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IMPACTS OF THE 14TH NOVEMBER 2016 KAIKŌURA EARTHQUAKE ON THREE WATERS SYSTEMS IN WELLINGTON, MARLBOROUGH AND KAIKŌURA, NEW ZEALAND: PRELIMINARY OBSERVATIONS

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ABSTRACT

We present preliminary observations on three waters impacts from the M_w7.8 14th November 2016 Kaikōura Earthquake on wider metropolitan Wellington, urban and rural Marlborough, and in Kaikōura township. Three waters systems in these areas experienced widespread and significant transient ground deformation in response to seismic shaking, with localised permanent ground deformation via liquefaction and lateral spreading. In Wellington, potable water quality was impacted temporarily by increased turbidity, and significant water losses occurred due to damaged pipes at the port. The Seaview and Porirua wastewater treatment plants sustained damage to clarifier tanks from water seiching, and increased water infiltration to the wastewater system occurred. Most failure modes in urban Marlborough were similar to the 2010-2011 Canterbury Earthquake Sequence; however some rural water tanks experienced rotational and translational movements, highlighting importance of flexible pipe connections. In Kaikōura, damage to reservoirs and pipes led to loss of water supply and compromised firefighting capability. Wastewater damage led to environmental contamination, and necessitated restrictions on greywater entry into the system to minimise flows. Damage to these systems necessitated the importation of tankered and bottled water, boil water notices and chlorination of the system, and importation of portaloos and chemical toilets. Stormwater infrastructure such as road drainage channels was also damaged, which could compromise condition of underlying road materials. Good operational asset management practices (current and accurate information, renewals, appreciation of criticality, good system knowledge and practical contingency plans) helped improve system resilience, and having robust emergency management centres and accurate Geographic Information System data allowed effective response coordination. Minimal damage to the wider built environment facilitated system inspections. Note Future research will include detailed geospatial assessments of seismic demand on these systems and attendant modes of failure, levels of service restoration, and collaborative development of resilience measures.

INTRODUCTION

We present preliminary observations of impacts on three waters systems (potable, waste and storm water) in wider metropolitan Wellington, the Marlborough region, and Kaikōura, Aotearoa/New Zealand, resulting from the M_w7.8 14th November 2016 Kaikōura Earthquake. Significant ground surface rupture and seismic shaking [1-5], and secondary co-seismic phenomena such as landslides [6], caused damage and disruption to regional transportation and electrical infrastructure lifelines [7, 8], while seismically-induced soil liquefaction had localised impacts [9]. The three waters systems (herein 'three waters') in urban centres and smaller rural communities in affected regions were also impacted to varying degrees, with both immediate and longer-term consequences for system functioning and levels of service.

Important insights into three waters seismic performance were previously gained through the 2010-2011 Canterbury Earthquake Sequence (CES), as well as general trends (albeit to different infrastructure component specifics) in worldwide earthquakes [10-13]. Particularly for the 22nd February 2011 Christchurch Earthquake, the close proximity of causative faults to Christchurch generated strong ground motions [14, 15], and triggered widespread liquefaction and permanent ground deformation that impacted the natural and built environments [16, 17]. Both transient and permanent ground deformation led to severe and extensive damage to the potable, wastewater and stormwater systems in Christchurch City and surrounding population centres [18-28]. Key nodes such as supply wells, reservoirs, pump stations and treatment plants were impacted; distribution/collection networks showed distinct patterns of damage corresponding to severity of transient and permanent ground deformation; and the age and construction materials of buried pipelines and their constituent components. Lessons from the CES three waters impacts and recovery provide a significant body of knowledge with which to understand patterns of damage resulting from the 14th November 2016 Kaikōura Earthquake, including key similarities and differences between these events.

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Building upon other initial lifelines reconnaissance assessments [29], presented below are more detailed preliminary observations of impacts on the three waters systems of Wellington, the Marlborough region and Kaikōura in particular, gathered during field investigations and system assessments conducted by researchers, asset managers and consultants. These observations lay the foundation for ongoing research on three waters systems, to help inform implementation of earthquake resilience initiatives.

STUDY AREA OVERVIEW

Here we focus on the wider metropolitan Wellington, Marlborough (specifically, the town of Blenheim, the rural Awatere Water Supply irrigation scheme in the Seddon area, and a rural irrigation scheme in the area around Ward), and Kaikōura (Figure 1). Wellington is Aotearoa/New Zealand's capital, and is the country's second most populous city with a population of ~405,000. As the seat of national government and home to its ministries, disruption to Wellington's essential services has significant potential ramifications in the event of disaster. Prior to 14th November 2016, initiatives were underway to address the city's three waters seismic resilience, as understanding of potential impacts from proximal fault rupture and seismic shaking has improved [30-32].

In Marlborough the resident populations of Blenheim, Seddon and Ward are ~30,000, ~500 and ~900, respectively. Blenheim is a regional centre servicing agricultural, horticultural, forestry and viticultural industries in the wider area. It is also a transit hub for Aotearoa/New Zealand's State Highway 1 and a main trunk railway line, and accordingly has many tourist and visitor accommodation businesses. Both Ward and Seddon have local agricultural industry serviced by local businesses, with Seddon also having salt and lime production operations.

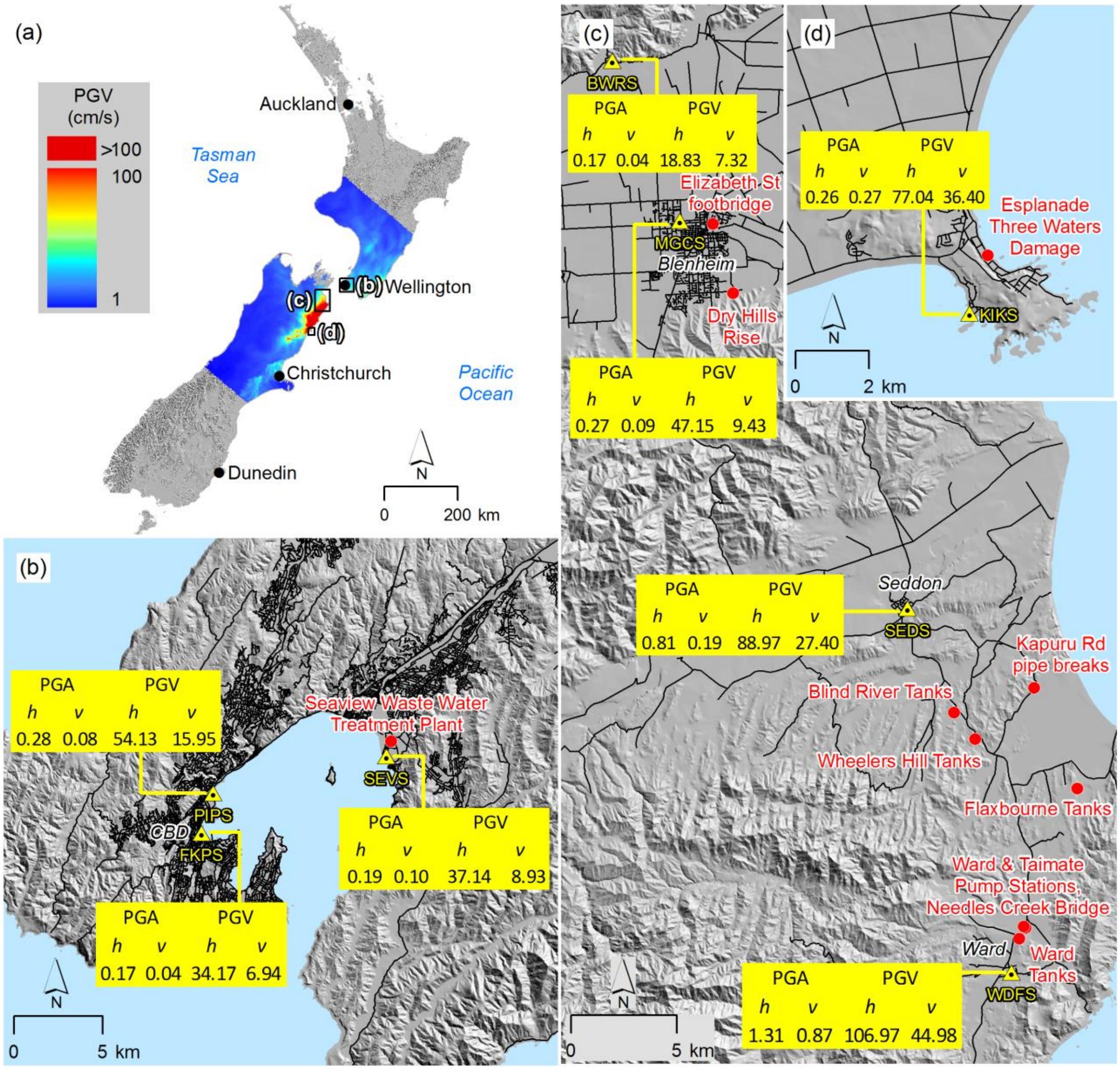

Figure 1. (a) Modelled maximum Peak Ground Velocity (PGV; cm/s) [4, 5] for central Aotearoa/New Zealand from the 14th November 2016 Kaikōura Earthquake. Locations of study areas (b-d) are shown. (b-d) Three waters damage locations; Selected Strong Motion Station locations (yellow triangles) shown, with measured Peak Ground Acceleration (PGA) and PGV values (cm/s); horizontal (h) and vertical (v) motions shown. Road networks also shown. (b) Wellington study area, with location of Seaview Wastewater Treatment Plant (Figure 2). SEVS = Seaview Station, FKPS = Frank Kitts Park Station, PIPS = Aotea Quay Pipitea Station. (c) Marlborough study area, with documented damage locations in Blenheim (Figure 3). See Figures 4-5 for Blind River Tanks observations and Figures 6-8 for Ward damage observations. BWRS = Waikakaho Road Station, MCGS = Marlborough Girls College Station, SEDS = Seddon Fire Station, WDFS = Ward Fire Station. (d) Kaikōura study area, see Figure 9 for Esplanade damage observations. KIKS = Kaikōura Station.

Across the Marlborough region there were prior impacts from the M_w5.7 21st July 2013 Seddon Earthquake, and the M_w6.6 16th August 2013 Lake Grassmere Earthquake [33, 34]. Following some minor damage observed in these prior events, the M_w7.8 14th November 2016 Kaikōura Earthquake afforded the opportunity to re-visit the region to observe impacts on Blenheim facilities, storage and pipe systems in Seddon, and a private water supply scheme in Ward.

Kaikōura's resident population is ~2,000. Kaikōura is also an agricultural service centre for pastoral and dairy farming in its hinterland, but is also a domestic and international tourist destination renowned for its mountainous coastal landscapes, opportunities for outdoor activities and to view marine wildlife, and for seafood delicacies. Kaikōura's transient population increases in summer with seasonal hospitality workers and tourists.

Seismic demand placed on the Wellington, Marlborough and Kaikōura areas by the M_w7.8 14th November 2016 Kaikōura Earthquake can be visualised with modelled regional maximum Peak Ground Velocity (PGV; cm/s) values [4-5] (Figure 1a). In the Wellington area, at Seaview the measured horizontal and vertical Peak Ground Acceleration (PGA) values were 0.19 g and 0.10 g, respectively; horizontal and vertical PGV values were 37.14 cm/s and 8.93 cm/s, respectively. In the Wellington Central Business District (CBD), horizontal and vertical PGA values ranged 0.17-0.28 g and 0.04-0.08 g, respectively; horizontal and vertical PGV values ranged 34.17-54.13 cm/s and 8.93-15.95 cm/s, respectively (Figure 1b). In the Blenheim area, horizontal and vertical PGA values ranged 0.17-0.27 g and 0.04-0.09 g, respectively; horizontal and vertical PGV values ranged 18.83-47.15 cm/s and 7.32-9.43 cm/s, respectively (Figure 1c). In Seddon, measured horizontal and vertical PGA values were 0.81 g and 0.19 g, respectively; horizontal and vertical PGV values were 88.97 cm/s and 27.40 cm/s, respectively (Figure 1c). In Ward, measured horizontal and vertical PGA values were 1.31 g and 0.87 g, respectively; horizontal and vertical PGV values were 106.97 cm/s and 44.98 cm/s, respectively (Figure 1c). Shaking levels are ~2 times stronger than experienced during the 2013 Lake Grassmere event, especially in Ward [33]. In Kaikōura, measured horizontal and vertical PGA values were 1.31 g and 0.87 g, respectively; horizontal and vertical PGV values were 106.97. The high values in Ward and Kaikōura reflect their close proximity to fault rupture zones, and lower values experienced in Seddon, Blenheim and Wellington reflect their increasing distance from the primary rupture zone [1, 2]. Some variability in shaking levels in the vicinity of each strong motion station is expected due to different soil conditions and topography. Below we describe initial functional impacts from this seismicity on three waters systems, with commentary on system performance and service level restoration.

THREE WATERS IMPACTS

Wellington

Potable water system

The Te Marua water supply reservoir ponds have a diameter of ~37 m, are ~4.5 m high and are usually full. They are relatively modern and as expected by asset managers there was no major structural damage to these or treatment plants, and connection pipes were undamaged. System assessments by Wellington Water showed that earthquake shaking disturbed accumulated sediments in reservoirs and pipes, resulting in increased turbidity through the network. In some parts of the region, increased turbidity was sufficiently high to change the water color, with attendant reports from customers. Supply was stopped temporarily to allow the sediments to settle, and affected customers were advised to run their taps until the water was clear. Within 24-30 hours from the event the turbidity level returned to normal and customer complaints had reduced. There was a slight increase in *E. coli* after the earthquake, but that went back to normal within 2 days.

In the days following the event, Wellington Water inspected all key components of the potable water network including supply wells, treatment plants, reservoirs, pump stations, bulk water pipes, and mains. Surface expression of liquefaction was observed around the Gear Island Wellfield in Petone, Wellington, with damage to the concrete well aprons. The single damaged reservoir was the Tawa Reservoir, which had minor non-structural cracking; this reservoir is ~50 years old and was empty at the time of the event because it was being retrofitted. The Silverstream pump station building roof was severely damaged by a falling pine tree.

Across the distribution network up to 15 pipe breaks occurred on different pipe material types and sizes. Most of the pipe breaks and fittings damage were deemed to be caused by poor installation practices or existing weaknesses. For example, a hydrant in Jervois Quay, Central Wellington, was damaged due to poor installation practice resulting in hydrant baseplate bolts popping out. Across Wellington, major breaks (bursts), and some other minor pipe failures, resulted in increased leakage from the network. After the earthquake, water usage in Wellington CBD (Figure 1b) increased from 15,000 to 20,000 m^3/day. In the week prior to 14th November 2016, water usage at Wellington port ranged 400 – 1,000 m^3/day. With ground deformation and pipe damage at the port, in the first 2 days after the earthquake 14,000 m^3 was lost, which equated to an increase in Wellington City water usage of 9 percent. Because Wellington Water supplies the port at a single point, supply was stopped to prevent further leakage.

Compared to usual maintenance budget expenditure prior to the event, there was an increase in maintenance costs after the Kaikōura Earthquake due to the discovery of new minor faults and damage; future work will address in detail the impacts on costs. Damage to the network has continued to manifest, with reports of leak-induced ground failure and network water loss [35, 36], and leak detection programmes are ongoing.

With respect to longer-term recovery and resilience, monitoring is required to determine effects of demolition and construction activities on the wider network. There were initial concerns that partial demolition of the Queensgate Mall in Lower Hutt, and in particular demolition of building foundation piles, would affect the Hutt Aquifer, but subsequent investigation showed this not to be an issue. Multiple-hazards can also hinder restoration; flooding the day after the Kaikōura Earthquake closed some of the state highways and isolated parts of the potable water network, and creating problems with regard to mobilising repair crews or equipment [37]. Wellington Water's post-event response planning now accounts for future closure of state highways in the region due to earthquake and other impacts, and repair equipment and spare parts have been located on both sides of the Wellington Fault to mitigate likely access issues.

Wastewater system

The four wastewater treatment plants in Wellington region are. Moa Point (Wellington), Seaview (Upper Hutt and Lower Hutt; see Figure 1a for location), Porirua and Western (Karori). In the Seaview and Porirua treatment plants, water seiching in the secondary clarifier tanks damaged the stilling well curtains and their holding rings that baffle mixed liquor influent to aid settling (Figure 2).

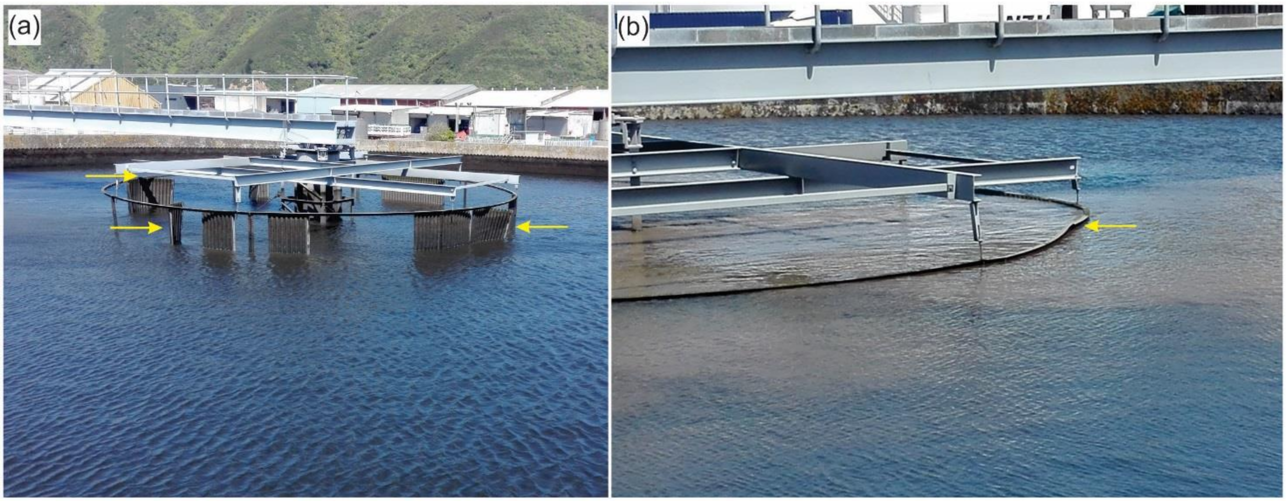

Figure 2. Damage at the Seaview Waste Treatment Plant. See Figure 1a for location. (a) Displaced curtain panels in the stilling well in one of the Seaview treatment plant clarifiers. (b) Damaged ring that holds the curtains of the stilling well in one the Seaview treatment plant clarifiers (Photos: Hutt Valley Water Services Ltd).

From an electricity interdependency perspective, the earthquake cut power from the Seaview treatment plant for ~3 hours, and ~8 pump stations lost mains power. Mobilising portable generators was not possible due to the tsunami inundation warning that was in place after the event. The tsunami warning also meant inspecting any of such as outfalls in the coastal areas was not possible due to safety concerns.

After the earthquake, in the Wellington CBD additional water infiltrated the wastewater network through damaged pipes, with increased pump run hours recorded at a number of pump stations. Most infiltration was sourced from the port area that experienced ground deformation and pipe damage. As a result, there was noticeable in-flow increase at Moa Point treatment plant to 50-70 L/s, above the normal flow of 770 L/s. A programme of Closed-Circuit Television (CCTV) wastewater pipe inspections was initiated to assess condition and identify damage locations – as a result repair work has been undertaken to allow flows to Moa Point to return to near-normal by the end of February 2017. As of March 2017, some pump stations were still experiencing over-flow, although the exact sources of this extra flow are still to be determined.

Wider earthquake response and recovery operations had implications for protection of the network. For example, with demolition of the earthquake-damaged multi-storey building at 61 Molesworth Street, Wellington, risks to the Wellington City wastewater interceptor that passes below the building had to be carefully managed during the demolition process, as there is no redundancy in that part of the network.

Wellington Water Support Services

From the event response perspective, a key issue for Wellington Water was damage to their offices within IBM House in Petone, Lower Hutt, which led to staff having to operate from both temporary office and locations and homes for ~2 months after the event, posing challenges to normal business processes and the coordination of repairs and restoration. This highlights the importance of business continuity planning to support effective operations post-event, including decentralising some operations and increased investment in information technology to allow staff to work efficiently following such disruption.

Marlborough

Water supply systems

The 2013 earthquake events had led to replacement of some less resilient systems, and the replacement systems generally performed well. Water supply wells in Blenheim appeared to have survived undamaged, but increased turbidity rendered them temporarily unusable and required flushing for ~1 hour. In the township of Renwick, 10 km west of Blenheim, high turbidity was not that different from that seen in flood events. Disturbance of sediment led to blockage of a flow meter by small sand-sized particles. Despite Renwick having a high proportion of heavily degraded AC wastewater pipelines with poor structural integrity, they did not suffer a particularly high break rate. Temporary repairs had been effective in restoring at least partial service within a week by engaging one to two repair crews. Isolation valves had been useful for managing the system. This included some post-event installation of valves. Overall, there were ~25 breaks across 170 km of 25-250 mm pipelines in Blenheim only (approximately 1.5 breaks per 10 km), mainly on Asbestos Cement (AC) pipes. Figure 3 shows lateral displacement at the Elizabeth Street footbridge in Blenheim, resulting in complete failure of the AC pipeline suspended from the bridge, deformation of galvanized steel pipelines or ducts suspended on a damaged bridge.

Storage tanks in the rural water supply systems in the Ward and Seddon areas experienced some damage (Figures 1, 4-6). Older ferrocrete concrete tanks in Ward installed in the 1950s suffered structural damage although one of the tanks remained partly operational. Newer tanks (both concrete and Polyethylene (PE)) appeared to have performed well. Where new concrete tanks had cracked this was minor and is expected to seal through autogenous healing. Concrete stave tanks had been damaged but remained serviceable, although with some additional leakage through cracks, some of which are likely to heal over time. If structural integrity has not been compromised, patch repair of damaged concrete may extend the useful life and defer the need for replacement. The tanks were generally located on hill tops, and hence were on good ground, and were not affected by liquefaction. As the hillside slopes were generally gentle, and the tanks were set back from the hillside slopes, the tanks were not affected by slope instability. Some cracks in the ground inferred to be due to slope displacements were observed

Figure 3. (a) Elizabeth Street Footbridge, Blenheim. The bridge carries a DN100 galvanized steel duct and an Asbestos Cement (AC) water supply pipeline. The galvanized steel duct was deformed and AC pipeline was damaged by displacement of the bridge approach. (b) Elizabeth Street Footbridge. AC water pipe damaged by contacting the concrete pillar (yellow arrow), and has sheared off at the collar (red arrow). Collars under the bridge show evidence of separation. (c), Blenheim. Detail of Elizabeth Street Footbridge AC water pipe sheared off at the collar. (d) Dry Hills Rise, Riverlands. Differential settlement of adjoining components observed in a stormwater pumping station. This is believed to be due to consolidation of poorly compacted fill saturated by rain, rather than by flotation or by liquefaction settlement. See Figure 1 for locations.

just outside the tank compound at the Blind River tank site. While modern tanks had performed well, some connecting pipework had failed due to excessive movement. Failures included pipes pulling out of tanks, Polyvinyl Chloride (PVC) solvent cemented joints being partially separated in tension, PE pipes partially pulling out of the tanks, fracture of threaded connections between metal and plastic pipes, loss of seal at over-deflected rocker pipe assemblies. The Wheelers Hill and Blind River tanks were both relatively recently built and both showed very similar forms and distribution of damage. High horizontal earthquake accelerations combined with the high vertical accelerations in the Ward area appear to have led to displacement/rotation of the relatively small tanks that were not tied into the ground, leading to failure of the in-ground pipe connections between the tanks. The earthquake ground shaking may have been amplified at these hilltop sites during topographical effects. Observed displacements included translational and rotational movement of the tank relative to the buried pipeline system, displacement of the tank roof relative to the tank. Buried boxes (e.g. valve chambers) around the tanks appeared to remain in place while the tank rotated, leading to displacement of the pipes relative to the box even where the pipe or fittings remained undamaged. Newer tanks were more resilient and the pipework layout allowed them to be bypassed quickly to restore some service.

Across Blenheim, Ward and Seddon there were many failures in AC pipelines and relatively few in more modern systems, although some older AC pipelines that were previously believed to be vulnerable due to deterioration had survived without apparent damage. Despite Renwick having a high proportion of heavily degraded AC pipelines with poor structural integrity, they did not suffer a particularly high break rate due to small ground motion amplitudes in this region. Damage tended to be clustered and was more concentrated in the lower Awatere network and Ward where there were much higher ground motion amplitudes; six failures occurred in an AC pipeline in Ward near a damaged bridge, and four AC pipeline failures had occurred near on Kapuru Road near Lake Grassmere (Figure 1). The pipelines at Lake Grassmere included DN50 AC pipelines that appeared to have failed in bending next to the joints and a deteriorated DN100 line that had longitudinal cracking. Longitudinal cracking usually results from excessive pressure, but this pipe had apparently failed from contact between the pipeline where it crossed a culvert. The DN50 pipelines were relatively shallow-buried and would probably have failed in compression at the joints if buried deeper. Four AC pipe breaks in low-lying paddocks within a small section in the Lake Grassmere area indicate that damage was concentrated in areas of relatively soft ground with brittle AC pipes, even in the absence of liquefaction or lateral spreading. Other reported failures included failure of joints at thrust blocks – possibly due to failure of the thrust block – and two failures at galvanized service connections on AC pipelines near Lake Grassmere.

In addition to the Elizabeth Street footbridge in Blenheim, damage occurred at several other pipe service bridges across the region. For example, pipelines between relatively rigid bridge abutments and the ground were damaged as observed at the Needles Creek bridge site along State Highway 1, north of Ward (Figure 7). Observed damage where pipes connect to bridges and other structures suggest more flexibility of the pipeline system would be important. A water supply well pump in Ward failed when movement of the water supply well relative to the nearby pump house resulted in the hold down bolts pulling out of the concrete base and displacement of the pump despite the presence of a rubber bellows joint. While this had caused an outage, it was believed that this had prevented failure of the pump itself (Figure 8).

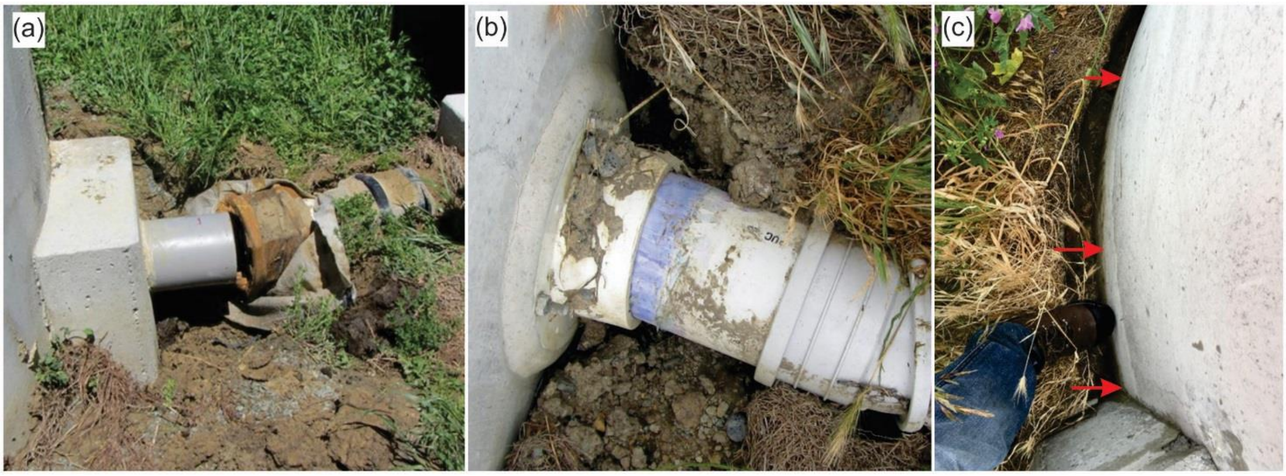

Figure 4. (a) Blind River Tanks. Failure of gibault on PVC due to excessive displacement (Photo: Marlborough District Council). (b) Blind River. Shear failure of solvent-cemented PVC joint on overflow pipeline (Photo: Marlborough District Council). (c) Wheelers Hill Tanks. Translational and rotational movements of tanks were observed. See Figure 1 for locations.

Figure 5. (a) Blind River Tanks. Failure failed threaded fitting due to horizontal displacement. (b) Flaxbourne, failed threaded fitting (Photo: Marlborough District Council). (c) Flaxbourne, failed threaded fitting and rotated galvanized pipe. The pipes rotated due to lateral ground movement. The seal around the pipes into the tanks has been compromised by the movement (Photo: Marlborough District Council). (d) Wheelers Hill. Pipe pulled out of tank wall due to relative displacement (Photo: Marlborough District Council). See Figure 1 for locations.

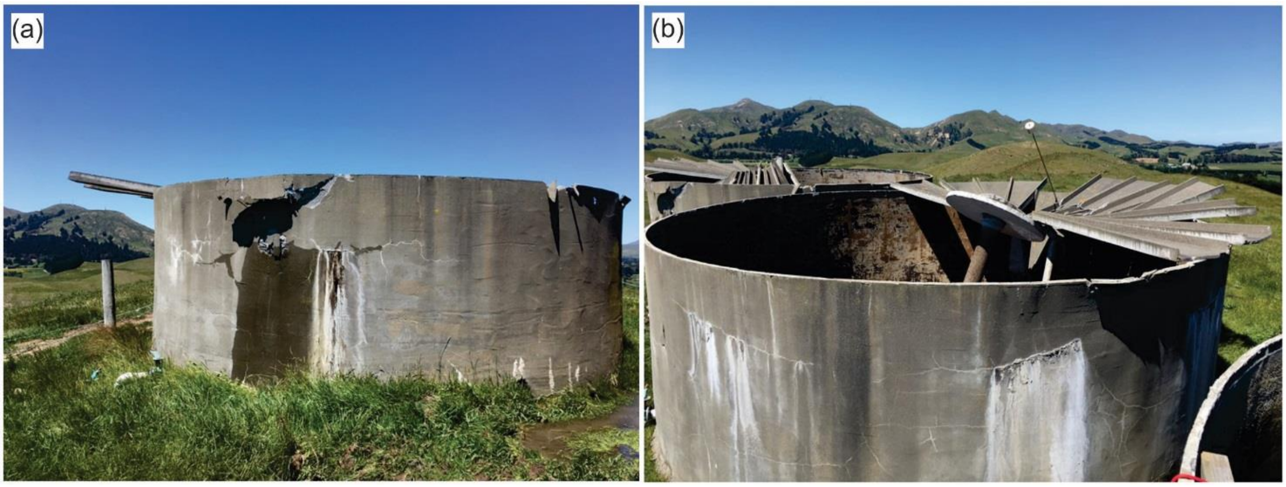

Figure 6. Ferrocement tanks at Ward, installed in the 1950s. (a) The thin ferrocement walls have failed and the segmented roof has collapsed (Photo: Marlborough District Council). (b) The segmented roof and the central pillar have collapsed (Photo: Marlborough District Council).

Figure 7. East side of the Needles Creek Bridge north of Ward on the SH1, viewed from the north. Original freshwater pipelines have failed and been replaced temporarily with ductile pipes (in black) (Photo: X. Bellagamba).

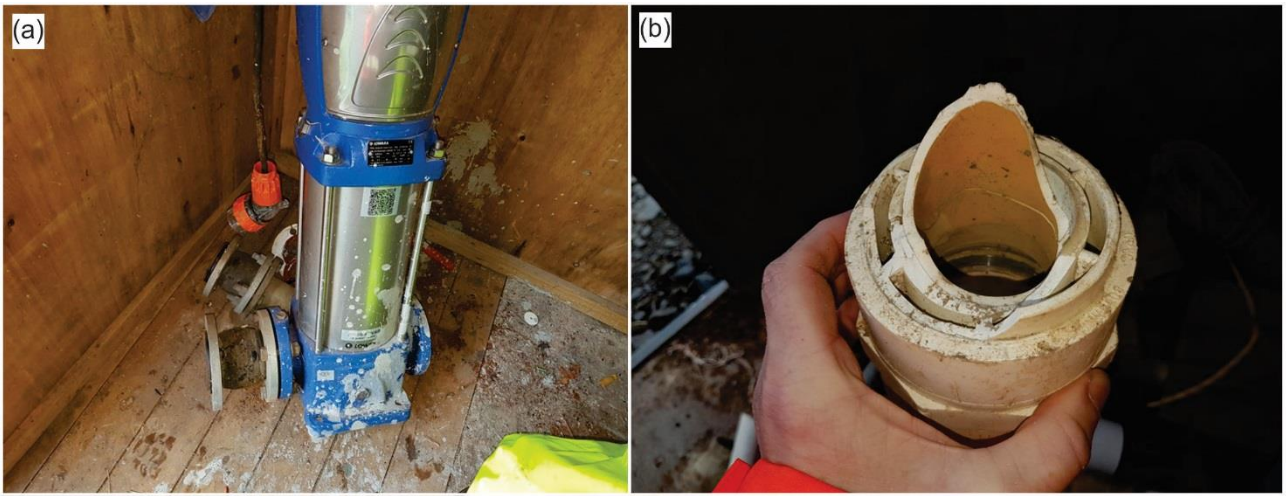

Figure 8. (a) Grundfoss pump in pump house at Ward. When the water supply well was displaced, the galvanized steel pipework pulled on the pump. The bolts holding the pump to the concrete slab then failed, causing the pump to topple. (b) Failed PVC pipework from the Taimate water supply well near Ward. The pump house building slid on its base, causing the water supply well pipework to fail.

System redundancy (dual pipelines, ring mains) and the ability to isolate damaged parts of the system helped manage the system after the events. In Ward, for example, despite severe damage to two of the three main concrete reservoirs, damage to the pump house and some of the bridge pipes, the situation was still quite manageable after the Kaikōura event, since the majority of houses had local water storage for ~36 hours.

Wastewater systems

Despite poor soil conditions and moderate shaking levels (~0.35 g; See Table 1) experienced towards the end of Hardings Road, Riverlands, there was no damage due to liquefaction or otherwise to the wastewater treatment plant located there. Marlborough District Council staff noted that earthenware pipeline failures in Blenheim in 2013 had shown an orientation effect with most failures oriented east-west; however any such effect remains to be verified by geospatial analysis and there were no orientation effects seen in the 2016 Kaikōura event. Many lines had been inspected with CCTV since 2013, and repeat surveys showed new damage in the majority of pipelines surveyed since 14th November 2016. Cured-In-Place pipe linings had been used in the Blenheim CBD to minimise disruption, although restoring service connections was an issue. Patch repairs were used as temporary fixes for local pipe collapse or other severe damage, to allow full line replacement or repair to be deferred. There were some concerns over the effectiveness of lining deformed pipelines, and of the ability of the liner to withstand being installed past protruding sharp fragments, and to survive longer term in contact with sharp fragments. Where pipelines had been lined since 2013, these appeared to be still functioning.

Lessons learnt

In the Marlborough region, having a robust emergency management centre in a safe location with a reliable power supply and good computer systems with Geographic Information System (GIS) data allowed effective coordination of the response for three-waters systems. Loss of power or limited power availability could have provided a major barrier to effective coordination of the response. Availability of power for mobile devices should also be considered (e.g. portable chargers for recharging phones and other devices when power is not readily available).

Modern systems (pipelines, tanks and other structures) generally performed better than older ones. The majority of failures seen were either in older systems known to have higher vulnerability, or were due to severe displacements that affected both old and new systems. Pipe joint failures were observed at the interface of structures (tanks and bridges) and in-ground pipelines, highlighting the need for flexibility of the pipeline systems connecting with structures. Brittle pipelines appears to be more vulnerable when located in areas of soft ground. Tanks often located at hilltops experience amplified ground shaking in earthquakes, and it is important that design of these tanks allow for the amplified shaking as well as vertical ground accelerations.

Good asset management practice for operational purposes (including updating of information, renewals for operational purposes, appreciation of criticality, good knowledge of the system and a practical contingency plan) helped improve overall system resilience. For example, exposure to soft aggressive water meant that galvanized steel and copper pipes had been replaced with PE, which has good tolerance to earthquake loading, so service line damage was low. Earthquake emergency shut off valves were set to trigger at 0.2 g, but the maximum reported PGA at valves was 0.18 g, so they did not trigger. Since there were no major system failures this did not result in any major issues, but a review of the settings may be prudent.

Kaikōura

Water supply systems

The Kaikōura supply system is a combination of water supply wells and hilltop reservoirs, which feed a reticulated supply to Kaikōura township and surrounding suburbs. The 14th November 2016 event shut down all power to the system, and in combination with severe damage to buried services the reticulated supply reduced to zero. At the time of the event one reservoir was full, but would have lasted only one day at normal demand (I. Walker, pers. comm.). Kaikōura District Council (KDC) initiated a rapid programme of assessment and repairs, and by 15th November was able to inform residents which streets had supply. Residents without supply were encouraged to approach others on streets that had supply to access water. By 19th November, water stations and had been set up at various locations around the township by the New Zealand Defence Force, as well as a mobile public shower unit. Due to system supply shortages, residents were instructed to not use showers in their homes, and to minimise all other water use. By 25th November supply had been sufficiently restored in the township to enable use of flush toilets and showers, although the community was asked to shower only every second day, and to not use washing machines or dishwashers. This reflected the fragility of the restored supply, as well as the inability of the waste water system to receive residential grey water (see below). Residents were also instructed to not water their gardens. By the beginning of December supply had been restored to the Kincaid area north of Kaikōura township, but ongoing system leaks did require restrictions to be reinstituted until repairs could be completed; water was distributed in tankers to these residents, and by 4th December reticulated supply had been reinstated. Full supply was restored to the Kincaid and Fernleigh water schemes by 9th December. Throughout the period 14th November to 22nd December a boil water notice was placed on all reticulated supply, and public water conservation messages were broadcast. These restrictions were lifted for most of Kaikōura township, suburbs and outlying supply schemes on 23rd December, due to system repairs and use of chlorination, although some individual households were required to continue boiling water before use. People returning to houses unoccupied since 14th November were urged to run water for 10 minutes and flush toilets, and conduct inspections of pipes and tanks on their properties. For damaged pipes on residential properties, owners were required to attend to these issues on their own initiative, sometime using temporary overlanding of supply (Figure 9a).

Ongoing repairs and discovery of leaks did require further restrictions and safety notices to be issued in January and February 2017. For example, construction work carried out on the Waimangarara River water intake to improve the water flows necessitated a dirty water notice being issued to some areas, and other repair programmes required the urgent issuing of further boil water notices. People with their own private water supplies were urged to look for obvious signs of damage to pipes and water supply well heads, and ensure their supply has been tested for the presence of bacteria by accredited laboratories.

Damage to the pressurised reticulated system posed immediate problems for firefighting capability in the days after 14th November. Despite the presence of one full hilltop reservoir, its distribution connections were damaged and this supply was inaccessible. The Kaikōura Volunteer Fire Brigade had one full water tanker available, but this would have been depleted rapidly in even a small fire event. Due to time of year, warmer weather meant that home fires were not in use, and a total fire ban was issued across the area. Loss of electrical power to the area also mininised fire risk. The loss of firefighting water supply was therefore mitigated, but this issue could be problematic in future events in colder weather where home fires are being used at the time of a damaging earthquake.

Wastewater and sanitation issues

Wastewater pipes experienced significant damage, compromising most of the system that is reticulated to the treatment plant north of Kaikōura township. As a result residents were advised to use available portaloos already present in Kaikōura, or to use buckets or holes dug in gardens to dispose of human waste. On November 18^{th} chemical toilets were delivered by the New Zealand Defence Force to be distributed to all households in Kaikōura, although the necessary supply of chemical solution for them was delayed by 2-3 days. Residents were informed of chemical toilet dump station locations (Figure 9b). Portaloos were also distributed across the township, and by November 24^{th} were sited so that there was a portaloo within 250 m from every property (Figure 9b). Due to the inability of the wastewater pipes to function from the 14^{th} to 24^{th} November, residents were urged to not flush toilets despite the return of reticulated portable water supply over this time. The entry on grey water into the system was also discouraged by urging residents to not use washing machines and dishwashers, and to otherwise minimise water use to prevent overloading the system. Environmental contamination by wastewater was recognised as a significant issue from 14^{th} November, with attendant restrictions on entering waterways swimming in the sea (Figure 9c), and restriction on water use were also aimed at reducing these environmental impacts. Throughout this time, the New Zealand Red Cross was present advising the community on basic sanitation measures to prevent illness. By November 25^{th} wastewater repairs had progressed to the point where toilets were able to be flushed in Kaikōura township; further repairs enabled the removal of portaloos from some areas by 1^{st} December.

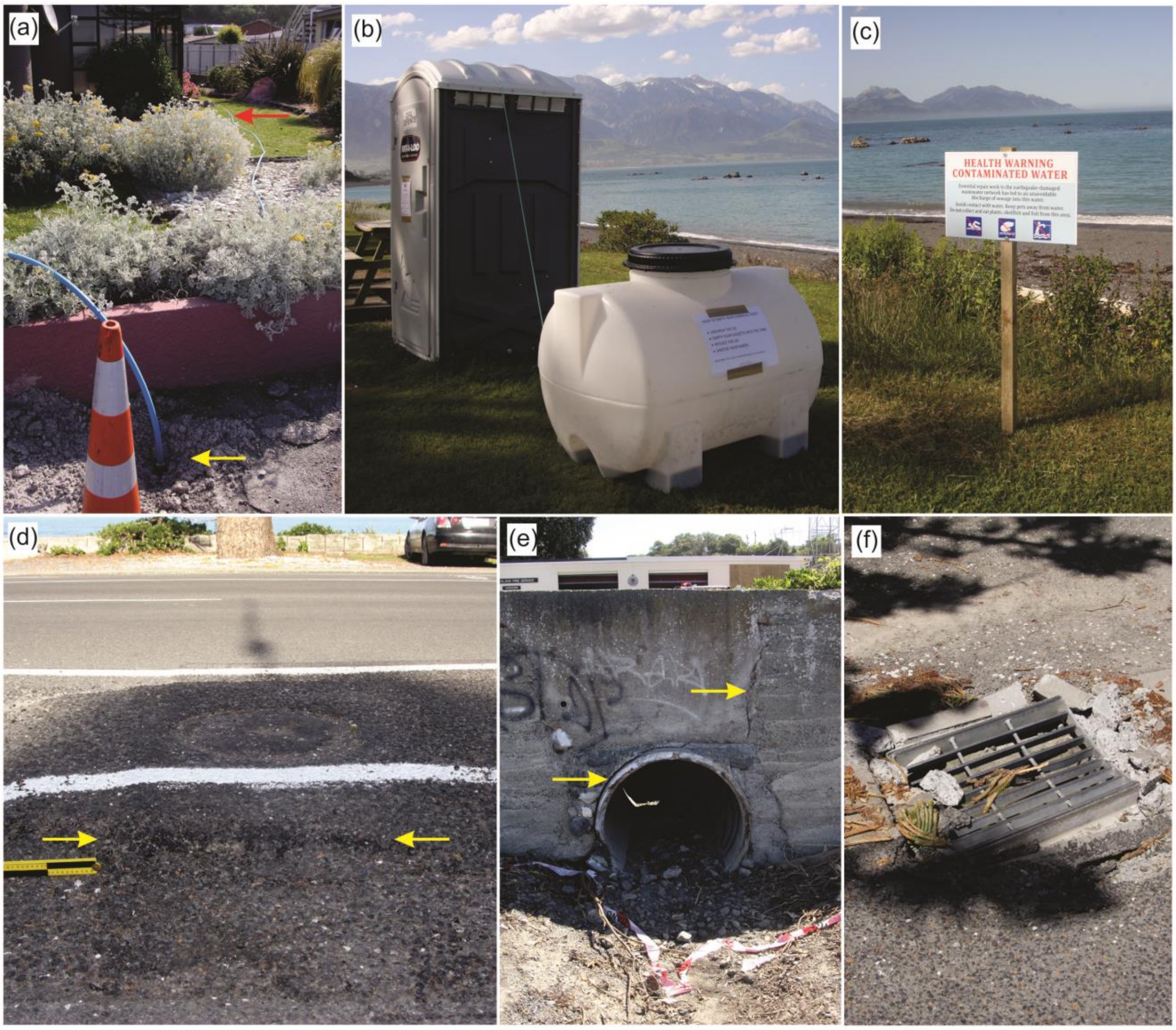

Figure 9. Three waters impacts along The Esplanade, Kaikōura. (a) Temporary overlanding of domestic water supply from the street connection (yellow arrow) to the house's kitchen area (red arrow). (b) Portaloo (left) and chemical toilet dump station (right). (c) Contaminated water warning, discouraging swimming, fishing and shellfish collection. (d) Differential manhole movement of ~3 cm (arrows). (e) Cracking in retaining wall (arrows) surrounding stormwater culvert. (f) Damaged concrete gutter due to impact by steel stormwater grate. (Photos: M.W. Hughes).

Through December 2016, repairs on the wastewater system continued and wider functionality returned, but residents were advised to retain their chemical toilets in the event of further failures. On 21st December the KDC requested residents abstain from using the system that night so that functionality of the wastewater treatment plant could be assessed at low flows, and subsequently wider functionality continued to be restored. However, as of 12th February 2017, residents were being advised that the system was still vulnerable to rainfall inflows and seismic aftershocks, and in the event these occurred there needed to be minimal use of the network to reduce introduction of greywater.

There was little physical manifestation of system damage along roadways, although at least one manhole was noted to have experienced slight differential movement through the 14th November event (Figure 9d). Pipe condition assessments via CCTV were occurring from the days after the event, supported by experience and expertise gained from condition assessments conducted in Christchurch through the 2010-2011 CES [21].

Stormwater system

Transient ground deformation imposed demands on roadways and attendant stormwater infrastructure in Kaikōura township. These effects manifested as cracked and shatters road dish channels and gutters, cracking around culverts that issue to the beach (Figure 9e), and disintegration of concrete surrounding steel stormwater grates (Figure 9f). Damage to these features may pose further issues, as overland flow in rainfall events will infiltrate the road subgrade, causing potentially further degradation of these corridors.

SUMMARY AND FUTURE RESEARCH

We have presented preliminary observations on three waters impacts from the M_w7.8 14th November 2016 Kaikōura Earthquake on wider metropolitan Wellington, urban and rural Marlborough, and in and around Kaikōura township. The three waters systems in these areas experienced widespread and significant transient ground deformation in response to seismic shaking generated by the event. Permanent ground deformation was more localised, in contrast to extensive liquefaction and lateral spreading phenomena that occurred in Christchurch City and surrounding centres during the 2010-2011 CES [18-28].

In Wellington, main impacts to potable water quality were from increased turbidity due to seismic stirring of fine sediment in the system. Leaks occurred that led to significant water losses, particularly around the port area that suffered ground deformation and attendant damage to pipes. Wellington's wastewater treatment plants in Seaview and Porirua had damage in secondary clarifier tanks due to water seiching. Increased water infiltration to the wastewater system from damaged pipes was also evident. Interdependencies with electricity became apparent when pumps stations were unable to be brought back online, and the threat of tsunami also compromised immediate assessments of pump stations. Disruption to business operations highlights the importance of continuity planning for effective responses post-event.

In Marlborough, most of the failures seen in Blenheim, Seddon and Ward were similar to those seen in the 2010-2011 CES. In the 2016 event, some structures experienced both rotational and translational movements that contributed to failure, notably in the supply tanks at Wheelers Hills and Blind River. This highlights the importance of allowing for flexibility in pipe connections with structures such as tanks and bridges. System resilience appeared to have improved since the 2013 events, mostly as a result of progressive renewals that can be attributed to good asset management practices. Recovery was aided by a secure emergency building with independent power supply, accurate records of the pipeline system and networks, and short-term management and repair of systems was aided by well-placed control valves.

In Kaikōura, damage to reservoirs, and pipes and fittings, led to loss of water supply and compromised firefighting capability. Wastewater damage led to environmental contamination, and necessitated restrictions on greywater entry into the system to minimise flows. Damage to these systems necessitated the importation of tankered and bottled water, boil water notices and chlorination of the system, and importation of portaloos and chemical toilets. Stormwater infrastructure such as road drainage channels was also damaged, which could compromise condition of underlying road materials.

Based on these preliminary observations, and similar observations made through the 2010-2011 CES, the following initial recommendations can be made:

- In the course of system repairs and ongoing maintenance and renewals programmes, flexible connections for pipe infrastructure should be considered for bridges, reservoirs and tanks, and access chambers.
- The vulnerability of pipe fittings and connections should be assessed, and where possible these should be replaced with more ductile or robust materials. Due to damage being observed in soils prone to liquefaction and lateral spread, these areas of anticipated ground deformation in future events will require specific liquefaction geotechnical considerations in system design.
- Detailed reviews of system interdependencies should be conducted, in particular dependencies between three waters networks and electricity supply. This should include assessments of the adequacy of backup generation.
- Asset managers should develop contingency plans in the event initial system assessments are hindered by multiple or cascading hazards e.g. earthquakes followed by tsunami alerts or flood events.

Future research on three water systems impacts from the M_w7.8 14th November 2016 Kaikōura Earthquake will include:

- Collation of GIS datasets of potable, wastewater and stormwater systems from relevant asset management organisations; datasets will include asset construction materials and ages. Also to be collated are break locations, failure modes, and repair timelines to assess restoration processes.
- Spatial analyses to correlate failure modes with intensities of transient and permanent ground deformation.
- Detailed determination of interdependencies between three waters systems and other infrastructure lifelines such as electricity, communications and transportation.
- Collaboration with asset managers to develop resilience indices that address components, networks and community levels of service in the event of further seismic impacts.

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