Environmental Impacts of Christchurch and Kaikoura Earthquakes: Lessons Learned to Inform Resilient Strategies

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Abstract

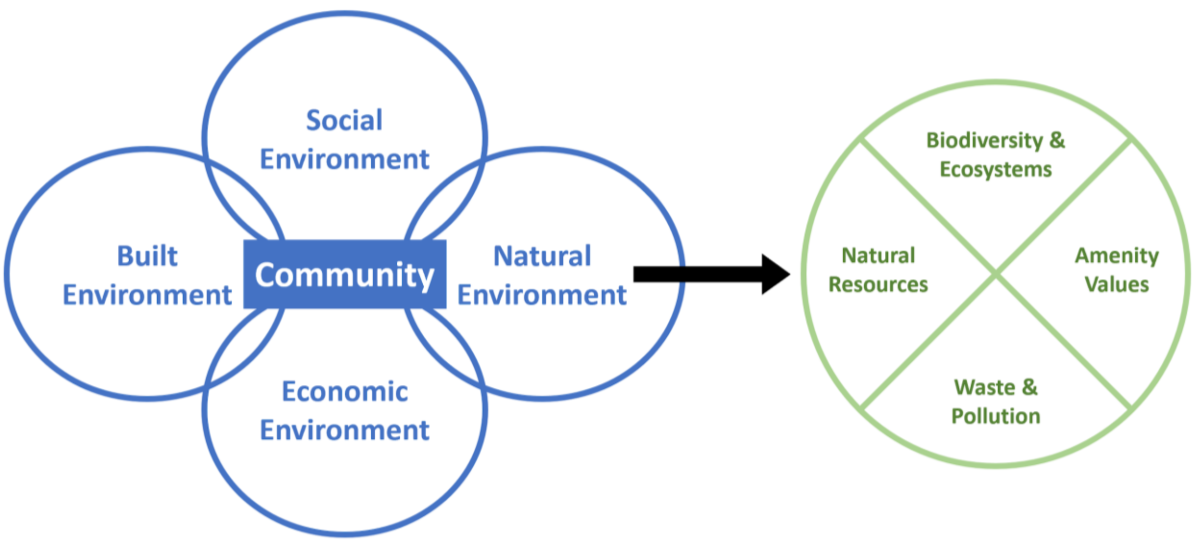
On May 5 - 11, 2019, program participants from the Earthquake Engineering Research Institute (EERI) Learning From Earthquakes (LFE) Travel Study Program went to New Zealand to study recovery and resiliency in Christchurch, Kaikoura, Marlborough, and Wellington from the 2010-2011 Canterbury earthquake sequence and 2016 Kaikoura earthquake. Through the lens of the natural environment, the team investigated impacts in each region to the natural environment subcategories of landscape, local fauna, and natural resources. The team then developed recommendations to inform resilient strategies moving forward for each subcategory in the natural environment. Common themes between all three included the need to ensure pre-existing networks for implementation and action post-event, a thorough understanding of the resources, and adaptability of systems.

1. Introduction

The 2019 Learning From Earthquakes (LFE) Travel Study Program was co-hosted by the Earthquake Engineering Research Institute (EERI) and QuakeCoRE - New Zealand Centre for Earthquake Resilience. Twenty-five participants from around the world traveled to New Zealand to evaluate the long-term recovery and resilience of communities affected by the 2010-2011 Canterbury earthquake sequence and the 2016 Kaikoura earthquake. Participants in the 2019 LFE program included young professionals and students from the fields of geotechnical and structural engineering, risk and recovery modeling, seismic hazard, geophysics, sustainable materials/structures, public policy, public health, and social impacts - resulting in a multidisciplinary team with diverse backgrounds and approaches to the issue of earthquake resilience.

The resilience framework for this evaluation was established by the New Zealand Ministry of Civil Defence & Emergency Management, in "Focus on Recovery: A Holistic Framework for Recovery in New Zealand" (2005). The components of this resilience framework were the built, social, economic, and natural environments. These components all contribute to the health and resilience of a community (Figure 1, left).

The co-authors of this report were assigned to the Natural Environment group, meaning that their observations of long-term resilience were to be viewed through the lens of impacts and interactions with the natural environment. The Ministry of Civil Defence & Emergency Management subdivided the natural environment into interrelated components of natural resources, biodiversity and ecosystems, waste and pollution, and amenity values. The resilience framework and natural environment components were summarized in the right half of Figure 1, below in green.



Source: Ministry of Civil Defence & Emergency Management, "Focus on Recovery: A Holistic Framework for Recovery in New Zealand"

Figure 1. Resilience framework and components of the natural environment.

From 5-11 May 2019, the team traveled to Christchurch, North Canterbury, Kaikoura, Blenheim, and Wellington, meeting with local, regional, and national representatives from numerous agencies involved in immediate response, emergency management, rebuild, and long-term recovery. The discussions and interactions with everyone the team met were enlightening and immensely appreciated. The combination of presentations, tours, and community engagement in support of this undertaking was truly an exceptional experience in learning about real-world development of community earthquake resilience.

Based on observations of long-term recovery following the Canterbury earthquake sequence and Kaikoura earthquake, the team re-evaluated the components of the Natural Environment (Figure 2) and established the following components specific to their observations:

- Landscape-related Damage and Impacts ("Knowing the land")
- Impacts on Local Fauna ("Considering the fauna")
- Impacts on Natural Resources ("Valuing water resources")

The following sections describe the team's observations from Christchurch and Kaikoura through these components of the natural environment, focusing on lessons learned regarding readiness, reduction, response, and recovery. In some cases, recovery efforts involved incorporating infrastructure improvements in order to carry out the notion of 'building back better.' Applications of these observations and lessons learned for cities engaged in earthquake preparedness, specifically the readiness and response aspects, are discussed. Wellington was used as an example case for implementation of long-term resilience strategies informed by experiences in past events.

Figure 2. Re-evaluation of components of the natural environment, based on the team's observations in Christchurch and Kaikoura from 5-11 May 2019.

Recognizing that a holistic approach to resilience planning often improves long-term recovery, the team closed this report by discussing a multi-hazard, systems approach to pre-event planning, inter-agency coordination, collaboration with the local indigenous population, and public scientific literacy.

2. Observations from Christchurch and Kaikoura Earthquakes

The 2010-2011 Canterbury earthquake sequence and 2016 Kaikoura earthquake occurred on previously undiscovered faults, and caused tremendous damage to the landscapes of their affected areas. In Kaikoura, the impacts of the 2016 event on the natural environment were generally attributed to large-scale landslides, rockfalls, surface fault rupture, and coastal uplift. The environmental effects of the 2010-2011 Canterbury earthquake sequence on Christchurch were primarily related to widespread liquefaction.

Impacts on the Landscape

Observations concerning the impacts of seismic events on the New Zealand landscape were conducted as part of the 2019 LFE travel study program as it related to the 2010-2011 Canterbury earthquake sequence and 2016 Kaikoura earthquake.

Observations from the 2010-2011 Canterbury Earthquake Sequence

The 2010-2011 Canterbury earthquake sequence consisted of four main earthquake events (4 September 2010 Darfield, 22 February 2011 Christchurch, 13 June 2011, 23 December 2011) and hundreds of aftershocks greater than M_w 4.0 (GeoNet – GNS Science). The team observed the short- and long-term effects that liquefaction had on the area.

- ***Liquefaction***

One of the most striking impacts of the 2010-2011 Canterbury earthquake sequence was widespread liquefaction along the Avon River and in the eastern areas of Christchurch. Liquefaction observations from the 2010 Darfield earthquake and 2011 Christchurch earthquake are shown in Figure 3. Liquefaction damage from the 2011 Christchurch earthquake was extensive throughout the city. While its effects on the built environment were severe and extremely well-documented, the environmental effects of such a significant liquefaction and lateral spreading event were also important, and could be felt for a longer period of time. Some of the most significant natural environment effects of the liquefaction were on water quality, due to drastic increases in suspended silt and sediment in waterways, as well as discharge of sewage due to lifeline failure (Potter et al. 2015). In addition to the disruption of vital services for residents, the degradation in water quality also severely impacted local flora and fauna, and highlighted the need for mitigation measures in order to avoid longer-term impacts to affected species.

Roughly 900,000 tonnes of surface ejecta were removed from Christchurch. The degree of earthwork required for such an undertaking, in combination with the amount of demolition needed for many of the damaged/destroyed buildings, resulted in a significant degradation in short-term air quality in the greater Christchurch area (Potter et al. 2015).

An ongoing land use issue in Christchurch, almost a decade after the 2010-2011 Canterbury earthquake sequence, concerned what should be done with the “Red Zone” area near the Avon River where the liquefaction effects were most severe. Due to the continuing severe liquefaction hazard in the area, homes in the Red Zone had been demolished and the area was currently maintained as open space rather than an area of rebuild. However, it was unclear as to whether the area would be turned into a designated public recreational area or “green belt,” a measure that had been suggested as a means for increasing the amenity value of the area.

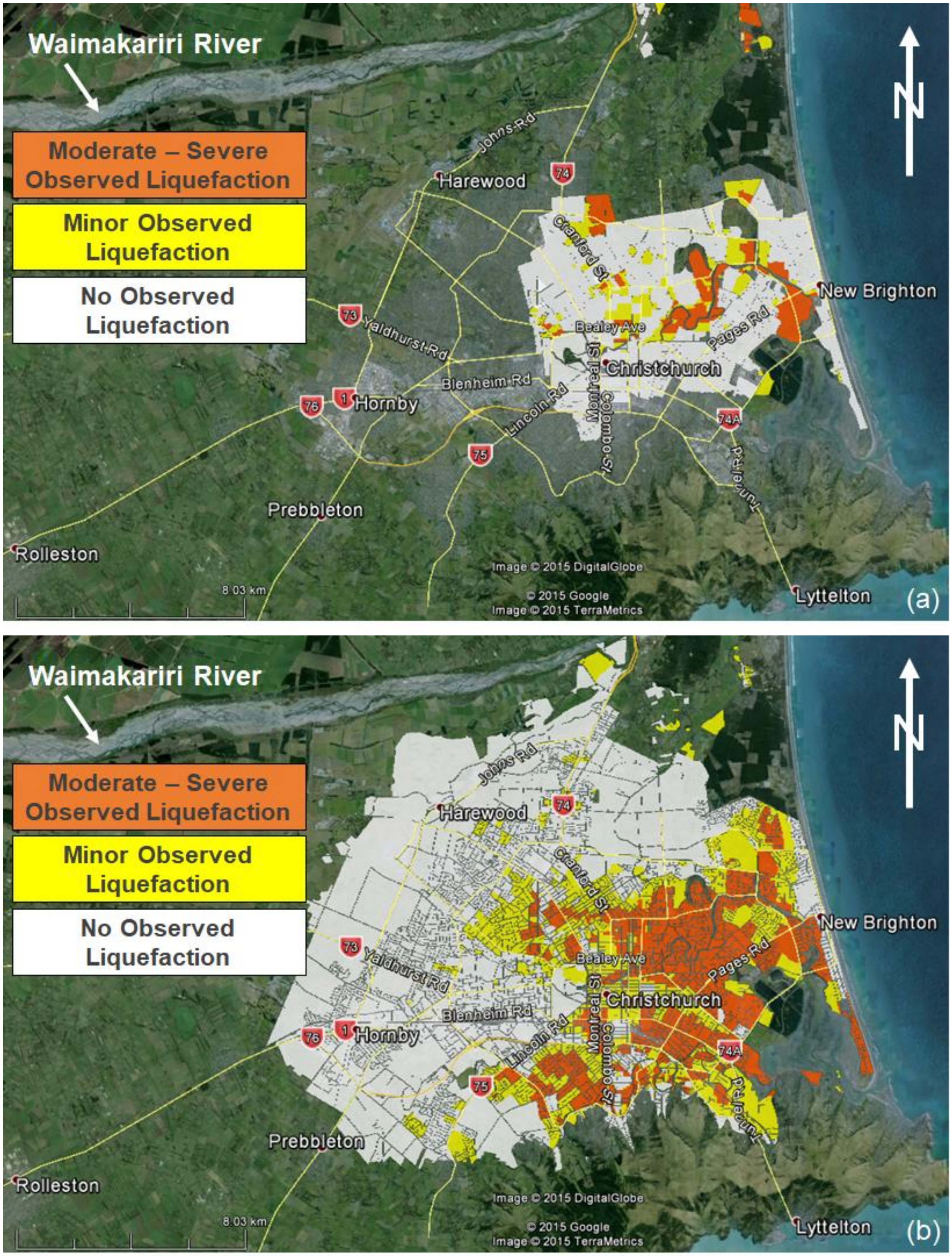


Figure 3. Liquefaction observations following (a) the M_w 7.1 4 September 2010 Darfield earthquake and (b) the M_w 6.2 22 February 2011 Christchurch earthquake as interpreted from aerial photography, from the New Zealand Geotechnical Database (after Beyzaei et al. 2018).

Observations from the 2016 Kaikoura Earthquake

The M_w 7.8 Kaikoura earthquake that occurred 14 November 2016 caused damage in both the South and North Islands of New Zealand. During the 2019 LFE Travel Study Program, the major impacts to the landscape and natural environment were observed to be landslides/rockfalls and surface fault rupture.

- ***Landslides/Rockfalls***

The 2016 Kaikoura earthquake occurred in a region of New Zealand with coastal and mountainous terrain. The earthquake initiated tens of thousands of landslides varying from a few cubic meters to millions of cubic meters of debris over an area of about 10,000 km^2 (Dellow et al. 2017, Kaiser 2017). At least 190 of the estimated landslides were known to have affected infrastructure and communities (Kaiser 2017). Due to the widespread nature of the affected area, the impacts of the landslides on the natural environment were numerous and varied, and resulted in a wide range of responses. During the LFE program, the damaging effect of landslides was observed in the context of a sheep farm and a major roadway.

The sheep farm was located on 2,000 hectares with approximately 3,500 sheep sold for merino wool as well as meat and 500 cows sold for meat. In particular, one large landslide occurred on the farm and formed a landslide dam with a volume of about 6 million cubic meters, shown in Figure 4. This landslide, known as the Leader Landslide (Massey et al. 2018), buried the farm's water pump system, dammed a river to create a lake, introduced increased levels of silt into the water sources on the farm, and damaged fences. The buried water pump system supplied stock water for all the farm animals, and was therefore an immediate cause for concern. In response, the farm owners needed to front an estimated $200,000 to install a gravity system to flow from a spring in order to provide water for the farm animals. The design and construction of the gravity system took about 3 months to become operational. The new gravity-fed system was more reliable and energy efficient than the old system, which made it an example of 'building back better' post-disaster.

(a) (b)

Figure 4. Lidar measurements (a) taken to quantify the volume displaced by the Leader landslide (b) that buried a structure on the sheep farm where the landslide occurred. Photos taken May 2019 as part of the LFE travel study program.

A large landslide occurred north of Kaikoura at Ohau Point causing a large volume of debris to cover a major roadway (State Highway 1) along the coast, as shown in Figure 5(a). The landslide limited access to communities connected via the blocked route for as long as one year. The rebuilding process was an extensive effort that involved at least 1,200 workers and an accelerated construction timeline. Removal of the landslide debris took 6 months where some debris was screened for fill, and an estimated 650,000 cubic meters was placed in dump sites. In order to mitigate the effects of unstable slopes, netting was anchored and covered the slope (Figure 6(a)) and barriers were built along the newly constructed roadway (Figure 6(b)). Figure 6 shows several examples of the barriers that were constructed along the roadway in response to the observed and anticipated slides, and the type of barrier construction used. In an effort to build back better, a viewpoint was constructed for visitors traveling along the coastal route and a wildlife crossing was built underneath the roadway to improve access to upstream habitats, shown in Figure 7.

(a) (b)

Figure 5: Landslide debris blocking a major roadway (State Highway 1) north of Kaikoura at Ohau Point (a) [Massey, 2018] and Ohau Point after roadway reconstruction (b). Photos taken May 2019 by authors as part of the LFE travel study program.

(a) (b) (c) (d)

Figure 6: Mitigation techniques for landslides and rockfalls. Netting and slope stabilization (a), barriers along roadside with different heights (b), a barrier stopping landslide debris (c), barrier construction type (d). Photos taken May 2019 as part of the LFE travel study program.

(a) (b)

Figure 7: Improvements made during reconstruction of the roadway (RH1) include a viewing and parking area (a) and a wildlife access point (b). Photos taken May 2019 as part of the LFE travel study program.

- ***Surface Fault Rupture***

The Kaikoura earthquake caused a large number of mapped and unmapped faults to rupture compared to previous seismic events, and visible surface damage was observed for at least 12 ruptured faults (Hamling, 2017). During the LFE program, damage due to surface rupture on the Leader Fault was observed, and the effect of the damage on the farm productivity was assessed. In addition, uplift along the coastline at Ohau Point was observed to affect the relative position of the waterline.

At the previously described sheep farm, surface rupture on the Leader Fault caused ponding and uplift damage to the landscape. An initial 3-meter-high fault scarp that slowly eroded over time was observed along with other evidence of uplift. In addition, several areas with low-lying depressions were formed where standing water accumulated throughout the landscape. The effect of the damage on farm productivity was mainly due to broken fence lines. At the time of the LFE program, fence lines were still not completely repaired years after the earthquake. Moreover, the fence repair was not covered by the submitted insurance claim and therefore became an additional expense for the farm owners. Following the earthquake, the damaged fence lines allowed the thousands of farm animals to roam beyond their allocated areas. One unforeseen result was that the sheep mated with rams roaming from a neighboring farm to produce an unexpected 400 lambs the year following the earthquake.

(a)

(b)

Figure 8: Surface rupture of the Leader Fault. An initial 3-meter-high fault scarp that has eroded over time (a) and evidence of water accumulating in depressed areas that formed (b). Photos taken by authors in May 2019 as part of the LFE travel study program.

Figure 9: Evidence of uplift observed on the sheep farm from surface rupture of the Leader Fault. Photo taken by authors in May 2019 as part of the LFE travel study program.

Coastal uplift was observed due to the 2016 Kaikoura earthquake at Ohau Point, which lowered the waterline along the coast. Looking forward, the observed uplift may contribute to offsetting the impacts of sea level rise on coastal infrastructure in the region.

Impacts on Local Fauna

While landscape changes due to the earthquakes created risk to man-made infrastructure, these changes also had significant impacts on the local fauna. The lens of the natural environment in earthquake resilience extends beyond a people-focused view and pays particular attention to native species, one of New Zealand's treasures, or *taonga*. Awareness of local fauna includes consideration of all creatures on the land, in the air, and in the surrounding offshore areas.

The surface rupture and landslides caused by the 2016 Kaikoura earthquake damaged livestock fences on farms, which led to interactions between different livestock, from different farms. As discussed about the sheep farm, for example, these interactions led to an early reproduction season of the livestock, and the unexpected newborns created strain in farm management.

The 2016 event also caused major coastal landslide and rockfall near Ohau Point, a natural culvert with an inland waterfall that served as a nesting and breeding place for the local seal population. While the damage to the road did not cause major casualties for the human population, the seal nesting ground was covered by debris. The earthquake occurred right after the seal breeding season, and many newborn seals were killed. This loss resulted in a decline of the local population. The debris covering their nesting ground was later removed by a hurricane, undoing some of the damage caused by the earthquake.

The Kaikoura event also caused coastal uplift and submarine landslides. Changes in sub-water landform resulted in disruptions to the local fishery industries. The uplift and submarine slides drastically affected local crayfish populations. However, this uplift may have helped mitigate the expected effects of climate change driven sea level rise.

Impacts on Water Resources

Although natural resources vary by region, water resources are likely to be critical to every community. Observations made throughout the LFE program indicated that water resources were a critical aspect of the earthquake damage, response, and recovery throughout the communities visited in New Zealand. Accordingly, water resources were selected as the focus of reported observations as it relates to the 2010-2011 Canterbury earthquake sequence and 2016 Kaikoura earthquake.

Immediately after the 22 February 2011 earthquake, the Ministry of Defence and Emergency Management estimated 80% of the Christchurch population (over 300,000 people) did not have access to reticulated water. Moreover, the potential for untreated sewage from the damaged wastewater system to contaminate the drinking water supply led to a 'boil water notice' to be issued and subsequently officially lifted on April 8th. A considerable effort was made to restore the water pipe network, it took up to 30 days in some cases to provide residents with access to reticulated water (Ministry of Health, 2012). Figure 10 shows the pipe network in Christchurch as it relates to liquefaction observed after the 22 February 2011 event, which illustrates the vulnerability of water supply systems to earthquake damage.

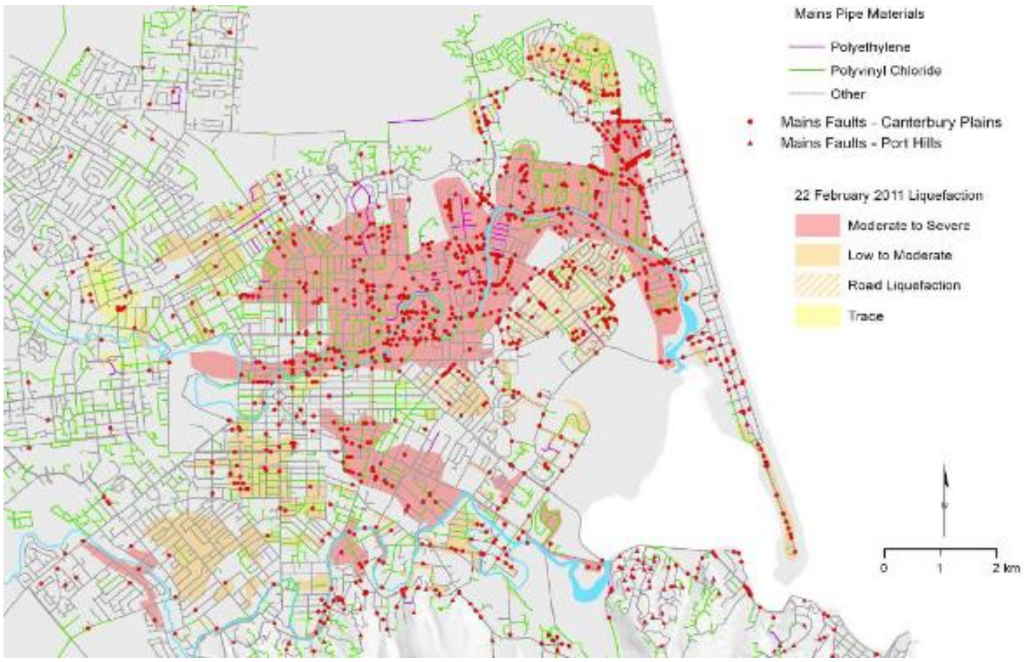


Figure 10: Map of the pipe network in Christchurch as it relates to areas of liquefaction from the 22 February 11 earthquake (Cubrinovski et al. 2014).

The 2016 Kaikoura earthquake triggered a large landslide (Figure 11) and surface fault ruptures on a sheep farm, which affected the surrounding water resources. As mentioned in a previous section, the large landslide buried the water pump system that supplied stock water for thousands of farm animals, and was therefore an immediate cause for concern. Ultimately, the water system was replaced with a gravity system that improved reliability and energy efficiency, but it took three months to become operational. In addition, the earthquake cracked several water tanks at different locations around the sheep farm causing a loss of water access and storage. The landslide caused an increased influx of sediment into the water sources surrounding the sheep farm. The landslide also created a dam that blocked the flow of a waterway resulting in the formation of a lake, thus changing the historical overland flow of water in the area. Finally, surface fault ruptures caused low-lying depressions where water accumulates, and these ponds now need to be monitored to prevent negative effects due to standing contaminated water.

Figure 11: Leader Landslide, triggered during the 2016 Kaikoura Earthquake. Photo taken May 2019 as part of the LFE travel study program.

The 2016 Kaikoura earthquake caused damage to winery facilities in the Marlborough region of New Zealand (Figure 12). Wine spills from the earthquake damage was smelled throughout the region and increased levels of liquid wine entered into the wastewater system. These wastewater systems were not designed to accommodate large amounts of unexpected contaminants, such as wine from the spills. Therefore, additional efforts needed to be taken to ensure that the wastewater was appropriately remediated.

Figure 12: A vineyard located in the Marlborough region of New Zealand. Photo taken May 2019 as part of the LFE travel study program.

3. General Recommendations for Resilient Communities

Recommendations for Landscape-Related Hazards

The 2010-2011 Canterbury earthquake sequence and the 2016 Kaikoura earthquake changed and evolved the perception of earthquake hazards and their impacts on land and land use. In both cases, unknown faults ruptured near populated areas, and hazard from these previously unmapped faults was not explicitly considered in seismic assessments. It is therefore important to rethink earthquake hazard for major cities in the context of potentially unknown hazards and an awareness of uncertainty. This should be further emphasized for regions such as Wellington, which contains a vast and complex fault network running through a major urban area.

Moreover, the impacts of these earthquakes need to be anticipated. Christchurch saw many regions impacted by liquefaction, and many areas are now empty fields with no current function. Wellington Central Business District is much denser in business and infrastructure, and similar empty land spaces would result in severe economic ramifications, many times worse than Christchurch experienced.

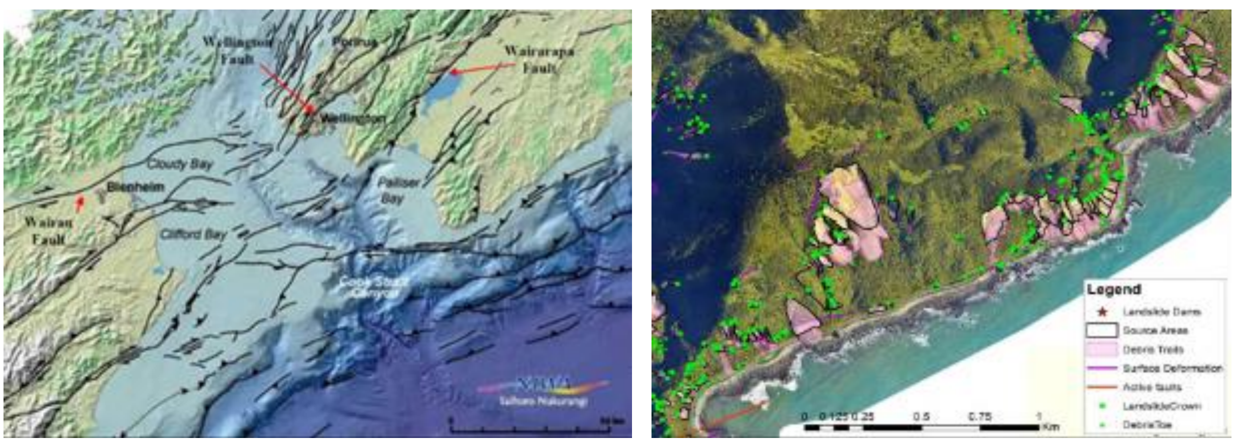
It is therefore important to recognize that cities such as Wellington, which contains critical infrastructure and services, must have its hazards and its impacts thoroughly understood. This can inform planners and designers of the vulnerabilities in the city and allows for “pre-event recovery” to begin before any disaster strikes.

The remainder of this section will illustrate one possible framework for considering hazards and consequences for land and land use.

- ***Individual Hazard***

Earthquakes can be considered as an individual hazard for Wellington. The city is located in the southern end of the Hikurangi subduction zone (150 km west of the Hikurangi Trench) and in the vicinity of a number of active faults which pose a hazard (Figure 13). Sitting astride the active boundary zone between two converging plates, the city is vulnerable to possible earthquakes originating in major active strike-slip faults such as the Wellington, Ohariu, Shepherds Gully, Wairarapa, Awatere, Wairau and Dry River Faults. Historic earthquakes with large reported damage to the Wellington region includes the 1848 Marlborough, 1855 Wairarapa, 1929 Murchison, and 1942 Masterton earthquakes (Semmens 2010). However, Christchurch illustrated that considering the hazard from these known faults alone does not capture the complete seismic hazard of the region. With complex fault networks such as these, it is likely that many unknown faults may also exist, as observed in Christchurch. Furthermore, unknown faults may connect some of the smaller faults in this region, creating a continuous fault rupture sequence as observed in Kaikoura. Clearly, defining and quantifying the risk from earthquake fault rupture is complex and these details must be considered. Better characterization of the seismic hazard can mitigate the underestimation of risk and inadvertent amplification of consequences when a seismic event does occur.

One can also start by considering a single impact from this individual hazard. Dellow et al. (2017) used the large landslide data inventory from the Kaikoura Earthquake to inform landslide hazard in Wellington. Figure 13 illustrates examples of some of the landslide observations which feed into this data inventory. The soil type and slope geometry were recognized as key parameters that must be assessed in Wellington. Dellow et al. (2017) found that landslides triggered by earthquakes were mostly on or adjacent to the earthquake rupture source, and for slopes with greywacke sandstones and argillites materials. As the Wellington fault is one of the major faults running through the city and along the cliffs, and these cliffs contain the same materials as those in Kaikoura, the risk for landslides is major. It is important to investigate such models in order to constrain the hazards and their potential impacts.



(a) (b)

Figure 13: (a) Known faults around the Wellington region (Van Dissen 2008). (b) Example of landslide inventory mapping on the coast north of Kaikoura (Dellow et al. 2017).

- ***Multi-Hazard***

Taking a step back, impacts from multiple hazards can be considered. The earthquake hazard from the previous section can be coupled with another hazard, such as large rainstorm events. Though earthquakes were recognized as the primary cause for landslide occurrence in Kaikoura, Dellow et al. (2017) recognized the ongoing risk on the long-term stability of slopes after the Kaikoura earthquake due to possible large rainstorm events. Water seepage into the cracks formed by the initial shaking further increases the risk of landslides occurring even well after the earthquake event. Many regions in Wellington also experience high winds, which may further amplify the potential landslide damage. Clearly, a single-hazard approach does not sufficiently capture the hazards of future impacts in Wellington.

The above is simply one example of multiple hazards and its impacts on the natural environment as observed during the Christchurch and Kaikoura earthquakes. Wellington is a city with vulnerabilities exposed to many hazards. Figure 14 illustrates a framework for considering these hazards in Wellington. It is important to recognize the hazards and impacts together in an integrated approach, rather than individually, as is often done.

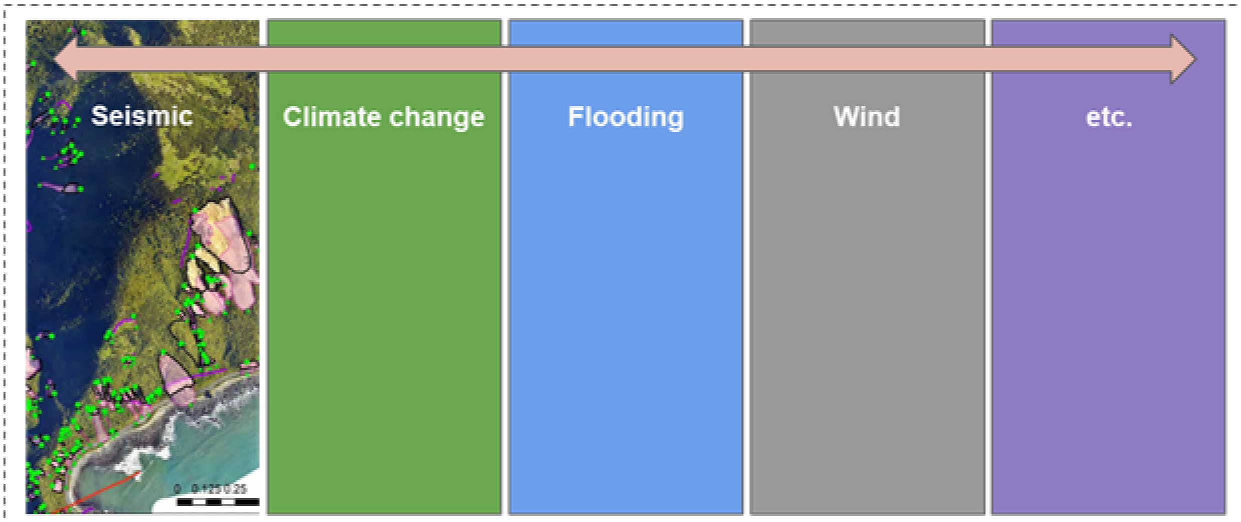


Figure 14: Multi-hazard approach in considering hazards on the natural environment

- ***System Approach***

Finally, taking one further step back, one must consider how hazards can lead to impacts on the land and its assets. The previous section highlighted the importance of considering multiple hazards in an integrated approach. Naturally, this will result in multiple impacts on the land as well. Landslides are only one impact of earthquakes, and many impacts should be expected. An area may experience liquefaction, particularly in reclaimed soils in the waterfront (Cubrinovski et al. 2017; 2018). Run-off landslide debris and silt ejecta from the ground could both be washed into the environment and our waters. As seen in Kaikoura and Christchurch, run-off debris and ejecta can lead to major impact on downstream assets and marine life (Dellow et al. 2017; Potter et al. 2015). One must not only consider multiple hazards, but now also consider how these hazards are interrelated and their impacts on natural assets. Further consequences to infrastructure are also inevitable, and this serves a link to the built environment. Figure 15 illustrates how this multi-hazard approach can feed into the system approach for considering hazards and their impacts on the natural environment.

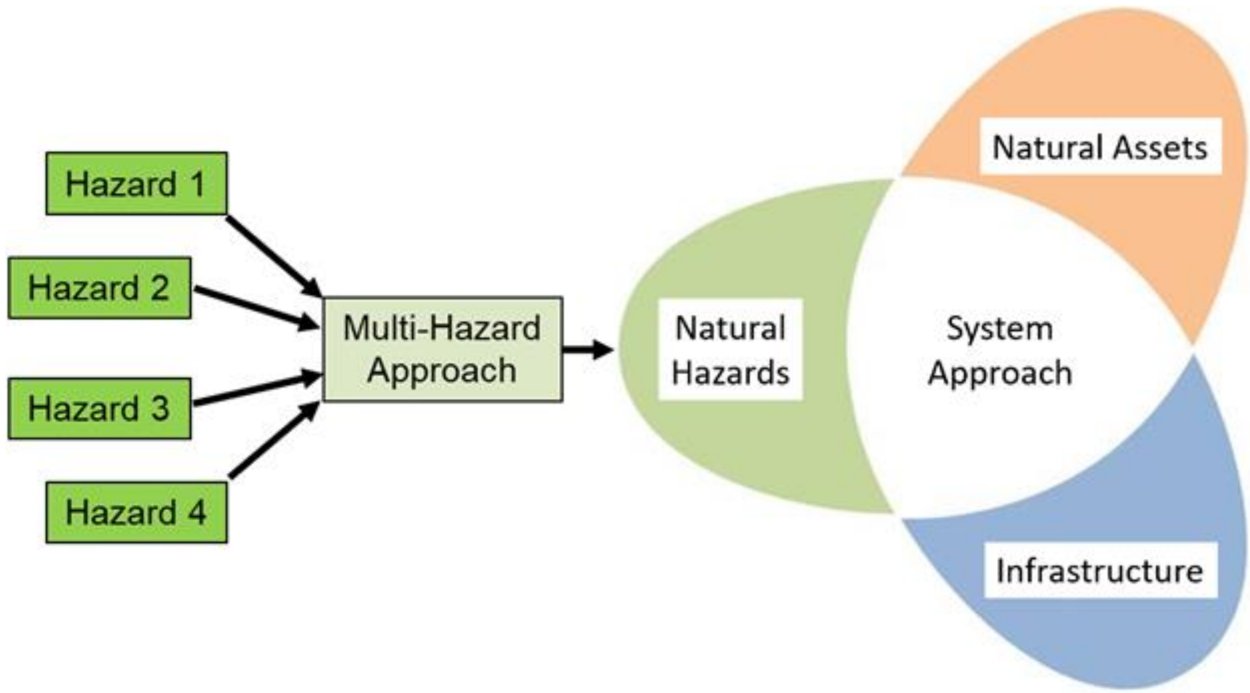


Figure 15: Framework for a system approach in considering the multi-hazard and their potential consequences to our natural environment. The system approach will couple the multi-hazard approach with natural assets and the infrastructure (overlap with the built environment).

Recommendations for the Protection of Fauna

New Zealand is home to many unique native birds, lizards and frogs. However, because of the absence of native land mammals, native species did not have many natural predators, which resulted in many native birds losing their ability to fly. Human settlement and introduction of mammals and pests have brought extinction to some of the endemic species which do not know how to protect themselves from these introduced mammals, while many other native species are endangered and remain vulnerable. To protect the remaining native wildlife from extinction, sanctuaries and reserves have been established across the country. Some are located in islands and thereby protected by water, whereas some are located inland which are sometimes protected by fences.

For example, Wellington is home to Zealandia, the world's first fully-fenced urban ecosanctuary (https://www.visitzealandia.com) located on the Wellington Valley. A near-fault earthquake can easily destroy the fences around Zealandia, which will expose native wildlife to predators. There is not much that can be done to prevent fences from breaking during an earthquake event, however, pre-disaster preparedness plans can be developed by and for these sanctuaries. This is also applicable to island sanctuaries which may become inaccessible during emergency situations.

Recommendations for the Protection of Natural Resources

Many of the impacts of the Christchurch and Kaikoura earthquakes highlighted the need to consider not only the immediate impacts of natural hazards on infrastructure, but also the added environmental effects and how they might threaten natural resources, particularly water quality. To that end, governments in hazard-prone areas should work to improve natural resource resiliency in the following ways:

- Identify critical lifelines and their vulnerabilities, including the concept of natural environment effects.
- Assess direct lifeline impacts, such as damage, repair cost and time, and service downtime.
- Prepare and make known a contingency plan for service gap for local residents.
- Characterize impacts on the resource itself, such as short- and long-term water quality degradation, and time until acceptable quality can be restored
- If resource impacts are above acceptable limits, take measures to improve lifeline resiliency.

Recognizing that it is impossible to design communities that are completely disaster-proof, and as such there will always be some level of damage resulting from large earthquakes, a key issue that local governments must consider in resilience planning is the disposal of debris in a sustainable and responsible manner. This should involve ensuring that there is adequate, fully-developed landfill capacity in the area. Furthermore, authorities should identify and maximize opportunities for debris reuse, and take measures to minimize adverse short- and long-term air quality impacts.

4. Māori Worldview

Māori (New Zealand indigenous people) have a traditional worldview where “the weather, birds, fish and trees, sun and moon are related to each other, and to the people of the land” (Te Ahukaramū Charles Royal, 2007a). Based on this worldview is the concept of “kaitiakitanga”, which means guardianship and protection as a way of managing the environment (Te Ahukaramū Charles Royal, 2007b). Much of what the team learned and observed from the program, such as the importance of knowing the land and protecting the natural environment, is rooted in these concepts. For example:

- The owner of the sheep farm that the team visited emphasized the importance of knowing their land.
- Māori communities and Maraes have proven to serve key functions during disasters, providing shelter and food to locals during the Kaikoura earthquake.

- Good communication between Māori community leaders and local councils can allow for post-disaster recovery with consideration and respect for Māori land and resources.

Moreover, New Zealand integrates this traditional Māori worldview into society in several ways such as:

- Including the concept of kaitiakitanga in legislation such as the Resource Management Act (RMA) 1991 and the National Disaster Resilience Strategy.
- Putting temporary bans (called rāhui) to restrict access in places such as forests and lakes to allow restoration of natural resources.
- Providing legal personhood to rivers and mountains (meaning these rivers and mountains have the same legal rights as a human person) (New Zealand Parliament, 2017; Beehive, 2017).

Overall, it can be observed that Māori's (and by extension, New Zealand's) regard to the relationship between humans and the environment is critical to resilience.

5. Summary & Conclusions

Through this lens of the natural environment, contextualized by the Māori worldview, the team explored resilience and recovery across New Zealand, focusing on the earthquakes from the 2010-2011 Christchurch and 2016 Kaikoura events. The impacts on landscape, local fauna, and natural resources were observed and characterized. Liquefaction, landslides, and surface fault ruptures drastically changed the landscape and damaged critical water-related infrastructure, such as water supply systems and wastewater pipelines. These changes also disrupted the habitats of wildlife and livestock alike.

These observations guided the team in identifying general recommendations for Wellington in preparation for its next earthquake event. The most comprehensive approach would be a system approach that includes preparation for a diversity of impacts caused by multiple hazards. To acquire this understanding, individual hazards must be characterized and experts must think critically about the uncertainty in models.

Including local fauna in pre-disaster preparedness plans is the best way to protect them. The needs and impacts of farm animals, pets, and wild species must be considered when a region is disrupted by an earthquake.

When considering natural resources, plans should include a focus on water, because water supply and wastewater systems are easily damaged in earthquakes and they are critical to post-event response and recovery. It is imperative to identify critical pipelines and implement contingency plans for when earthquake damage disrupts the water systems' ability to function.

In conclusion, while the 2010-2011 Christchurch sequence and 2016 Kaikoura earthquake caused severe damage, these events also provided robust examples of disaster resilience and recovery. Studying these events can inform disaster preparedness, not only in Wellington or other regions of New Zealand, but in other parts of the world for years to come.

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