELLING AND ANALYSIS – MAJOR REPORTS

Appendix 3 contains brief summaries of (a) two major reports on modelling earthquake damage to water supply networks, and (b) one detailed modelling study of damage during a single earthquake. Its purpose is to extract data and models that might be used in modelling the damage to and restoration of bulk water supply systems in Wellington.

A3.1 ATC-13 AND WELLINGTON EARTHQUAKE LIFELINES GROUP

In 1985, the United States Federal Emergency Management Agency commissioned the Applied Technology Council (ATC) to develop earthquake damage models for many kinds of building and infrastructure assets found in California. The report, ATC-13 (Rojahn and Sharpe, 1985), was based on an extensive literature survey and expert opinions as to the likely damage to a wide range of assets exposed to earthquake shaking.

Underground pipe networks were one of the asset types considered. Points labelled "ATC-13 Rock" in Figure A 3.1 are the ATC-13 recommendations for pipelines in ground that was not susceptible to either liquefaction or landsliding. For ground that liquefied, they made the assertion that damage levels would be ten times as great as for normal ground, and developed a damage estimation procedure based on (a) the liquefaction susceptibility, and (b) the probability of failure, for various classes of ground. A similar procedure was described for landslide failure.

In 1993, the Wellington Earthquakes Lifelines Group (WELG) applied the methodologies to a case study of water distribution pipelines in Miramar, Wellington (WELG, 1993). Points labelled "ATC-13/WELG Soft Ground" in Figure A 3.1 are the fragilities developed by WELG, using the ATC-13 methodology, for pipelines in soft ground that is highly susceptible to liquefaction.

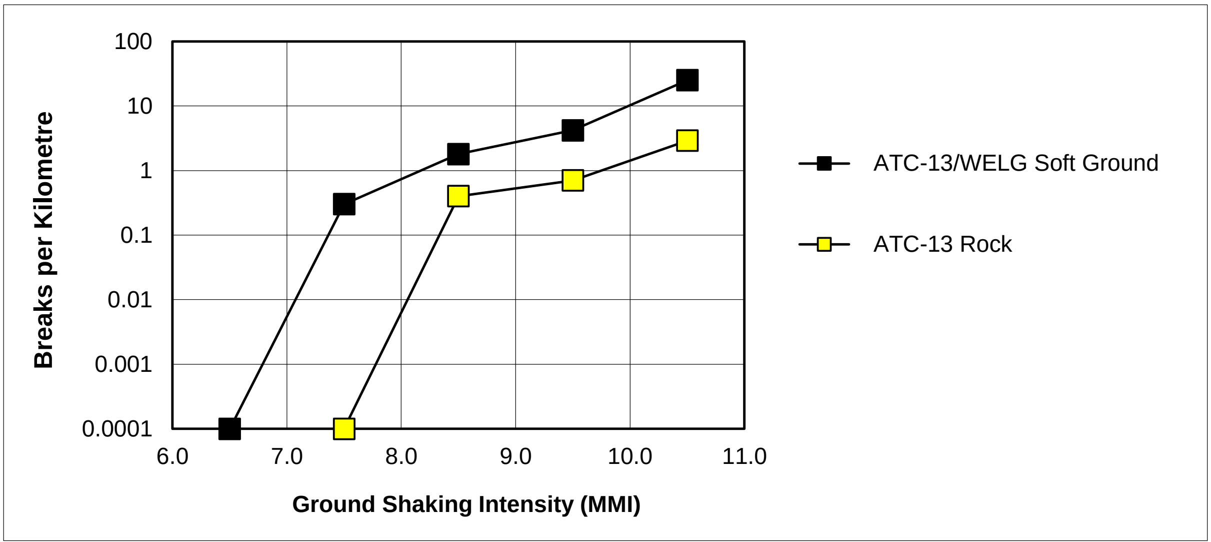

Figure A 3.1 Expert's assessments of earthquake damage to small diameter pipelines, of average quality, in ground that has (a) high (Soft Ground) and (b) zero susceptibility (Rock) to liquefaction. Note that the two points plotted at 0.0001 represent zero breaks / km.

A3.2 American Lifelines Alliance, Report and Guidelines

The American Lifelines Alliance is a public-private partnership between the Federal Emergency Management Agency (FEMA) and the National Institute of Building Sciences (NIBS) (preceded by the American Society of Civil Engineers, ASCE). In 2001, it funded a project that reviewed (a) the damage to water distribution systems in historical earthquakes and (b) attempted to model various kinds of damage as functions of the strength of shaking (ALA 2001). In 2005, the review work was followed by development of design guidelines for water pipelines (ALA 2005).

Most damage reports dealt with distribution systems and so mainly involved small diameter pipes (< 300 mm), but there was some information for large diameter bulk supply pipes (> 300 mm). Several of the reports are covered in the historical reviews above.

Care was taken by the ALA to separate damage due to ground shaking from damage due to ground failure. Figure A 3.2 shows the basic dataset for ground shaking. Most of the data originated from four earthquakes, viz. San Fernando (USA) 1971, Loma Prieta (USA) 1989, Northridge (USA) 1994, and Kobe (Japan) 1995, and most of the data were from distribution systems, with cast-iron pipes dominating. Ductile pipe types were ductile iron and steel. Brittle pipe types were cast iron, asbestos cement and concrete.

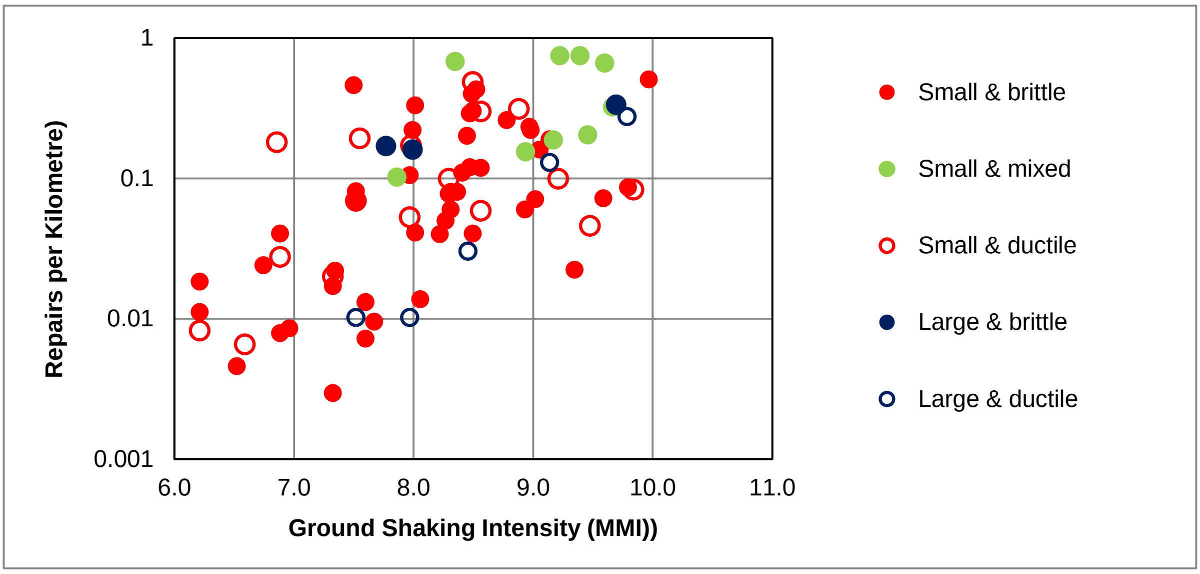

Figure A 3.2 Data from historical earthquakes on damage to water supply pipelines (ALA 2001). MMI values as used in the figure were derived from PGV values in the ALA dataset using the model of Atkinson and Kaka (2007).

Several pipe damage models were discussed in ALA (2001), with the one most easily adaptable to the current work being plotted in Figure A 3.3. The use of straight lines was a pragmatic decision based (a) on the high degree of scatter in the data, and (b) lack of metadata for many of the data points. Also largely pragmatic was the decision (by the authors of ALA 2001) that the fragility of large diameter pipes should be 25% of that for small diameter pipes, because there was not a great deal of data available for calibration, and while there was clear evidence that large diameter pipes suffered less damage than small diameter ones, there were exceptions. Note also that there were no data at all in the very important shaking zone from MM10 to MM11.

ALA (2001) also developed repair rate models for ground failure situations. Because the models were based on permanent ground displacements they were not easily translated to an MM scale, and so the x-axis positioning of the two "Ground Failure" points plotted in Figure A 3.3 is largely arbitrary. Nevertheless, it is clear that the rates of pipe failure due to ground failure are one to two orders of magnitude higher than the rates for ground shaking alone.

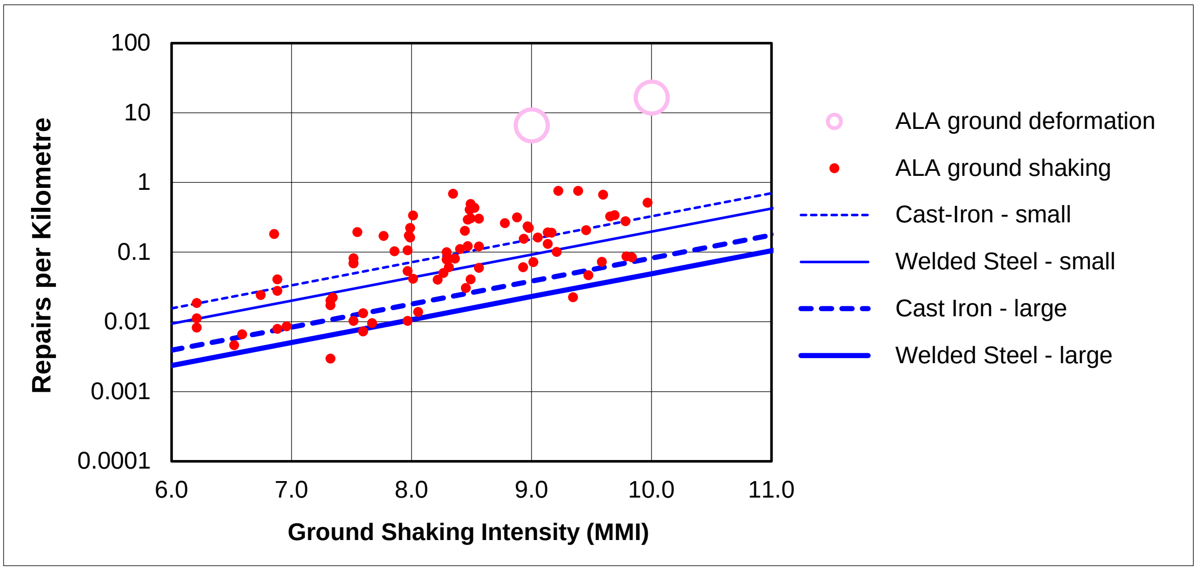

Figure A 3.3 Data (symbols) and models (lines) for damage to water supply pipelines (ALA 2001). MMI values as used in the figure were derived from PGV values in the ALA dataset using the model of Atkinson and Kaka (2007).

A3.3 NORTHRIDGE EARTHQUAKE – DETAILED MODELLING

Pipeline damage caused by the Northridge Earthquake has been exhaustively modelled in a series of PhD theses and related work at Cornell University. For example, Wang (2006) provided analyses of damage to trunk lines (diameter ≥ 600 mm), and distribution lines, and went on to develop relationships between peak ground velocity (PGV) and repair rate. Shi (2006) modelled the various modes of failure and applied a network damage model to the Northridge water supply system. Jeon & O'Rourke (2005) compared damage to pipelines and housing.

Some basic information drawn from the studies is as follows

- Damage to bulk supply system: 82 failures in 1044 km of pipeline.
- Diameter range of pipes: 760 to 2440 mm.
- One-third of failures were due to ground shaking, the remainder due to permanent ground deformation (e.g. landsliding).
- Welded joint (steel) pipeline: 12 failures due to shaking, 4 due to permanent ground deformation, in 469 km.
- Repairs involved adding welded butt straps (5), repair of gasket (1), re-welding fracture (1), and unknown (5).
- Failures in other steel line types were all due to permanent ground deformation, as follows, welded bell & spigot (15 failures), welded butt strap (6) and mechanical coupling (19).

- Failure rate vs PGV relations were developed for welded joint steel, riveted steel and concrete types, for ground shaking.
- The Wang (2006) data and model are plotted in Figure A 3.3, after converting PGV to MMI using the relationship of Atkinson and Kaka (2007). The Wang straight-line model is quite different to the ALA2001 model, and extrapolates to much lower failure rates at low MMIs.

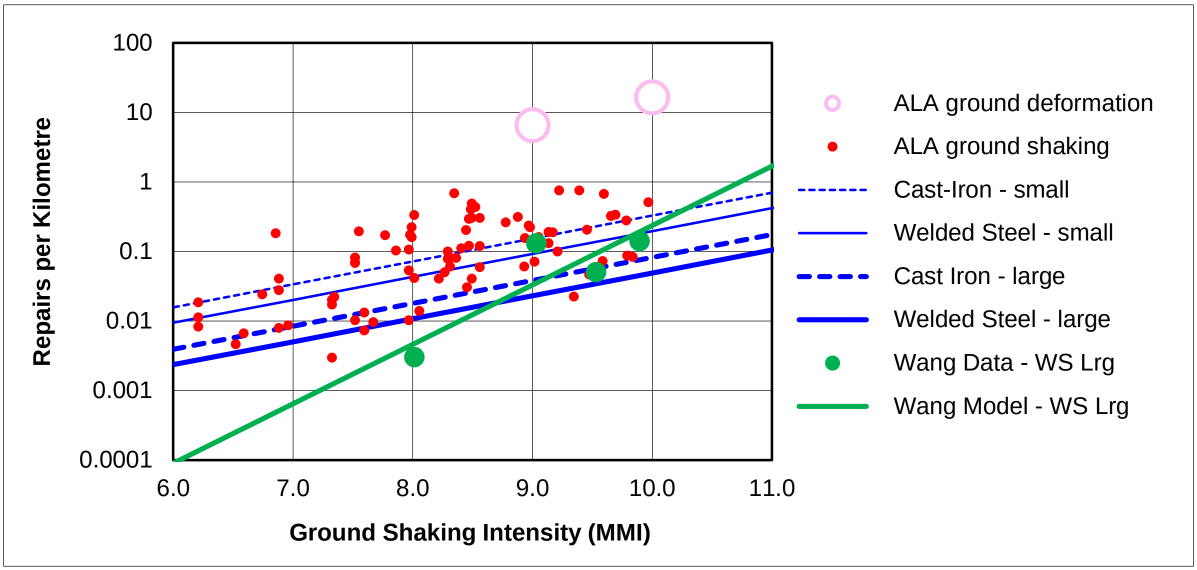

Figure A 3.4 Data and models as for Figure A 3.2, with addition of Wang (2006) data and model for damage to large-diameter welded-steel pipelines, due to ground shaking (green symbols and lines). “WS Lrg” is welded steel, large diameter.

APPENDIX 4: DAMAGE AND RESTORATION MODELLING FOR WELLINGTON

Appendix 4 uses the information presented in Appendices 2 and 3 to develop models for earthquake damage to Wellington's bulk supply system, and of the restoration of basic functionality. The main outputs are tables of the times needed to restore emergency-level supply of potable water to reservoirs and other emergency supply points in Wellington.

A4.1 PERFORMANCE OF INTAKES AND OTHER STRUCTURES

Well-designed concrete and earth dams appear to survive strong shaking well. The only reported major failure of a concrete dam was in one that straddled a fault rupture with 8 m of horizontal offset (see above, Chi-Chi Earthquake, Taiwan, 1999). The dam was essentially a series of about 20 floodgates, of which only the few in the immediate vicinity of the fault offset were severely damaged, with the remainder experiencing zero to light damage.

No specific information was found for weirs, but given (a) their low heights and similarity to concrete gravity dams, and (b) the fact that the ones in the Wellington bulk supply are founded in strong rock, they can be expected to perform very well in strong shaking.

Artesian wells appear to be moderately to highly resistant to strong shaking. In two cases involving shaking as strong as that expected from a Wellington Fault earthquake, i.e. Napier in the 1931 Hawke's Bay Earthquake, and Akashi and Kobe in the 1995 Kobe Earthquake, wells continued to function. In one other case, the 2001 Bhuj Earthquake, three quarters of approximately 400 wells continued to provide water. At lower intensities of shaking, MM8 to MM9, damage to wells appears to be minimal. Experience with bores was mixed in the 1987 Edgecumbe Earthquake. During the Canterbury earthquake sequence of 2010-2011, many of the 170 wells were damaged during the earthquakes, but most continued to function.

Modern, and presumably well-designed, treatment plants and pumping stations appear resistant to strong shaking. An exception appears to have been from the 1999 ChiChi (Taiwan) earthquake where 8 of 22 treatment plants near the fault rupture suffered "great" damage.

A4.2 PERFORMANCE OF LARGE DIAMETER PIPELINES

Early data and modelling based on it are well summarised in ALA (2001) and used in design methodologies recommended in ALA (2005) (Appendix 4). Preliminary data from the Canterbury earthquake sequence appear consistent with the earlier data.

Large diameter bulk-supply pipelines appear to be more robust than small diameter (<400 mm) distribution systems. Reasons suggested for this were that, compared with small diameter pipelines, large diameter pipelines:

- Tend to have better quality joints (e.g. it is easier to weld large diameter pipes).
- Have fewer connections (branches, customer feeds etc).
- Have fewer appurtenances (hydrants, valves etc).
- Tend to be laid in better ground.
- Are made from better materials (steel rather than cast-iron and asbestos cement).
- Simply by being large require higher standards of design, construction, and quality assurance.

Some general observations (ALA 2001) were that:

- Continuous welded steel pipelines built in accordance with modern codes of practice have generally performed better than other pipelines in past earthquakes.
- Jointed pipelines with flexible rubber gaskets tend to perform better than those with rigid (e.g. cement or lead-type) joints.
- Pipeline damage tends to concentrate at discontinuities such as pipe elbows, tees, in-line valves, reaction blocks and service connections.
- Age and corrosion will accentuate damage, especially in segmented steel, threaded steel and cast-iron pipes, with age effects possibly being strongly correlated with corrosion.
- Permanent ground deformations associated with landsliding, liquefaction and faulting result in greatly increased repair rates.

For shaking damage, ALA (2001) recommended the following expression for estimating the repair rate in large diameter (≥ 400 mm) pipelines as a function of earthquake ground shaking:

$$RR_{GS} = K \times 0.00036 \times PGV$$ **Equation A 4.1**

where RR_{GS} is the repair rate in repairs per km and PGV is the peak ground velocity (geometric mean of two horizontal components) in cm/s. K is a factor that allows use of the function for materials other than welded steel, as per Table A 4.1. A factor-of-4 multiplier was suggested for pipes with diameters less than 400 mm.

Table A 4.1 Material factors for use with Equation A 4.1.

Pipe Material	K
Steel (lap, arc-welded)	1
Ductile Iron (flexible joints)	0.8
PVC (flexible joints)	0.8
Cast-Iron (rigid joints)	1.7

Equation A 4.1 was intended for pipelines with unknown corrosion status. Where the ground was known to be non-corrosive a factor of 0.5 was suggested, and for corrosive conditions a factor of 1.5. Both were based largely on engineering judgement.

Since the Wellington hazard modelling is based on MMI, MMI was converted to PGV using the inverse of the Atkinson and Kaka (2007) model, as follows:

$$PGV = 10^{((MMI - 3.54) / 3.03)}$$ **Equation A 4.2**

The final formula therefore became

$$RR_{GS} = K \times 0.00036 \times 10^{((MMI - 3.54) / 3.03)}$$ **Equation A 4.3**

A4.3 PERMANENT GROUND DEFORMATION

In principal, a state-of-the-art approach would have been to model damage due to liquefaction and landsliding as a function of the resultant permanent ground displacement. Such an approach was presented in ALA (2001). For the whole-of-network modelling required for the Wellington application, however, there were two significant problems with that method. Firstly, the quality of the available ground information was insufficient to support the highly detailed requirements of the modelling, and (b) the computational requirements would have well beyond the time and funding available for the project. The decision was therefore made to use a method that relied on simple ground classifications and judgement factors (see ALA (2001) for examples). For the current project the ground was classified as Low, Moderate, High and Extreme risk for pipeline damage due to (a) liquefaction and (b) landsliding, using data from GNS's geological databases and the results of an aerial inspection of the pipeline routes. Then a simple factorial method was applied to allow for the enhanced damage due to any ground failure that might occur during strong shaking. The pipe repair rate estimated from the shaking intensity was multiplied by a factor that depended on the ground classifications. This approach also had the advantage of being consistent with the factorial method of allowing for variations in pipe material and pipe size.

A4.4 FACTORS FOR PIPE MATERIAL, PIPE SIZE AND GROUND DEFORMATION

The base case for estimating repair rates was large-diameter, modern welded-steel pipeline, with either welded or coupled joints, buried in ground that had negligible potential for liquefaction or landslide failure. With this in mind, the expression for estimating the repair rate for any other case became

$$RR = K1 \times K2 \times K3 \times K4 \times K5 \times RR_{GS} \quad \textbf{Equation A 4.4}$$

where RR_{GS} is the base repair rate (for ground shaking alone), and K1 to K5 are factors that allow for pipe material, coupling type and age, pipe size, landslide hazard, and liquefaction hazard. They were assumed to be 1.0, unless specified otherwise in Table A 4.2. The factors were based on judgement that was guided by the results and models summarised in Appendices 2 and 3.

For example, (a) the factors for a welded steel pipeline, installed in 2000, of 1050 mm diameter, in good ground would be 1 x 1 x 1 x 1 x 1 = 1, whereas (b) the combined factors for a steel pipeline with couplings, installed in 1953, of 250 mm diameter, on ground of high landslide hazard, negligible liquefaction hazard, would be 1 x 2 x 4 x 9 x 1 = 72.

Table A 4.2 Relative fragility factors. Note that the factors are one unless specified otherwise here.

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

A4.5 Comparison of Model with Data

Figure A 4.1 compares examples of the resultant repair rates based on Equation A 4.3 and Equation A 4.4 with the data and estimates summarised in Figure A 2.1, Figure A 3.1 and Figure A 3.3.

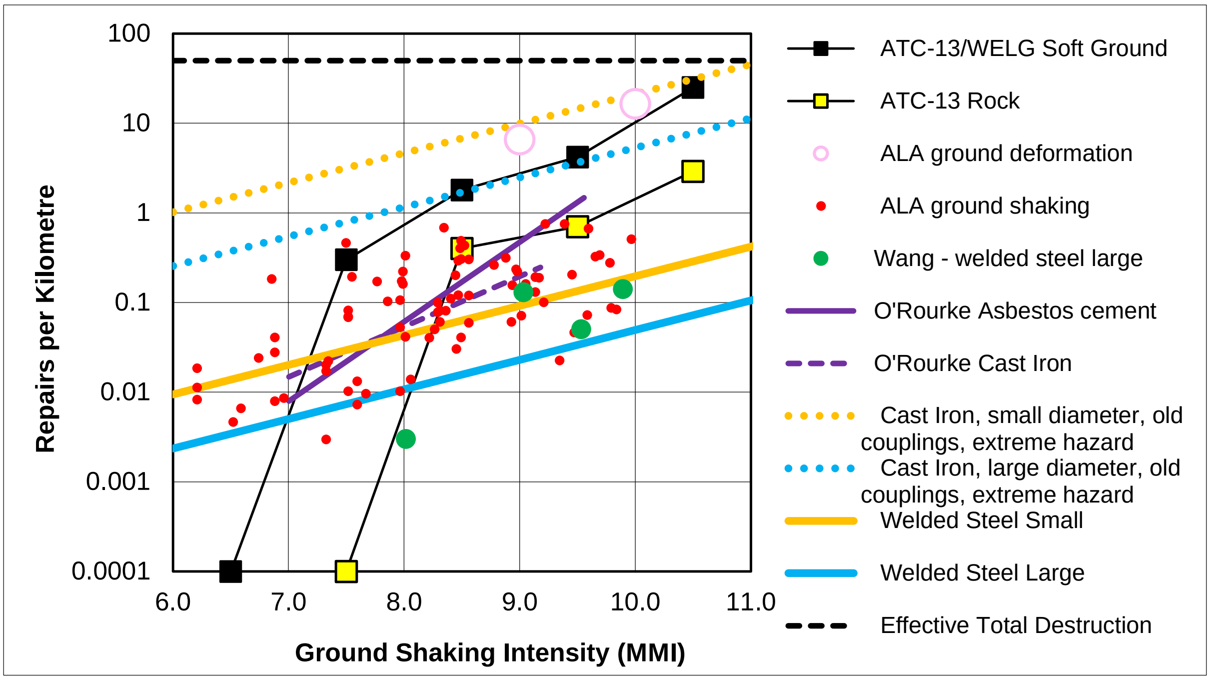

Figure A 4.1 Repair Rates, comparison of a simple ALA2001-based model with data from historical earthquakes.

The heavy blue line is the base case, i.e. modern welded steel pipeline, of large diameter, in good ground. The dotted blue line is the worst-case for large diameter pipeline, which is derived from the base case by allowing for old couplings (factor of 2 increase), change of material to Cast-Iron (another factor of 2), and extreme hazard (another factor of 27, giving an overall factor of 108). The orange lines are a similar sequence for small diameter pipelines, all a factor of 4 higher than the large diameter cases.

Although in theory it is possible to achieve very high repair rates of 100/km or more, there is a practical upper limit beyond which it is likely to be quicker and cheaper to replace a pipe than to repair it. As a matter of engineering judgement this upper limit has been set at 50 repairs/km, i.e. one repair for each 20 m of pipeline (WELG, 1993). The black dashed line plotted in Figure A 4.1 shows that effective upper limit.

The model lines span the range of data in a plausible fashion, with the least fragile case, the base case, lying towards the bottom of the data "cloud", and the most fragile case above the top of the data. However, the overall fit is not good at the highest and lowest intensities, with the model (the lines) appearing to be perhaps too low for intensities above MM9, and definitely too high for intensities below MM8.

A better match to the data was obtained by replacing the linear repair rate model (Equation A 4.1) with a power-law formula similar to one developed by Cousins (2004) to model earthquake damage ratios for buildings. It was tuned to give the same results as the ALA model for MM9, and gave a greatly improved overall fit to the data "cloud" (Figure A 4.2). The "Cousins" formula was

$$RR_{GS} = A \times 10^{(B/(MMI-C))}$$ **Equation A 4.5**

where MMI is the shaking intensity and A, B and C are fitted constants. As above, RR_{GS} is the base repair rate due to shaking alone, for large, modern, welded steel pipelines in good ground, and for that case the constants are A = 1600, B = -40 and C = 0.6. The application of factors for pipe attributes and ground hazards (Equation A 4.4) remained unchanged.

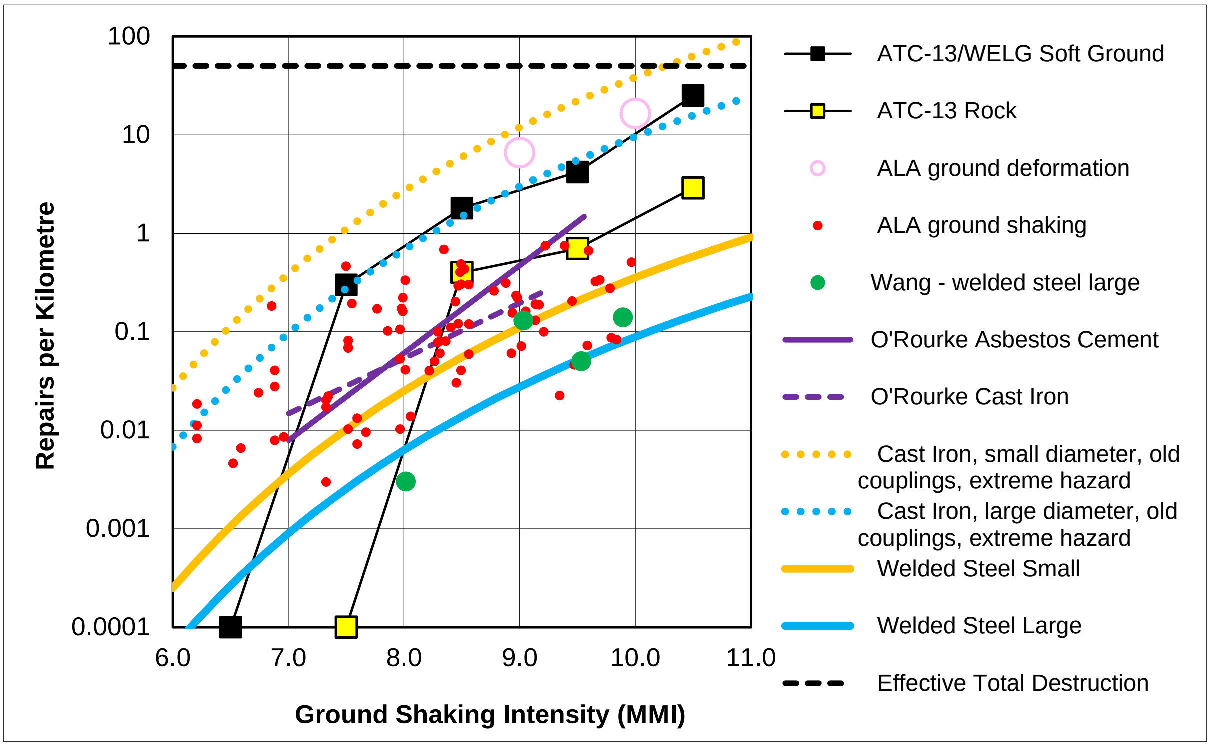

Figure A 4.2 Repair rates – preferred model, comparison of Cousins model with data from historical earthquakes. Visually this matches the available data better than the ALA (2001) linear model.

A4.6 WHAT CONSTITUTES FAILURE?

Pipe failure can range from minor leakage at a distorted coupling to complete annular rupture, and depends strongly on the pipe material and the jointing method (Shi 2006). Of considerable importance are assertions by Shi (2006) that (a) the only failure mechanism for steel pipeline with welded joints is compressive buckling in the bell section of the bell and spigot joint, and (b) only 20% of such failures proceed to tearing or splitting of the wall and hence leakage. For the present modelling it has been assumed that all leaks will be repaired soon after the earthquake because of the need to restore water to people as quickly as possible, but that non-leaking buckles will be left for later repair.

Figure A 4.3 illustrates the range of immediate repair rates that was generated in the modelling of the Wellington network. It extends above and below the range shown in Figure A 4.2. The extension above resulted from a combination of small-diameter brittle pipe, with old couplings, in ground extreme liquefaction hazard and high landslide hazard. Although such a combination of hazards seems unlikely, it can occur, in this case for pipes laid in near-shore liquefiable ground close to the base of a steep ridge. The indication of total loss at MM10 seems entirely reasonable for such a situation. The extension below resulted from the assumption that for modern steel pipelines of large diameter only one in five buckles (failures) would leak sufficiently badly that immediate repair would be necessary.

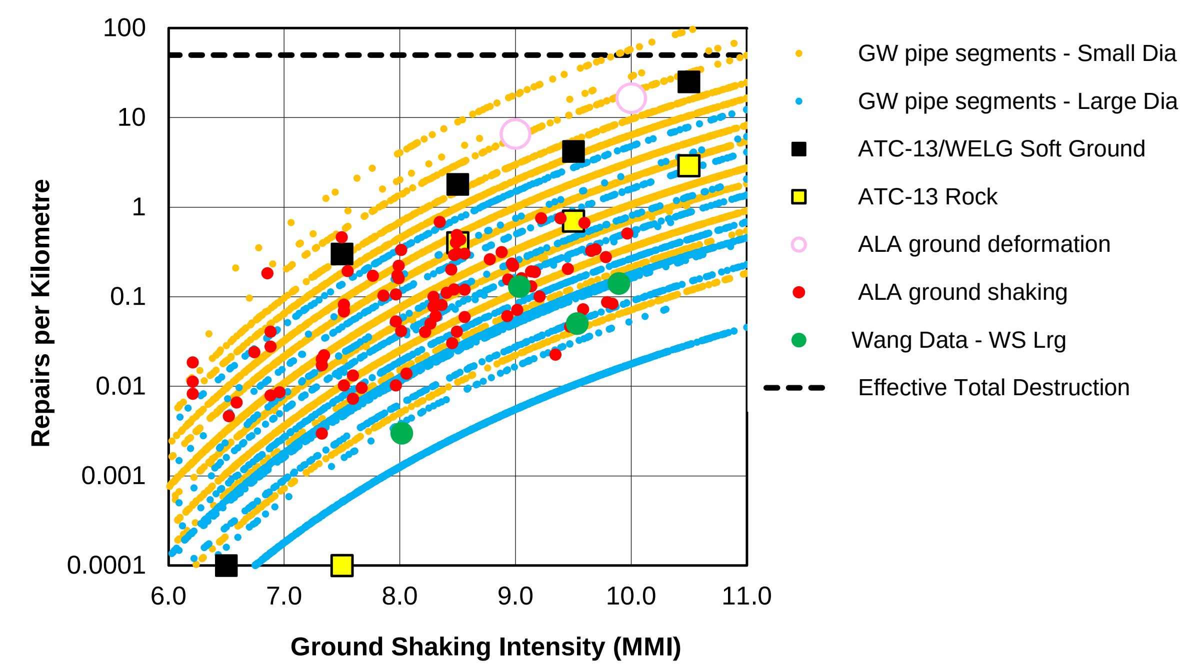

Figure A 4.3 Estimated repair rates, comparison of the final model (Equation A 4.4 and Equation A 4.5) with data from historical earthquakes, for the combinations of shaking intensity and pipe type actually present in the Wellington bulk supply network.

A4.7 RESTORATION SEQUENCE

Some failure points, like fault ruptures, are known in advance and for them repair work can start as soon as men, materials and equipment can be assembled on site. Times for the repair of such known damage sites were recommended by staff of Greater Wellington Regional Council (Table A 4.3) (McCarthy 2009).

Most pipe ruptures, however, cannot be located in advance, and according to current practice are generally found using a laborious process of isolating and pressuring lengths of pipe with water. When the pressure in the length of pipe is not maintained a leak is assumed to be present and is searched for visually. For a system where there is essentially just one pipe between source and distribution points, like the bulk supply to feeder reservoirs in Wellington, the restoration process becomes a simple case of close the valve at the end of the first pipe segment, open the valve at the start, pressurise the segment, check for leaks, if any are found depressurise the segment, repair leaks, re-pressurise, check, if pressure is maintained move on to the next segment, and continue until all leaks have been found and repaired.

Table A 4.3 Times required for various pipe-repair activities. Most were taken from McCarthy (2009), the exception being "Prospect for leaks, Judgeford to Reservoirs", which was a judgement derived from the McCarthy (2009) times. Note that because the locations of the fault breaks are known in advance the repair of them can start before water pressure is available (work-stream 1), and so can be carried out in parallel with repairs to headworks and repairs to the pipeline from Kaitoke to Silverstream (work-stream 2).

Activity	Item	Estimated Time MIN (days)	Estimated Time MAX (days)
Kaitoke Work-stream 1	Secure personal situation	1	1
Repair fault break	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	Secure personal situation	1	1
Repair other damage	Inspection and Planning	2	2
	Repair major damage to headworks	6	6
Whakatikei	Secure personal situation	1	1
Other damage	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	

A4.8 CALCULATION SEQUENCE

The basic method for modelling the damage and repair process was to estimate a probability of failure for each segment of pipe, taking into account the strength of shaking and the various attributes attached to the segment, and then to use a random number to determine whether or not a failure would occur. When a failure did occur the time to repair it was estimated. This was done for every segment in the pipe network, and the results were summed to give an overall result for the earthquake. The process was repeated many times for each earthquake so as to give mean numbers of failures and measures of the variability. Details are as follows:

- Given the magnitude and location of the earthquake, use the Dowrick and Rhoades (2005) attenuation model to estimate the average MM intensity at the centroid of the pipe segment. Allow for uncertainty in the attenuation modelling.
- Allow for soft soil amplification / rock de-amplification by applying the adjustments shown in Figure A 1.10.
- Estimate the repair rate, in repairs per km, using the fragility function of Equation A 4.6. It is based on Equation A 4.5 with the addition of the factors K1 to K5 to allow for pipe material, joint type, pipe size, and geological hazards. The factors are given in Table A 4.2.

$$RR = K1 \times K2 \times K3 \times K4 \times K5 \times A \times 10^{(B/(MMI-C))}$$ **Equation A 4.6**

- Multiply the repair rate (RR) by the segment length (in km) to give the repair rate specific to the segment. Where the segment length is greater than 20 m allow for the possibility of multiple repairs at a rate of one per 20 m.
- Treat the segment repair rate as a probability of repair for the segment, generate a random number in range 0 to 1, and if the random number is less than the probability of repair assume that the segment has failed and needs to be repaired.
- Allow for fault damage. The failure probability is assumed to be 1 wherever the Wellington Fault crosses a pipeline, and the failure type is complete rupture.
- Accumulate the numbers of failures between intake and reservoir, for each reservoir, also the repair times using the activity times given in Table A 4.3. Where the maximum and minimum times in Table A 4.3 are different select randomly from the range.
- For each earthquake model, repeat the above procedure many times, typically 5000, so that the variability can be estimated.
- Carry out the above modelling for all earthquakes of interest.

Other significant modelling assumptions were as follows:

- Kaitoke Work-stream 1 (Repair fault Breaks) applied only to the Wellington Fault earthquake.
- Kaitoke Work-stream 1 (Repair fault breaks) and Work-stream 2 (Repair other damage, including pipe failures from Te Marua to Silverstream) were carried out in parallel for the Wellington Fault case, with the greater of the two repair times being selected.
- The activity times for Kaitoke Work-stream 2 (Repair other damage) and Whakatikei (Other damage) were reduced for earthquakes less severe than the Wellington Fault Earthquake. For an MM9 event the times used were randomly selected from a range of 50% to 100% of the times given in Table A 4.3, for an MM8 event selection was from a range of 0% to 50% of the Table A 4.3 times, and for MM7 and smaller events the times were set to zero.
- Prospecting for leaks was done only when there were repairs to be mended in a particular length of pipeline, with the discrete lengths being (a) Te Marua to Silverstream, (b) Silverstream to Judgeford, (c) Whakatikei to Judgeford, and (d) a separately modelled length from Judgeford to each of the reservoirs.
- Where there were multiple repairs in a single pipe segment, it was assumed that multiple repair crews would be employed with one repair crew per repair. Given the close proximity of the repairs this seemed a reasonable assumption to make.
- Reservoirs that were close together, i.e. within about 100 m, were grouped for modelling purposes. This reflects reality in that as one is emptied people will simply move to the next. Table A 4.4 lists such groupings and the reservoir names used in subsequent tables of results.
- For restoration modelling three nominal reservoirs were created at places expected to be used as supply points during the emergency period after the earthquake (Table A 4.4).

Table A 4.4 Alphabetical list of reservoirs showing (a) those which were combined for modelling purposes, and (b) abbreviated names as used in output tables below.

Full Name	Modelling Name
Alexander Rd	Alexander
Aramoana	Aramoana
Aro	Kelb&TeAro
Beacon Hill	BeacnHill&HL
Beacon Hill HL	
Bell Road	BellRoad
Broadmeadows	Brdmdws&HL
Broadmeadows HL	
Brooklyn #1	Brook1&2
Brooklyn #2	
Brooklyn West	BrookW
Carmichael	Carmichael
Chester	Chester
Churton North	ChurtonN
Churton Park	ChurtonPrk
Croydon	Croydon
Frobisher	Frobisher
Grenada North	GrenadaN
Grenada North HL	GrenadaNHL
Grenada South	GrenadaS
Highbury (3)	Highbury
Highland Park	EXCLUDED (1)
Johnsonville #1	Jville1&2
Johnsonville #2	
Johnsonville West	JvilleWest
Karori South	KaroriS
Karori West	KaroriW
Karori West HL	KaroriWHL
Kelburn	See Aro

Full Name	Modelling Name
Lincolnshire	Linc_Wood
Linden	Linden
Macalister Park	McAlist
Maldive #2	Maldive
Maupuia #1 & 2	Mapuia1&2
Melrose #1	Melrose1&2
Melrose #2	
Messines	Messines
Mount Albert	MtAlbert
Mount Crawford	Crawford
Mount KauKau	Kaukau
Mount Wakefield (3)	MtWakefield3
Newlands #1	Newlnds1&2
Newlands #2	
Ngaio	Ngaio
Onslow #1	Onslow1&2
Onslow #2	
Redwood (timber)	Redwood
Roseneath #1	Rsneath
Roseneath #2	
Rossaveel	Rossaveel
Seatoun Heights (2)	SeatHgts
Tawa	Tawa
Wadestown	Wadestown
Wilton (Pembroke)	Wilton
Woodridge	See Lincolnshire
Wrights Hill	Wrights
nominal supply point	CBD_Nom
nominal supply point	CBD_Nom
nominal supply point	Lindn_Nom

Note 1: The Highland Park reservoir is supplied from the Wainuiomata/Orongorongo bulk supply system, not the Kaitoke system, hence it is assumed not to be available for storage and distribution of restored bulk water in the current modelling that involves just the Kaitoke system. Because it is not fitted with an auto-shut valve, any water in it at the time of an earthquake is assumed to be lost and not available for consumption after the earthquake.

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APPENDIX 5: RESULTS: NUMBERS OF BREAKS, AND RESTORATION TIMES

Two outputs of the above modelling are presented, (a) numbers of pipeline breaks between the water intakes and locations of interest, and (b) times to restore water to the locations.

One key location is Judgeford junction, the point where the bulk supply lines from the existing Kaitoke and proposed Whakatikei intakes meet (Figure 1.2). Table A 5.1 and Table A 5.2 compare, respectively, the numbers of pipeline breaks between the intakes and the junction, and the times to restore water to the junction, for nine earthquake scenarios.

Numbers of pipeline breaks between the sources and individual reservoirs are listed in Table A 5.3 (Kaitoke source) and A5.4 (Whakatikei source). Times (in days) to restore water from the sources to the reservoirs are listed in Table A 5.5 (Kaitoke source) and Table A 5.6 (Whakatikei source).

The results presented in Table A 5.1 to Table A 5.6 are median estimates derived from the outputs from 10,000 runs of the damage/restoration model, for each scenario earthquake. The order of listing of the reservoirs in Table A 5.3 to Table A 5.6 is increasing distance from intake

Table A 5.1 Numbers of pipeline breaks to be repaired between each of the two intakes and Judgeford junction. Numbers of pipe breaks caused by fault rupture are indicated (e.g. "2f" means 2 breaks at fault crossings) (applies to the Wellington Fault scenario only).

Intake	Wellington Fault	Wairarapa 1855	Oharui South	Whitemans	Akatarawa-Otaki	Tararua	MM9	MM8	MM7
Kaitoke	1 (+2f)	2	0	1	1	0	1	0	0
Whakatikei	0	0	0	0	0	0	0	0	0

Table A 5.2 Times (in days) needed to restore bulk supply from each of the two intakes to Judgeford junction. Repairs at fault crossings are included (applies to the Wellington Fault scenario only).

Intake	Wellington Fault	Wairarapa 1855	Oharui South	Whitemans	Akatarawa-Otaki	Tararua	MM9	MM8	MM7
Kaitoke	17	13	0	5	13	8	12	3	0
Whakatikei	4	3	0	1	4	3	3	1	0

Table A 5.3 Numbers of pipeline breaks to be repaired between the Kaitoke intake and reservoirs in Wellington. Numbers of pipe breaks caused by fault rupture are indicated (e.g. +2f) (applies to the Wellington Fault scenario only).

Reservoir	Wellington Fault	Wairarapa 1855	Oharui South	Whitemans	Akatarawa-Otaki	Tararua	MM9	MM8	MM7
Tawa	2 (+ 2f)	2	1	1	1	0	2	0	0
GrenadaN	2 (+ 2f)	2	1	1	1	1	2	0	0
GrenadaNHL	3 (+ 2f)	3	1	1	1	1	2	0	0
GrenadaS	3 (+ 2f)	2	1	1	1	1	2	0	0
ChurtonPrk	4 (+ 2f)	3	1	1	1	1	2	0	0
Linden	6 (+ 2f)	3	2	2	2	1	3	0	0
Jville1&2	4 (+ 2f)	3	2	2	1	1	2	0	0
Newlnds1&2	5 (+ 2f)	3	2	2	1	1	2	0	0
Rossaveel	6 (+ 2f)	4	2	2	2	1	3	0	0
LindnNom	6 (+ 2f)	4	2	2	2	1	3	0	0
Maldive	4 (+ 2f)	3	1	2	1	1	2	0	0
JvilleWest	7 (+ 2f)	4	3	2	2	1	3	0	0
ChurtonN	8 (+ 2f)	4	3	2	2	1	3	0	0
Brdmdws&HL	7 (+ 2f)	4	3	2	2	1	3	0	0
Linc_Wood	9 (+ 2f)	4	3	3	2	1	3	1	0
Onslow1&2	7 (+ 2f)	4	3	2	2	1	3	0	0
Ngaio	8 (+ 2f)	4	3	2	2	1	3	0	0
Redwood	9 (+ 2f)	5	4	3	2	1	4	1	0
Chester	14 (+ 2f)	7	6	4	3	1	5	1	0
Kaukau	12 (+ 2f)	5	5	3	2	1	4	1	0
Wilton	8 (+ 2f)	4	4	2	2	1	3	1	0
Wadestown	11 (+ 2f)	5	5	2	2	1	3	1	0
Kelb&TeAro	10 (+ 3f)	5	5	2	2	1	3	1	0
Messines	11 (+ 2f)	5	6	2	2	1	4	1	0
Croydon	11 (+ 2f)	5	6	2	2	1	4	1	0
Highbury	11 (+ 3f)	5	6	3	2	1	4	1	0
CBDnom	13 (+ 3f)	6	7	3	2	1	4	1	0
Brook1&2	13 (+ 3f)	6	7	3	2	1	4	1	0
MtWakefield3	18 (+ 2f)	7	10	3	2	1	5	1	0
BellRoad	14 (+ 3f)	6	7	3	2	1	4	1	0
BrookW	14 (+ 3f)	6	8	3	2	1	4	1	0
Wrights	17 (+ 2f)	7	11	3	2	1	5	1	0
McAlist	18 (+ 3f)	8	9	4	2	1	5	1	0
KaroriW	21 (+ 2f)	8	14	4	2	1	6	1	0
KaroriWHL	21 (+ 2f)	9	15	4	2	1	6	1	0
Carmichael	21 (+ 3f)	9	11	4	2	1	6	1	0
KaroriS	25 (+ 2f)	10	19	4	2	1	7	1	0
MtAlbert	24 (+ 3f)	11	13	5	2	1	7	2	0
Melrose1&2	26 (+ 3f)	12	14	5	2	1	8	2	0
Frobisher	29 (+ 3f)	14	16	6	2	1	9	2	0
Rsneath	37 (+ 3f)	18	21	9	3	2	12	3	1
Alexander	37 (+ 3f)	18	21	9	3	2	12	3	1
MirNom	42 (+ 3f)	23	22	11	3	2	15	4	1
SeatHgts	44 (+ 3f)	24	22	12	4	2	16	4	1
BeacnHill&HL	45 (+ 3f)	25	23	12	4	2	16	4	1
Aramoana	95 (+ 3f)	56	49	29	8	5	36	11	4
Mapuia1&2	99 (+ 3f)	58	50	30	9	5	38	11	4
Crawford	101 (+ 3f)	59	50	31	9	5	38	11	4

Table A 5.4 Numbers of pipeline breaks to be repaired between the proposed Whakatikei intake and reservoirs in Wellington. Numbers of pipe breaks caused by fault rupture are indicated (e.g. +1f) (applies to the Wellington Fault scenario only).

Reservoir	Wellington Fault	Wairarapa 1855	Oharui South	Whitemans	Akatarawa-Otaki	Tararua	MM9	MM8	MM7
Tawa	1	0	0	0	0	0	0	0	0
GrenadaN	2	1	0	0	0	0	0	0	0
GrenadaNHL	2	1	1	1	0	0	1	0	0
GrenadaS	2	1	1	0	0	0	1	0	0
ChurtonPrk	3	1	1	1	0	0	1	0	0
Linden	5	2	2	1	0	0	1	0	0
Jville1&2	3	1	1	1	0	0	1	0	0
Newlnds1&2	4	1	1	1	0	0	1	0	0
Rossaveel	5	2	2	1	0	0	2	0	0
LindnNom	6	2	2	1	0	0	2	0	0
Maldive	3	1	1	1	0	0	1	0	0
JvilleWest	6	2	2	1	0	0	1	0	0
ChurtonN	7	2	3	1	0	0	1	0	0
Brdmdws&HL	6	2	3	1	0	0	1	0	0
Linc_Wood	9	3	3	2	0	0	2	0	0
Onslow1&2	7	2	3	1	0	0	1	0	0
Ngaio	7	2	3	1	0	0	1	0	0
Redwood	8	3	3	2	1	0	2	0	0
Chester	13	5	6	3	1	0	4	1	0
Kaukau	11	4	5	2	0	0	2	0	0
Wilton	8	2	4	1	0	0	2	0	0
Wadestown	10	3	5	2	0	0	2	0	0
Kelb&TeAro	9 (+1f)	3	5	1	0	0	2	0	0
Messines	10	3	5	2	0	0	2	0	0
Croydon	10	3	5	2	0	0	2	0	0
Highbury	11 (+1f)	4	6	2	0	0	2	0	0
CBDnom	12 (+1f)	4	6	2	0	0	3	0	0
Brook1&2	12 (+1f)	4	7	2	0	0	3	0	0
MtWakefield3	17	5	9	3	0	0	3	1	0
BellRoad	13 (+1f)	5	7	2	0	0	3	0	0
BrookW	14 (+1f)	5	7	2	0	0	3	0	0
Wrights	16	6	10	2	1	0	3	1	0
McAlist	17 (+1f)	6	9	3	1	0	4	1	0
KaroriW	20	7	14	3	1	0	4	1	0
KaroriWHL	21	7	14	3	1	0	4	1	0
Carmichael	20 (+1f)	8	11	4	1	0	5	1	0
KaroriS	25	8	18	4	1	0	5	1	0
MtAlbert	23 (+1f)	9	13	4	1	0	6	1	0
Melrose1&2	25 (+1f)	10	14	5	1	0	6	1	0
Frobisher	28 (+1f)	12	15	5	1	0	8	2	0
Rsneath	36 (+1f)	16	21	8	2	1	11	3	1
Alexander	36 (+1f)	16	21	8	2	1	11	3	1
MirNom	41 (+1f)	21	21	10	2	1	13	4	1
SeatHgts	44 (+1f)	23	22	11	2	1	14	4	1
BeacnHill&HL	44 (+1f)	23	22	11	2	1	15	4	1
Aramoana	95 (+1f)	55	48	28	7	4	35	11	4
Mapuia1&2	98 (+1f)	56	49	30	7	4	36	11	4
Crawford	100 (+1f)	57	50	30	7	4	37	11	4

Table A 5.5 Times (in days) needed to restore bulk supply from the Kaitoke intake to reservoirs in Wellington. Repairs at fault crossings are included (applies to the Wellington Fault scenario only).

Reservoir	Wellington Fault	Wairarapa 1855	Oharui South	Whitemans	Akatarawa-Otaki	Tararua	MM9	MM8	MM7
Tawa	20	15	3	7	13	8	13	4	0
GrenadaN	21	15	4	7	14	8	14	4	0
GrenadaNHL	22	16	4	7	14	8	14	4	0
GrenadaS	23	16	4	8	14	8	14	4	0
ChurtonPrk	24	16	4	8	14	8	15	4	0
Linden	23	16	5	8	14	9	15	4	0
Jville1&2	24	17	5	8	14	8	15	4	0
Newlnds1&2	24	17	5	8	14	8	15	4	0
Rossaveel	24	17	5	8	14	9	16	4	0
LindnNom	24	17	5	9	14	9	16	4	0
Maldive	27	18	5	8	14	8	15	4	0
JvilleWest	27	18	6	9	14	9	16	4	0
ChurtonN	27	18	6	9	14	9	16	4	0
Brdmdws&HL	27	18	6	9	14	9	16	4	0
Linc_Wood	29	19	7	10	14	9	17	4	0
Onslow1&2	31	19	8	10	14	9	17	4	0
Ngaio	31	20	8	10	14	9	17	4	0
Redwood	27	19	7	9	15	9	16	5	0
Chester	32	21	9	11	16	9	18	5	0
Kaukau	35	21	11	11	15	9	18	5	0
Wilton	35	21	11	11	14	9	18	4	0
Wadestown	37	22	13	11	14	9	19	5	0
Kelb&TeAro	40	23	15	12	15	9	20	6	0
Messines	40	23	15	12	15	9	20	6	0
Croydon	41	23	15	12	15	9	20	6	0
Highbury	41	23	15	12	15	9	20	6	0
CBDnom	43	24	16	12	15	9	20	6	0
Brook1&2	43	24	17	13	15	9	20	7	0
MtWakefield3	43	24	16	13	15	9	20	6	0
BellRoad	44	25	17	13	15	9	21	7	0
BrookW	44	25	18	13	15	9	21	7	0
Wrights	46	25	20	13	16	9	21	7	0
McAlist	49	27	20	14	16	10	22	8	0
KaroriW	51	27	24	14	16	10	22	8	0
KaroriWHL	51	27	24	14	16	10	22	8	0
Carmichael	53	29	22	15	16	10	23	8	0
KaroriS	52	28	26	14	16	10	23	8	0
MtAlbert	55	30	24	16	17	10	24	9	0
Melrose1&2	57	31	25	16	17	11	25	9	0
Frobisher	60	33	27	17	18	11	26	10	0
Rsneath	62	34	29	19	19	13	28	11	5
Alexander	63	35	29	19	19	13	28	11	5
MirNom	69	41	32	21	20	13	31	12	5
SeatHgts	72	42	33	22	20	13	33	12	5
BeacnHill&HL	72	43	33	23	20	13	33	12	5
Aramoana	99	62	50	35	25	17	48	19	8
Mapuia1&2	102	64	52	37	25	18	49	19	8
Crawford	105	65	52	37	25	18	50	19	8

Table A 5.6 Times (in days) needed to restore bulk supply from the proposed Whakatikei intake to reservoirs in Wellington. Repairs at fault crossings are included (applies to the Wellington Fault scenario only).

Reservoir	Wellington Fault	Wairarapa 1855	Oharui South	Whitemans	Akatarawa-Otaki	Tararua	MM9	MM8	MM7
Tawa	8	4	0	2	4	3	4	1	0
GrenadaN	8	6	0	2	4	3	4	1	0
GrenadaNHL	9	6	3	3	4	3	5	1	0
GrenadaS	10	7	3	3	4	3	5	1	0
ChurtonPrk	11	7	4	3	4	3	6	1	0
Linden	11	7	4	4	4	3	6	1	0
Jville1&2	11	7	4	3	4	3	6	1	0
Newlnds1&2	12	7	4	4	4	3	6	1	0
Rossaveel	12	8	4	4	4	3	6	1	0
LindnNom	12	8	4	4	4	3	6	1	0
Maldive	14	8	5	4	4	3	7	1	0
JvilleWest	14	8	5	5	4	3	7	1	0
ChurtonN	15	8	5	5	4	3	7	1	0
Brdmdws&HL	15	8	5	5	4	3	7	1	0
Linc_Wood	16	9	6	6	4	3	8	2	0
Onslow1&2	18	10	7	5	4	3	8	1	0
Ngaio	19	10	8	6	4	3	8	1	0
Redwood	15	9	6	5	6	3	7	2	0
Chester	19	11	8	7	7	4	9	3	0
Kaukau	22	11	10	7	4	3	9	2	0
Wilton	22	11	10	7	4	3	9	2	0
Wadestown	24	12	11	7	4	3	10	2	0
Kelb&TeAro	27	14	13	8	4	3	11	2	0
Messines	27	14	14	8	4	3	11	2	0
Croydon	28	14	14	8	4	3	11	2	0
Highbury	28	14	14	8	4	3	11	2	0
CBDnom	30	15	15	8	4	3	11	2	0
Brook1&2	30	15	16	8	4	3	12	2	0
MtWakefield3	30	14	15	8	4	3	11	4	0
BellRoad	31	15	16	9	4	3	12	2	0
BrookW	32	15	16	9	4	3	12	2	0
Wrights	33	16	19	9	6	3	12	5	0
McAlist	36	18	19	10	7	3	14	6	0
KaroriW	38	17	22	9	8	3	13	6	0
KaroriWHL	38	18	23	10	8	3	13	6	0
Carmichael	40	19	21	11	8	3	15	6	0
KaroriS	40	18	24	10	9	3	14	6	0
MtAlbert	42	21	23	11	9	3	16	7	0
Melrose1&2	44	22	24	12	9	3	16	7	0
Frobisher	47	24	26	13	9	4	17	7	0
Rsneath	49	25	27	14	10	8	19	8	5
Alexander	50	25	28	14	10	8	19	8	5
MirNom	57	31	30	17	10	8	23	9	5
SeatHgts	59	33	32	18	10	8	24	9	5
BeacnHill&HL	59	33	32	18	11	8	24	10	5
Aramoana	86	53	49	31	15	12	39	16	8
Mapuia1&2	89	55	50	32	15	12	40	16	8
Crawford	92	56	51	33	15	12	41	16	8

Table A 5.7 Estimated numbers of breaks and repair times (in days) for hypothetical bulk-supply networks constructed entirely of modern steel pipes with welded joints.

Water Source	Kaitoke	Whakatikei	Kaitoke	Whakatikei
Reservoir	Number of Breaks		Time to Repair (days)	
Tawa	1 (+2f)	0	17	4
GrenadaN	1 (+2f)	1	19	7
GrenadaNHL	2 (+2f)	1	20	8
GrenadaS	2 (+2f)	2	21	8
ChurtonPrk	2 (+2f)	2	21	8
Linden	3 (+2f)	2	21	8
Jville1&2	2 (+2f)	1	20	8
Newlnds1&2	2 (+2f)	1	20	8
Rossaveel	3 (+2f)	3	22	9
LindnNom	3 (+2f)	2	21	9
Maldive	1 (+2f)	1	20	8
JvilleWest	5 (+2f)	4	24	11
ChurtonN	6 (+2f)	5	25	12
Brdmdws&HL	5 (+2f)	4	24	11
Linc_Wood	5 (+2f)	5	25	12
Onslow1&2	2 (+2f)	2	22	10
Ngaio	2 (+2f)	2	22	10
Redwood	6 (+2f)	6	24	12
Chester	4 (+2f)	3	22	10
Kaukau	8 (+2f)	7	27	14
Wilton	2 (+2f)	2	23	10
Wadestown	4 (+2f)	4	25	12
Kelb&TeAro	3 (+3f)	2 (+1f)	24	11
Messines	3 (+2f)	2	24	11
Croydon	3 (+2f)	3	25	12
Highbury	4 (+3f)	4 (+1f)	25	13
CBDnom	2 (+3f)	2 (+1f)	23	11
Brook1&2	2 (+3f)	2 (+1f)	24	11
MtWakefield3	7 (+2f)	7	28	15
BellRoad	2 (+3f)	2 (+1f)	24	11
BrookW	3 (+3f)	3 (+1f)	25	12
Wrights	4 (+2f)	3	25	13
McAlist	3 (+3f)	2 (+1f)	25	12
KaroriW	8 (+2f)	8	30	17
KaroriWHL	9 (+2f)	9	31	18
Carmichael	3 (+3f)	3 (+1f)	25	13
KaroriS	13 (+2f)	12	32	19
MtAlbert	3 (+3f)	3 (+1f)	26	13
Melrose1&2	4 (+3f)	3 (+1f)	26	13
Frobisher	5 (+3f)	5 (+1f)	28	15
Rsneath	16 (+3f)	15 (+1f)	35	22
Alexander	16 (+3f)	16 (+1f)	35	23
MirNom	5 (+3f)	5 (+1f)	28	15
SeatHgts	6 (+3f)	6 (+1f)	29	16
BeacnHill&HL	7 (+3f)	6 (+1f)	29	17
Aramoana	12 (+3f)	11 (+1f)	34	21
Mapuia1&2	15 (+3f)	15 (+1f)	38	25
Crawford	17 (+3f)	17 (+1f)	40	27

APPENDIX 6: DURATIONS OF EXCEEDANCES OF SHORTFALL LEVELS

Appendix 6 provides tabulated estimates of the lengths of time for which various minimum quantities of water need to be supplied from sources other than the normal bulk supply system, in order to meet the estimated post-earthquake shortfalls in conventional supply. They match the data provided graphically in Figure 6.1 to Figure 6.9.

The basic modelling conditions of water source, percentage retention in reservoirs, water consumption rate, and earthquake scenario are given at the head of each table. With reference to the Wellington Fault (earthquake) column in Table A 6.1, the way to interpret the data is as follows: 3,000,000 litres/day will be needed for 1 day, at least 2,000,000 litres/day for 20 days, and at least 1,000,000 litres/day for 34 days.

Table A 6.1 Times, in days, for which various minimum daily quantities of water must be provided from alternative sources, for the eight strongest earthquake scenarios.

Shortfall Exceedance Level (litres/day)	Water Source: Kaitoke							
	Water Retained in Reservoirs Post-Event: 50%							
	Consumption Rate: 20 litres per person per day							
	Wellington Fault	Wairarapa 1855	Oharui South	Whitemans	Akatarawa-Otaki	Tararua	MM9	MM8
20,000	67	37	27	17	14	7	27	5
50,000	66	37	27	17	13	6	27	4
100,000	64	34	25	15	13	4	25	1
200,000	63	34	25	15	12	3	25	-
300,000	63	34	25	15	12	3	25	-
400,000	55	27	21	11	11	-	20	-
500,000	49	24	16	7	8	-	17	-
600,000	48	23	15	5	8	-	17	-
700,000	44	20	12	4	7	-	15	-
800,000	41	19	10	1	6	-	14	-
900,000	41	19	9	-	6	-	14	-
1,000,000	34	15	5	-	5	-	11	-
1,100,000	32	13	4	-	4	-	10	-
1,200,000	32	13	2	-	2	-	10	-
1,300,000	31	12	1	-	2	-	8	-
1,400,000	29	11	-	-	1	-	8	-
1,500,000	28	11	-	-	1	-	8	-
1,600,000	27	10	-	-	-	-	7	-
1,700,000	27	10	-	-	-	-	7	-
1,800,000	26	8	-	-	-	-	3	-
1,900,000	21	7	-	-	-	-	1	-
2,000,000	20	6	-	-	-	-	-	-
2,100,000	20	4	-	-	-	-	-	-
2,200,000	16	1	-	-	-	-	-	-
2,300,000	15	-	-	-	-	-	-	-
2,400,000	11	-	-	-	-	-	-	-
2,500,000	10	-	-	-	-	-	-	-
2,600,000	7	-	-	-	-	-	-	-
2,700,000	6	-	-	-	-	-	-	-
2,800,000	6	-	-	-	-	-	-	-
2,900,000	3	-	-	-	-	-	-	-
3,000,000	1	-	-	-	-	-	-	-

Table A 6.2 Times, in days, for which various minimum daily quantities of water must be provided from alternative sources, for the eight strongest earthquake scenarios.

Shortfall Exceedance Level (litres/day)	Water Source: Kaitoke							
	Water Retained in Reservoirs Post-Event: 75%							
	Consumption Rate: 20 litres per person per day							
	Wellington Fault	Wairarapa 1855	Oharui South	Whitemans	Akatarawa-Otaki	Tararua	MM9	MM8
20,000	64	35	25	14	11	4	25	-
50,000	64	34	24	12	10	1	24	-
100,000	61	32	23	10	9	-	23	-
200,000	60	31	22	6	6	-	22	-
300,000	60	31	22	5	6	-	22	-
400,000	53	25	18	3	4	-	18	-
500,000	46	20	12	1	4	-	14	-
600,000	45	20	8	-	4	-	13	-
700,000	42	18	-	-	1	-	13	-
800,000	38	16	-	-	1	-	10	-
900,000	38	16	-	-	1	-	9	-
1,000,000	31	12	-	-	-	-	6	-
1,100,000	29	10	-	-	-	-	3	-
1,200,000	28	7	-	-	-	-	1	-
1,300,000	27	6	-	-	-	-	-	-
1,400,000	23	5	-	-	-	-	-	-
1,500,000	23	3	-	-	-	-	-	-
1,600,000	23	-	-	-	-	-	-	-
1,700,000	22	-	-	-	-	-	-	-
1,800,000	21	-	-	-	-	-	-	-
1,900,000	16	-	-	-	-	-	-	-
2,000,000	15	-	-	-	-	-	-	-
2,100,000	10	-	-	-	-	-	-	-
2,200,000	8	-	-	-	-	-	-	-
2,300,000	1	-	-	-	-	-	-	-
2,400,000	-	-	-	-	-	-	-	-
2,500,000	-	-	-	-	-	-	-	-
2,600,000	-	-	-	-	-	-	-	-
2,700,000	-	-	-	-	-	-	-	-
2,800,000	-	-	-	-	-	-	-	-
2,900,000	-	-	-	-	-	-	-	-
3,000,000	-	-	-	-	-	-	-	-

Table A 6.3 Times, in days, for which various minimum daily quantities of water must be provided from alternative sources, for the eight strongest earthquake scenarios.

Shortfall Exceedance Level (litres/day)	Water Source: Whakatikei							
	Water Retained in Reservoirs Post-Event: 50%							
	Consumption Rate: 20 litres per person per day							
	Wellington Fault	Wairarapa 1855	Oharui South	Whitemans	Akatarawa-Otaki	Tararua	MM9	MM8
20,000	54	27	26	12	4	-	18	-
50,000	53	27	26	12	3	-	18	-
100,000	51	25	24	10	1	-	16	-
200,000	50	25	24	5	-	-	16	-
300,000	50	24	24	3	-	-	15	-
400,000	42	17	20	1	-	-	11	-
500,000	36	13	14	-	-	-	6	-
600,000	35	11	14	-	-	-	3	-
700,000	31	11	11	-	-	-	-	-
800,000	28	7	7	-	-	-	-	-
900,000	28	3	6	-	-	-	-	-
1,000,000	20	2	3	-	-	-	-	-
1,100,000	18	1	1	-	-	-	-	-
1,200,000	18	-	-	-	-	-	-	-
1,300,000	17	-	-	-	-	-	-	-
1,400,000	14	-	-	-	-	-	-	-
1,500,000	13	-	-	-	-	-	-	-
1,600,000	13	-	-	-	-	-	-	-
1,700,000	12	-	-	-	-	-	-	-
1,800,000	11	-	-	-	-	-	-	-
1,900,000	7	-	-	-	-	-	-	-
2,000,000	5	-	-	-	-	-	-	-
2,100,000	1	-	-	-	-	-	-	-
2,200,000	-	-	-	-	-	-	-	-
2,300,000	-	-	-	-	-	-	-	-
2,400,000	-	-	-	-	-	-	-	-
2,500,000	-	-	-	-	-	-	-	-
2,600,000	-	-	-	-	-	-	-	-
2,700,000	-	-	-	-	-	-	-	-
2,800,000	-	-	-	-	-	-	-	-
2,900,000	-	-	-	-	-	-	-	-
3,000,000	-	-	-	-	-	-	-	-

Table A 6.4 Times, in days, for which various minimum daily quantities of water must be provided from alternative sources, for the eight strongest earthquake scenarios.

Shortfall Exceedance Level (litres/day)	Water Source: Whakatikei							
	Water Retained in Reservoirs Post-Event: 75%							
	Consumption Rate: 20 litres per person per day							
	Wellington Fault	Wairarapa 1855	Oharui South	Whitemans	Akatarawa-Otaki	Tararua	MM9	MM8
20,000	51	25	24	6	-	-	15	-
50,000	51	24	23	5	-	-	14	-
100,000	48	23	22	2	-	-	11	-
200,000	47	22	21	-	-	-	7	-
300,000	47	20	20	-	-	-	4	-
400,000	40	11	16	-	-	-	2	-
500,000	33	7	8	-	-	-	-	-
600,000	32	3	4	-	-	-	-	-
700,000	28	-	-	-	-	-	-	-
800,000	24	-	-	-	-	-	-	-
900,000	23	-	-	-	-	-	-	-
1,000,000	15	-	-	-	-	-	-	-
1,100,000	13	-	-	-	-	-	-	-
1,200,000	13	-	-	-	-	-	-	-
1,300,000	13	-	-	-	-	-	-	-
1,400,000	9	-	-	-	-	-	-	-
1,500,000	7	-	-	-	-	-	-	-
1,600,000	6	-	-	-	-	-	-	-
1,700,000	3	-	-	-	-	-	-	-
1,800,000	-	-	-	-	-	-	-	-
1,900,000	-	-	-	-	-	-	-	-
2,000,000	-	-	-	-	-	-	-	-
2,100,000	-	-	-	-	-	-	-	-
2,200,000	-	-	-	-	-	-	-	-
2,300,000	-	-	-	-	-	-	-	-
2,400,000	-	-	-	-	-	-	-	-
2,500,000	-	-	-	-	-	-	-	-
2,600,000	-	-	-	-	-	-	-	-
2,700,000	-	-	-	-	-	-	-	-
2,800,000	-	-	-	-	-	-	-	-
2,900,000	-	-	-	-	-	-	-	-
3,000,000	-	-	-	-	-	-	-	-

Table A 6.5 Times, in days, for which various minimum daily quantities of water must be provided from alternative sources, for the eight strongest earthquake scenarios.

Shortfall Exceedance Level (litres/day)	Water Source: Kaitoke							
	Water Retained in Reservoirs Post-Event: 50%							
	Consumption Rate: 6 litres per person per day							
	Wellington Fault	Wairarapa 1855	Oharui South	Whitemans	Akatarawa-Otaki	Tararua	MM9	MM8
20,000	51	13	-	-	-	-	1	-
50,000	48	5	-	-	-	-	-	-
100,000	44	-	-	-	-	-	-	-
200,000	17	-	-	-	-	-	-	-
300,000	-	-	-	-	-	-	-	-
400,000	-	-	-	-	-	-	-	-
500,000	-	-	-	-	-	-	-	-
600,000	-	-	-	-	-	-	-	-
700,000	-	-	-	-	-	-	-	-
800,000	-	-	-	-	-	-	-	-
900,000	-	-	-	-	-	-	-	-
1,000,000	-	-	-	-	-	-	-	-
1,100,000	-	-	-	-	-	-	-	-
1,200,000	-	-	-	-	-	-	-	-
1,300,000	-	-	-	-	-	-	-	-
1,400,000	-	-	-	-	-	-	-	-
1,500,000	-	-	-	-	-	-	-	-
1,600,000	-	-	-	-	-	-	-	-
1,700,000	-	-	-	-	-	-	-	-
1,800,000	-	-	-	-	-	-	-	-
1,900,000	-	-	-	-	-	-	-	-
2,000,000	-	-	-	-	-	-	-	-
2,100,000	-	-	-	-	-	-	-	-
2,200,000	-	-	-	-	-	-	-	-
2,300,000	-	-	-	-	-	-	-	-
2,400,000	-	-	-	-	-	-	-	-
2,500,000	-	-	-	-	-	-	-	-
2,600,000	-	-	-	-	-	-	-	-
2,700,000	-	-	-	-	-	-	-	-
2,800,000	-	-	-	-	-	-	-	-
2,900,000	-	-	-	-	-	-	-	-
3,000,000	-	-	-	-	-	-	-	-

Table A 6.6 Times, in days, for which various minimum daily quantities of water must be provided from alternative sources, for the eight strongest earthquake scenarios.

Shortfall Exceedance Level (litres/day)	Water Source: Kaitoke							
	Water Retained in Reservoirs Post-Event: 75%							
	Consumption Rate: 6 litres per person per day							
	Wellington Fault	Wairarapa 1855	Oharui South	Whitemans	Akatarawa-Otaki	Tararua	MM9	MM8
20,000	37	-	-	-	-	-	-	-
50,000	26	-	-	-	-	-	-	-
100,000	18	-	-	-	-	-	-	-
200,000	-	-	-	-	-	-	-	-
300,000	-	-	-	-	-	-	-	-
400,000	-	-	-	-	-	-	-	-
500,000	-	-	-	-	-	-	-	-
600,000	-	-	-	-	-	-	-	-
700,000	-	-	-	-	-	-	-	-
800,000	-	-	-	-	-	-	-	-
900,000	-	-	-	-	-	-	-	-
1,000,000	-	-	-	-	-	-	-	-
1,100,000	-	-	-	-	-	-	-	-
1,200,000	-	-	-	-	-	-	-	-
1,300,000	-	-	-	-	-	-	-	-
1,400,000	-	-	-	-	-	-	-	-
1,500,000	-	-	-	-	-	-	-	-
1,600,000	-	-	-	-	-	-	-	-
1,700,000	-	-	-	-	-	-	-	-
1,800,000	-	-	-	-	-	-	-	-
1,900,000	-	-	-	-	-	-	-	-
2,000,000	-	-	-	-	-	-	-	-
2,100,000	-	-	-	-	-	-	-	-
2,200,000	-	-	-	-	-	-	-	-
2,300,000	-	-	-	-	-	-	-	-
2,400,000	-	-	-	-	-	-	-	-
2,500,000	-	-	-	-	-	-	-	-
2,600,000	-	-	-	-	-	-	-	-
2,700,000	-	-	-	-	-	-	-	-
2,800,000	-	-	-	-	-	-	-	-
2,900,000	-	-	-	-	-	-	-	-
3,000,000	-	-	-	-	-	-	-	-

Table A 6.7 Times, in days, for which various minimum daily quantities of water must be provided from alternative sources, for the eight strongest earthquake scenarios.

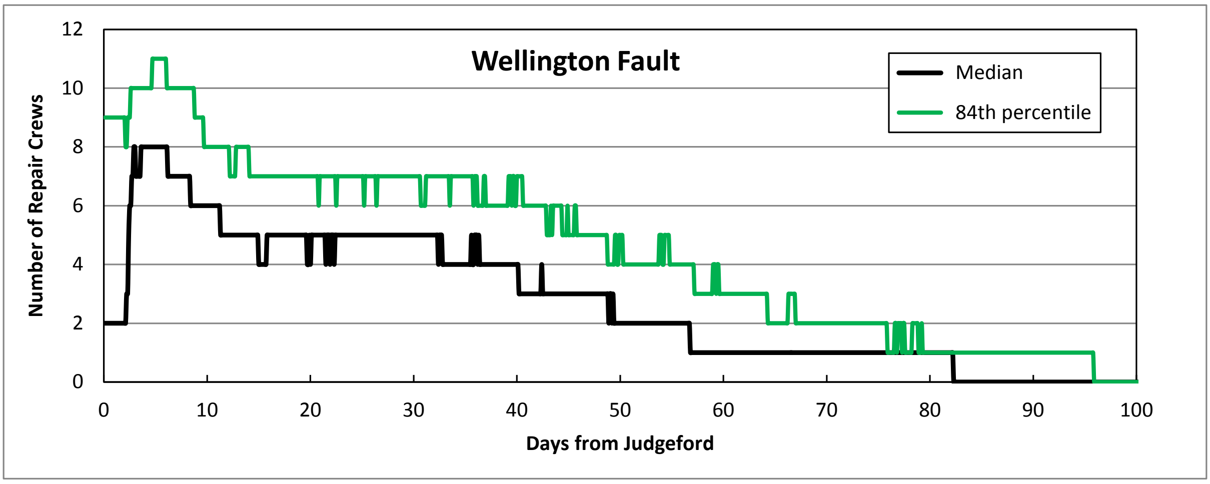
Shortfall Exceedance Level (litres/day)	Water Source: Whakatikei							
	Water Retained in Reservoirs Post-Event: 50%							
	Consumption Rate: 6 litres per person per day							
	Wellington Fault	Wairarapa 1855	Oharui South	Whitemans	Akatarawa-Otaki	Tararua	MM9	MM8
20,000	37	-	-	-	-	-	-	-
50,000	31	-	-	-	-	-	-	-
100,000	13	-	-	-	-	-	-	-
200,000	-	-	-	-	-	-	-	-
300,000	-	-	-	-	-	-	-	-
400,000	-	-	-	-	-	-	-	-
500,000	-	-	-	-	-	-	-	-
600,000	-	-	-	-	-	-	-	-
700,000	-	-	-	-	-	-	-	-
800,000	-	-	-	-	-	-	-	-
900,000	-	-	-	-	-	-	-	-
1,000,000	-	-	-	-	-	-	-	-
1,100,000	-	-	-	-	-	-	-	-
1,200,000	-	-	-	-	-	-	-	-
1,300,000	-	-	-	-	-	-	-	-
1,400,000	-	-	-	-	-	-	-	-
1,500,000	-	-	-	-	-	-	-	-
1,600,000	-	-	-	-	-	-	-	-
1,700,000	-	-	-	-	-	-	-	-
1,800,000	-	-	-	-	-	-	-	-
1,900,000	-	-	-	-	-	-	-	-
2,000,000	-	-	-	-	-	-	-	-
2,100,000	-	-	-	-	-	-	-	-
2,200,000	-	-	-	-	-	-	-	-
2,300,000	-	-	-	-	-	-	-	-
2,400,000	-	-	-	-	-	-	-	-
2,500,000	-	-	-	-	-	-	-	-
2,600,000	-	-	-	-	-	-	-	-
2,700,000	-	-	-	-	-	-	-	-
2,800,000	-	-	-	-	-	-	-	-
2,900,000	-	-	-	-	-	-	-	-
3,000,000	-	-	-	-	-	-	-	-

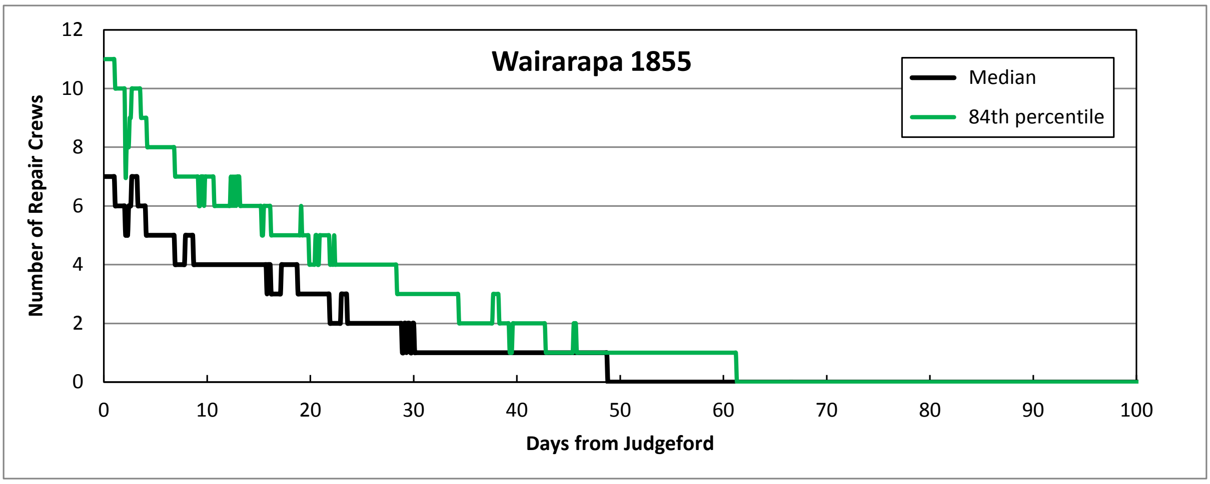
Table A 6.8 Times, in days, for which various minimum daily quantities of water must be provided from alternative sources, for the eight strongest earthquake scenarios.

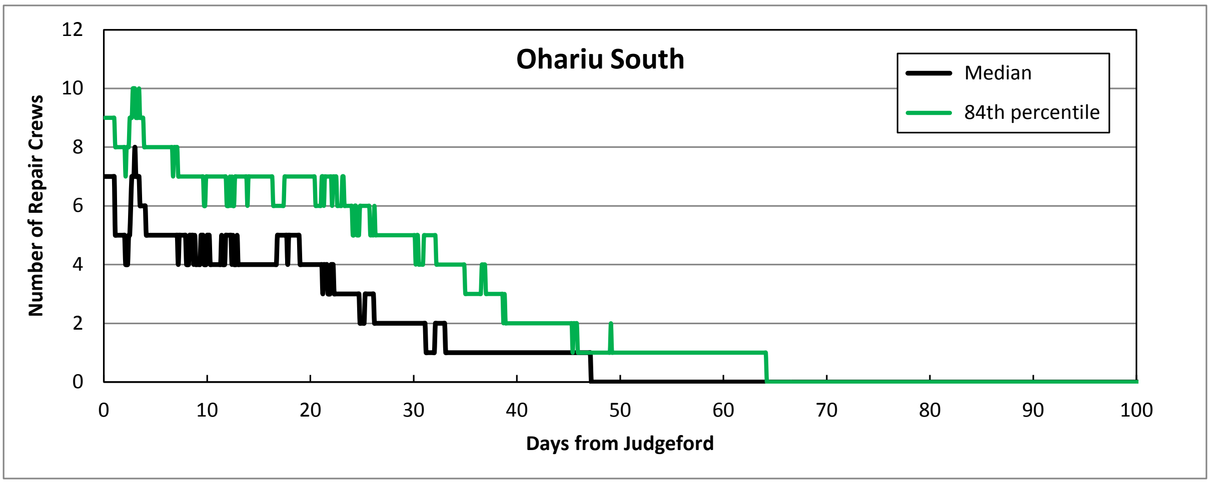
Shortfall Exceedance Level (litres/day)	Water Source: Whakatikei							
	Water Retained in Reservoirs Post-Event: 75%							
	Consumption Rate: 6 litres per person per day							
	Wellington Fault	Wairarapa 1855	Oharui South	Whitemans	Akatarawa-Otaki	Tararua	MM9	MM8
20,000	16	-	-	-	-	-	-	-
50,000	9	-	-	-	-	-	-	-
100,000	-	-	-	-	-	-	-	-
200,000	-	-	-	-	-	-	-	-
300,000	-	-	-	-	-	-	-	-
400,000	-	-	-	-	-	-	-	-
500,000	-	-	-	-	-	-	-	-
600,000	-	-	-	-	-	-	-	-
700,000	-	-	-	-	-	-	-	-
800,000	-	-	-	-	-	-	-	-
900,000	-	-	-	-	-	-	-	-
1,000,000	-	-	-	-	-	-	-	-
1,100,000	-	-	-	-	-	-	-	-
1,200,000	-	-	-	-	-	-	-	-
1,300,000	-	-	-	-	-	-	-	-
1,400,000	-	-	-	-	-	-	-	-
1,500,000	-	-	-	-	-	-	-	-
1,600,000	-	-	-	-	-	-	-	-
1,700,000	-	-	-	-	-	-	-	-
1,800,000	-	-	-	-	-	-	-	-
1,900,000	-	-	-	-	-	-	-	-
2,000,000	-	-	-	-	-	-	-	-
2,100,000	-	-	-	-	-	-	-	-
2,200,000	-	-	-	-	-	-	-	-
2,300,000	-	-	-	-	-	-	-	-
2,400,000	-	-	-	-	-	-	-	-
2,500,000	-	-	-	-	-	-	-	-
2,600,000	-	-	-	-	-	-	-	-
2,700,000	-	-	-	-	-	-	-	-
2,800,000	-	-	-	-	-	-	-	-
2,900,000	-	-	-	-	-	-	-	-
3,000,000	-	-	-	-	-	-	-	-

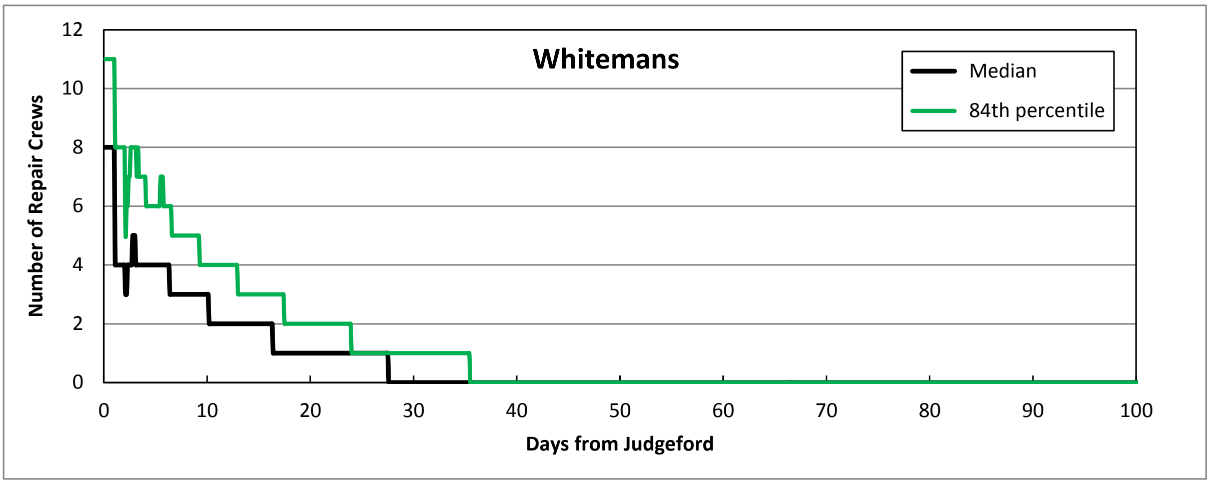
APPENDIX 7: INDIVIDUAL REPAIR-CREW PLOTS

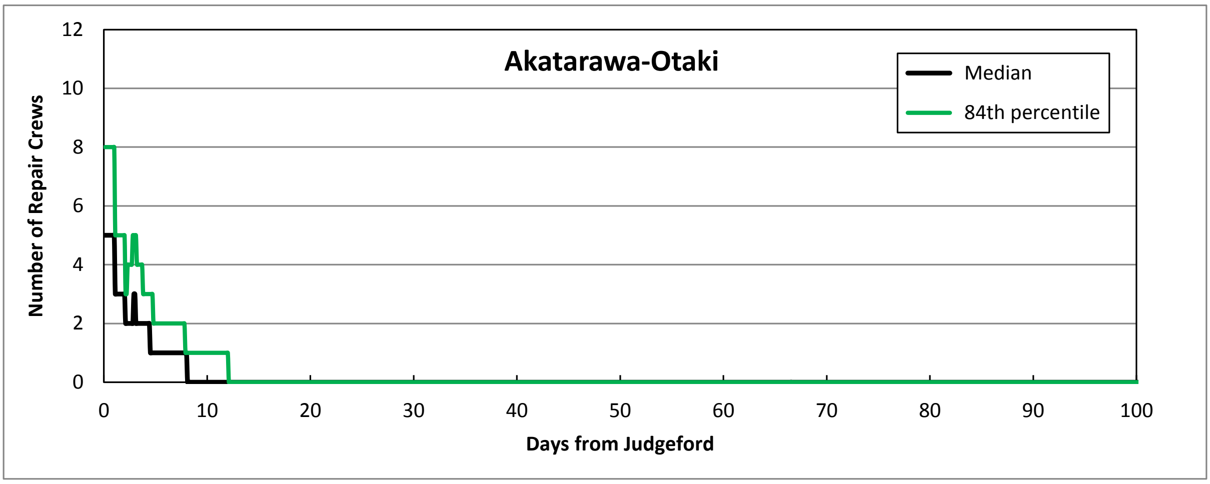
Repair-crew number vs time plots are provided for all nine scenario earthquakes. Both median and 84th percentile estimates are shown. See Section 6.8 for further information. The first nine plots are for the existing pipeline, and have a common Y-axis scale. The final plot is for a Wellington Fault scenario, assuming a network in which all pipes have been upgraded to modern welded steel or other construction of equivalent robustness.

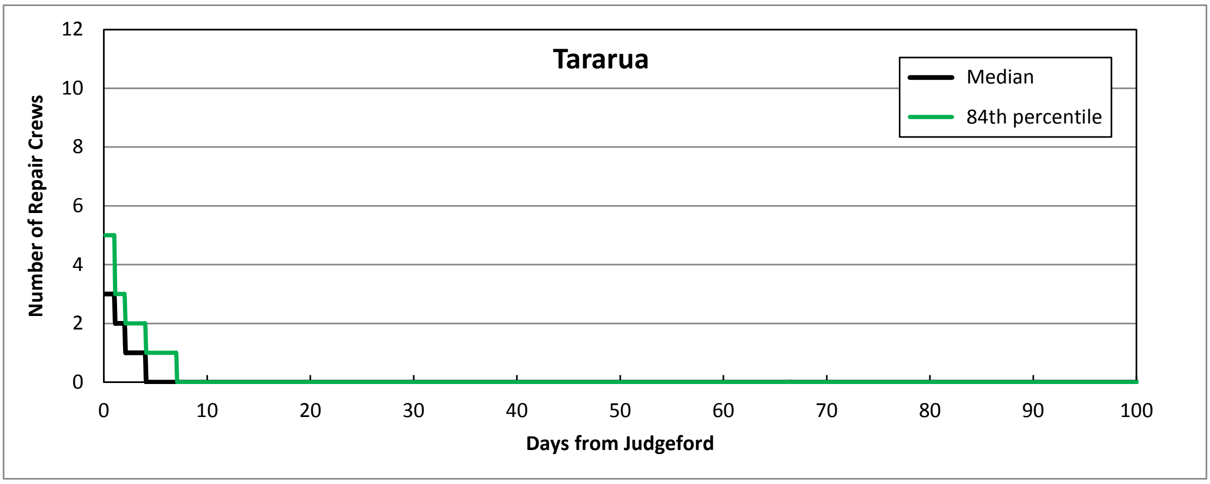


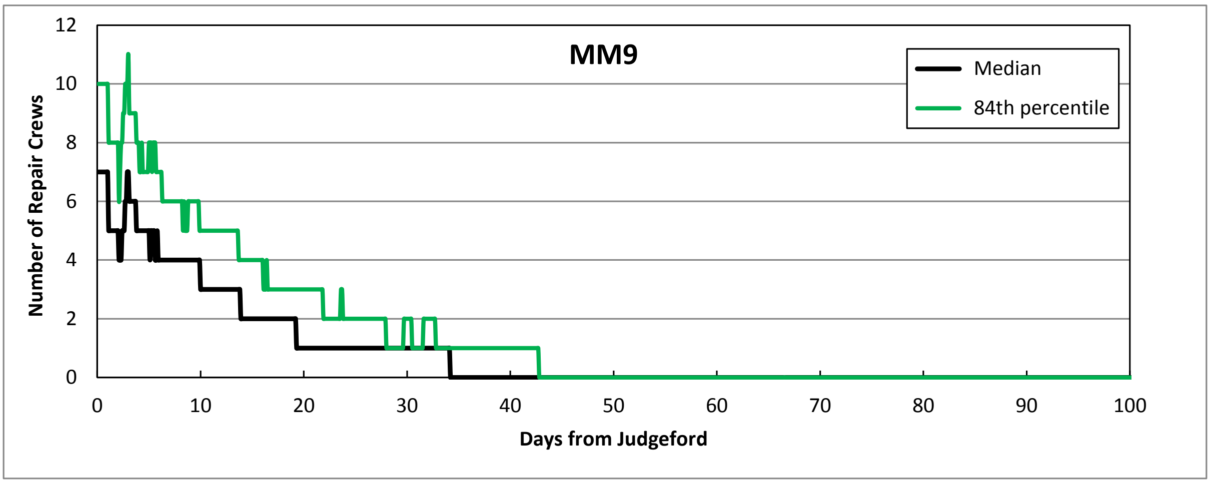




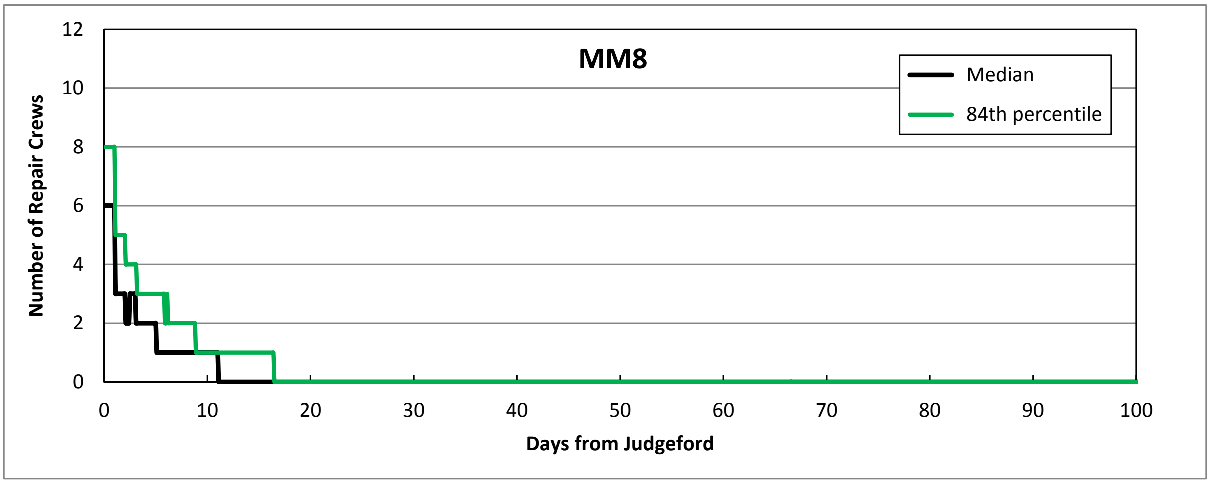

Whitemans
Median
84th percentile
Number of Repair Crews
Days from Judgeford
0
2
4
6
8
10
12
0
10
20
30
40
50
60
70
80
90
100


Akatarawa-Otaki
Median
84th percentile
Number of Repair Crews
Days from Judgeford
0
2
4
6
8
10
12
0
10
20
30
40
50
60
70
80
90
100

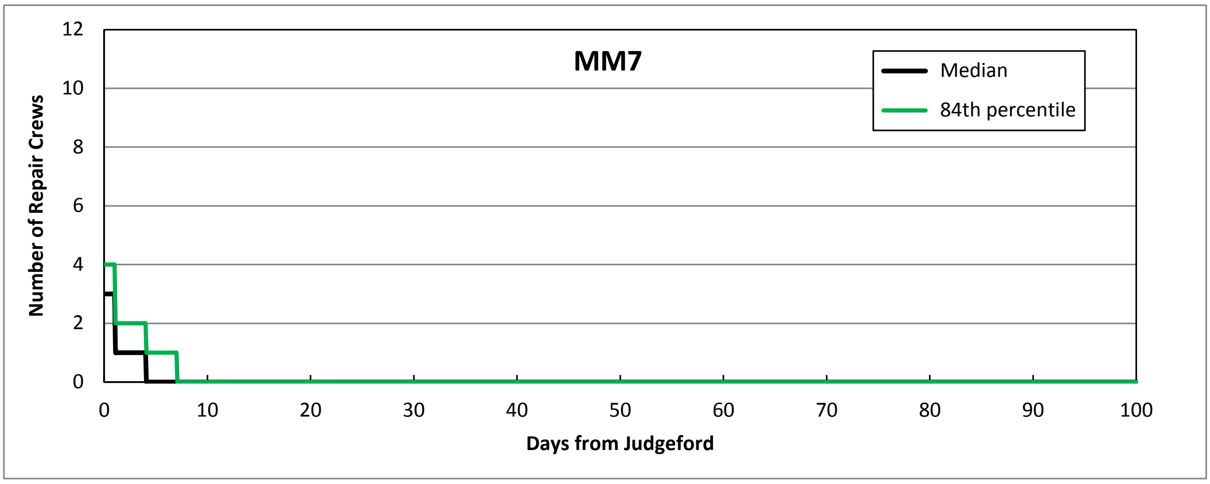

Tararua
Median
84th percentile
Number of Repair Crews
Days from Judgeford
0
2
4
6
8
10
12
0
10
20
30
40
50
60
70
80
90
100



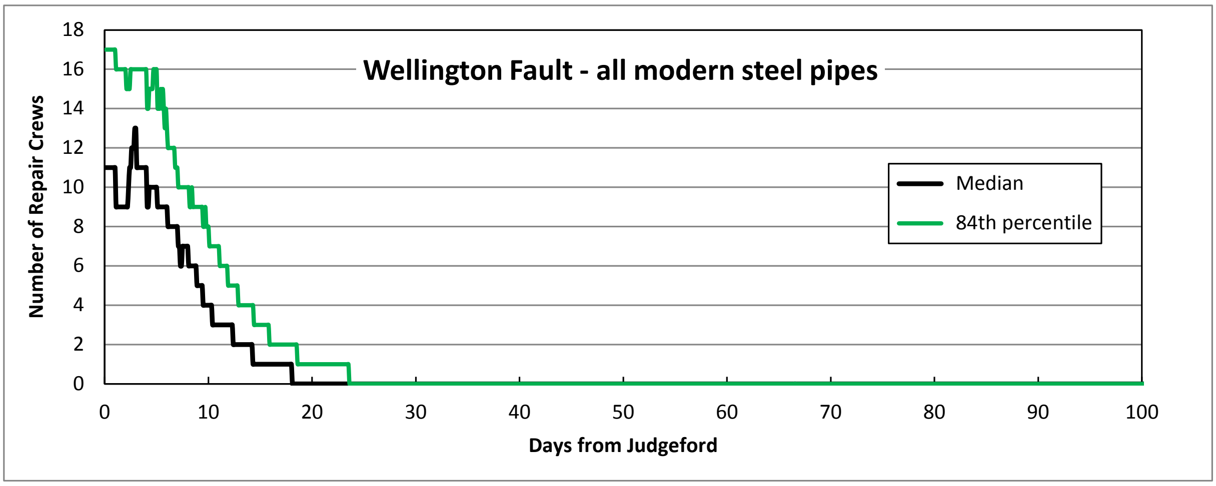
MM9
Median
84th percentile
Number of Repair Crews
Days from Judgeford



MM8
Median
84th percentile
Number of Repair Crews
Days from Judgeford



MM7
Median
84th percentile
Number of Repair Crews
Days from Judgeford


Wellington Fault - all modern steel pipes
Number of Repair Crews
Days from Judgeford
Median
84th percentile
0
2
4
6
8
10
12
14
16
18
0
10
20
30
40
50
60
70
80
90
100

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