

SCIENCE TO EMERGENCY MANAGEMENT RESPONSE: KAIKŌURA EARTHQUAKES 2016

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(Submitted *March 2017*; Reviewed *April 2017*; Accepted *April 2017*)

ABSTRACT

The M7.8 Kaikōura Earthquake in 2016 presented a number of challenges to science agencies and institutions throughout New Zealand. The earthquake was complex, with 21 faults rupturing throughout the North Canterbury and Marlborough landscape, generating a localised seven metre tsunami and triggering thousands of landslides. With many areas isolated as a result, it presented science teams with logistical challenges as well as the need to coordinate efforts across institutional and disciplinary boundaries. Many research disciplines, from engineering and geophysics to social science, were heavily involved in the response. Coordinating these disciplines and institutions required significant effort to assist New Zealand during its most complex earthquake yet recorded. This paper explores that effort and acknowledges the successes and lessons learned by the teams involved.

INTRODUCTION

At 12.02 a.m. on the 14th of November 2016, a large earthquake tore through 150 kilometres of land from North Canterbury to Marlborough in the upper South Island, New Zealand. This M7.8 earthquake, later named the Kaikōura Earthquake due to the location of peak intensity of shaking, caused 21 faults to rupture and generated a 7 metre tsunami in localised areas [1]. The earthquake was felt strongly from Christchurch to Wellington, with more than 15,000 GeoNet Felt Rapid reports recorded in 15 minutes [2]. The strength, location and size of this earthquake impacted thousands of people, disrupted transportation networks and other lifeline utilities, and isolated communities [3]. The specific characteristics of the earthquake and its impacts are presented in more detail in a number of papers in this journal special issue.

The scientific response began almost as soon as the ground stopped shaking, some two minutes later, with the GeoNet duty team activating. The Kaikōura Earthquake required a multi-disciplinary response across natural sciences, engineering, and social sciences, including the communication of science to the general public through a range of channels. Researchers from Crown Research Institutes, universities and consultancies throughout New Zealand contributed to this response.

This paper explores existing science coordination arrangements in New Zealand and how these interface with emergency management structures to ensure science can effectively inform response activities. Key developments in science coordination and provision to end-users is detailed for the first four days of the initial response, until formal science sector reporting was established on Thursday 17 November. During such large events, the emergency management sector evolves to support the unique challenges presented by the

event. This paper describes the changes to existing legislation to convey how science practitioners and researchers have to be responsive to a changing statutory environment.

Lessons from the science to practice engagement are still being identified, but we highlight some key lessons on how science coordination in the New Zealand context was undertaken, how uncertainty was dealt with in respect to conveying future aftershock probability forecasts, and the potential for social media to be used to more efficiently understand the needs of the broader community.

SCIENCE AND EMERGENCY MANAGEMENT ARRANGEMENTS IN NEW ZEALAND

Response and recovery structures and processes have been developed over the past 25 years to ensure that, after disasters, a range of relevant policy, practitioner, and other networks are activated and brought to bear on the accelerated decision making required in the post disaster environment [4-6]. In New Zealand, the modular coordinating incident management system (CIMS) was introduced in 2004 (2nd edition released in 2014) as a nested framework, feeding from local through regional or group level to the national level [7]. This brings a range of relevant agencies together with providers of critical infrastructure, welfare, and emergency services to provide a decision-making structure that can be used after hazard events. Requiring that those involved in such responses meet regularly to train, plan, and conduct exercises together, this system is designed to build local and national networks, and thus lay the groundwork for future response operations [8].

This modular incident management system was introduced as part of a decentralising, deliberative, and integrated national approach to both managing and researching natural hazard and disaster risk [6, 8-10]. Devolving responsibility for risk to local and regional levels, with the goal of increasing both

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horizontal and vertical networking at (and between) those levels, this approach is explicitly aimed at increasing the overall resilience of the larger complex system that includes both natural hazards and society [8-10].

The Crown Research Institutes (CRI) Act 1992, established the National Institute of Water and Atmospheric Research (NIWA) and the Institute of Geological and Nuclear Sciences (GNS Science) as crown-owned companies required to conduct scientific research for the benefit of New Zealand (Sections 4 and 5.1(a), CRI Act [11]). At about the same time the Earthquake Commission Act 1993 Section 5.1(e) required the Earthquake Commission (EQC) to facilitate research and education about matters relevant to natural disaster damage and methods of reducing or preventing natural disaster damage. This has been primarily at a strategic level through research funding. An example of this shared responsibility for natural hazard and disaster science in the national interest is GeoNet, a partnership between EQC, GNS Science and Land Information New Zealand (LINZ). The GeoNet project was established in 2001 to build and operate a modern geological hazard monitoring system in New Zealand which provides high quality and timely data and information for emergency management and research.

During and after disasters, both CRIs are responsible for connecting into the incident management system to provide science support and advice to agencies responding to disaster events, and together with the EQC, lead the coordination of post-disaster research activity. Specifically, this role is to "... provide definitive scientific advice or to communicate risk..." while responding to requests from MBIE to coordinate efforts with universities and private organisations (Section 85, National Civil Defence Emergency Management Plan Order, [12]).

In 2009, the Natural Hazards Research Platform (NHRP) joined this busy space. Launched by the Ministry of Business Innovation and Employment (MBIE), New Zealand government's largest science funding agency, this research consortium brought together national research organisations with existing hazard and disaster research capacity, but with distinct existing priorities. What was new about the NHRP was it brought CRIs together not only with Opus, a private research consultancy, but also with three of New Zealand's eight universities, the Universities of Canterbury and Auckland and Massey University. In addition to integrating research activities across these different organisations, the new consortium (NHRP) was required to integrate relevant disciplines into five broad thematic areas: geohazards, weather, risk, engineering, and societal. The National Civil Defence Emergency Management Plan Order 2015, previously 2005, empowers MBIE during and after an emergency to take additional steps to;

- integrate consistent and coherent scientific advice to agencies and CDEM Groups; and
- divert existing funding or allocate new funding to ensure that the appropriate technical resources in core physical and social science, engineering, and risk management are available nationally to support the needs of agencies and CDEM Groups.

The NHRP was responsible for research coordination after the 2010/2011 Canterbury Earthquake Sequence in support of response and recovery agencies [12-14] as it was again during the 2016 Kaikōura Earthquake.

In 2013 MBIE initiated the development of a new disaster resilience related research funding initiative, Resilience to Nature's Challenges (RNC), one of 11 National Science Challenges (NSC). The NSC's are strategic (10-year) investments in science capability and capacity focused on

issues of national importance. RNC was set up largely in parallel with NHRP, and seeks to work collaboratively with government, industry, communities and other stakeholders to build shared understanding of natural hazards and risks, and to develop practical risk reduction solutions. With the NHRP contract due to end in November 2019, expectations are that it will merge with the RNC at that time, though at the time of writing the details of this are still unclear.

In 2015 'QuakeCoRE – New Zealand Centre for Earthquake Resilience' (QuakeCoRE) was selected and funded by the Tertiary Education Commission (TEC) as a Centre of Research Excellence (CoRE). QuakeCoRE aims to establish and link multi-institutional national research programmes that are internationally networked and foster research excellence. The research programmes will advance the science and implementation pathways of earthquake resilience through system-level science with highly integrated collaborations coordinated across the physical, engineering and social sciences and relevant research institutions. The centre brings together researchers from the University of Canterbury, University of Auckland, Victoria University of Wellington, GNS Science, Massey University, the University of Waikato, University of Otago, Resilient Organisations and the Building Research Association of New Zealand.

The architecture of disaster and hazards research in New Zealand, in addition to local government's role in the collection of some science information, means that New Zealand had three recent, large research initiatives, two longer standing CRIs, and EQC all with post-disaster research coordination responsibilities at the time of the Kaikōura Earthquake. The NHRP and CRIs retained responsibility for assisting the nation to respond to significant hazard events and all five entities carried similar responsibilities for capitalising on the learning opportunities. The relatively uncoordinated establishment of these entities, by different research funding bodies, has meant that while the NHRP has a mandate to coordinate research, the roles and responsibilities of other research programmes and how these interface with each other and the NHRP, are not explicitly clear for the immediate response phase, providing the potential for confusion and/or duplication.

To manage this complex environment, mechanisms were established through the coordinated deployment of science leadership into GNS Science, as custodians of the NHRP, and the establishment of a research clearinghouse as a platform to effectively share information.

SCIENCE AND EMERGENCY MANAGEMENT RESPONSE

Immediate Science Response

At 00.02 NZDT on 14 November 2016, GeoNet seismic sensors detected the first movement associated with the initiation of the Kaikōura earthquake. Within six minutes, GeoNet duty staff had reviewed seismic data and confirmed preliminary earthquake characteristics of M7.5 at 15km depth with an epicentre located 15km north-east of Culverden. An immediate notification was received by the Ministry of Civil Defence and Emergency Management (MCDEM) staff with national emergency management response procedures activated [15]. Public information and volcanic duty officers also responded, communicating with the public and assisting with locating aftershocks, respectively.

Concurrently, in response to the scale of the earthquake, the Tsunami Experts Panel convened to assess the risk of tsunami and provided technical advice to the National Crisis Management Centre (NCMC). This advice, informed by observations of tsunami waves recorded on GeoNet's real-

time network (Figure 1), resulted in MCDem issuing a National Warning - Tsunami Marine, Beach and Land Threat for the east coast of New Zealand from East Cape to Southland, including Wellington and the Chatham Islands. A National Warning – Tsunami Marine and Beach threat was issued for the remainder of New Zealand [15].

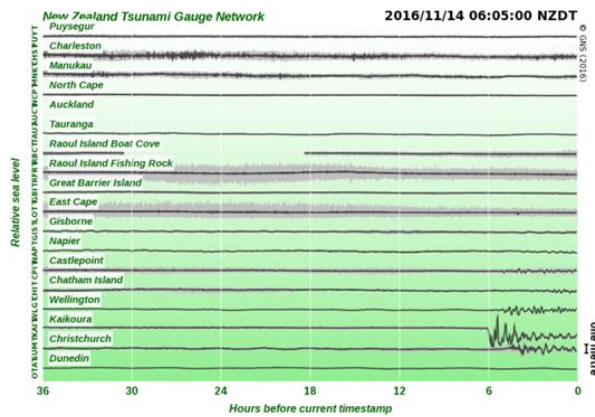


Figure 1: Image from the New Zealand Tsunami Gauge network approximately 6 hours following the Kaikōura earthquake, retrieved from www.geonet.org.nz.

GeoNet's website, www.geonet.org.nz, sustained heavy load during this time, with more than 250 million hits in 24 hours; a speed of 33,000 hits per second. The website and its data, which streams at almost real time, maintained the critical service during this time, due to a migration of streaming data to cloud service providers; Fastly and Amazon. Further, 109 million push notifications were produced by the GeoNet Quake App during the first week of the aftershock sequence. GeoNet continued to provide immediate science information and data for the duration of the response particularly aftershock, tsunami forecast and landslide dam information.

Science and Research Coordination

Daily science meetings were held at GNS Science (with Skype connection for offsite participants), initially morning and late afternoon, to share, deliberate and agree the current state of the science information. The results of these meetings informed ministerial briefings and science sector situation reports provided to the NCMC and regional Emergency Coordination Centres (ECC) to inform emergency response activities. The frequency of these meetings reduced later in the response.

Monday 14 November 2016

To capture an initial understanding of the scale and extent of landform change in Marlborough and Canterbury, GeoNet deployed landslide specialists and earthquake geologists to undertake field reconnaissance. Further, GeoNet technicians were deployed to the affected areas to repair damaged sites and install nine new sites, including more Global Positioning System (GPS) equipment, strong motion sensors and seismographs.

At 09:00 NZDT the Natural Hazards Research Platform (NHRP) initiated an email and video conference dialogue to coordinate engineering-specific research activities between the New Zealand Society of Earthquake Engineering (NZSEE), QuakeCoRE, the Resilience to Nature's Challenges (RNC) programme and NHRP activities. By 10:30 NZDT, representatives of these research organisations, including the Alpine Fault Magnitude 8 (Project AF8) initiative, had formally met to decide which research streams were to be led by the respective research groups.

Following this meeting, activities were to be coordinated through the establishment of an online clearinghouse which would facilitate the sharing of information and details regarding research response activities. Clearinghouse establishment was led by personnel with direct communication links to QuakeCoRE, RNC, NZSEE and GNS Science. The decision was made to be physically based at GNS Science to provide direct input the GeoNet science update meetings and report back to the respective organisations.

By 13:00 NZDT, funding support was also secured for representatives from the Geotechnical Extreme Events Response (GEER) team to arrive on 20 November to support field research activities. GeoNet continued to analyse aftershock data with a M6.3, 30km north of Cheviot occurring at 13:34 NZDT.

By 15:45 NZDT landslide reconnaissance teams had observed and reported widespread slope failure, including the formation of landslide dams in the Clarence and Conway Rivers, with some observations noting very large landslides in the order of 1 million cubic metres. In addition, analysis of the New Zealand Tsunami Gauge Network identified 2–3m wave observations in Kaikōura, 1m waves at Christchurch and wave observations at Wellington and Castlepoint (Wairarapa). GNS Science scientists also developed several scenarios for how future earthquakes, including aftershocks, may continue to occur over time [16].

During the afternoon science meeting, leaders for engineering groups (geotechnical, structural, infrastructure, landslides, active faults, etc.) were identified to disseminate information to the wider research community. Regular updates were provided to NHRP management through this collaborative, multi-disciplinary structure that was further developed over the next two days.

At 16:40 NZDT the landslide dam on the Clarence River breached, sending a wall of water downstream [17]. Using landslide dam reconnaissance information, CDEM authorities provided sufficient warning for downstream residents to evacuate to high ground. By 20:30 NZDT it was estimated that around 100,000 landslides had occurred with many blocking roads, including State Highway 1 north and south of Kaikōura [18].

Tuesday 15 November 2016

On Tuesday, science and research activities were well underway or being planned across a range of key areas including earthquake (observations and forecasts), tsunami, landslides and building performance. By 08:00 NZDT, arrangements had been established for the Earthquake Engineering Research Institute (EERI), an international technical society, to host an online clearinghouse, accessible to all researchers and interested parties, to store and share science findings and data. The GeoNet public information team created google drive documents to share across agencies, so that key scientists could share messages and information with the media in a coordinated fashion.

By 11:30 NZDT, temporary instrumentation was set up in selected Wellington buildings, led by researchers from the University of Auckland in partnership with private consulting firms. The strategy for this collaboration was established between QuakeCoRE and GeoNet. At 12:00 NZDT, GeoNet issued an aftershock probability forecast (Table 1) and accompanying range of scenarios (Table 2) to describe and quantify future evolution of the earthquake sequence [19]. Aftershock probability forecasts and scenarios were then updated daily.

Table 1: Aftershock probability forecast as at 08:00 NZDT 15 November 2016.

| | Average number of M4.0-4.9 | Range* of M4.0-4.9 | Average number of M4.0-4.9 | Average number of M5.0-5.9 | Range* of M5.0-5.9 | Average number of M5.0-5.9 | Average number of M6.0-6.9 | Range* of M6.0-6.9 | Average number of M6.0-6.9 | Average number of M≥7.0 | Range* of M≥7.0 | Average number of M≥7.0 |
|----------------|----------------------------|--------------------|----------------------------|----------------------------|--------------------|----------------------------|----------------------------|--------------------|----------------------------|-------------------------|-----------------|-------------------------|
| Within 1 Day | 55 | 41-71 | >99% | 5 | 1-10 | >99% | 0.5 | 0-2 | 38% | 0.05 | 0-1 | 5% |
| Within 7 Days | 175 | 150-202 | >99% | 16 | 9-25 | >99% | 1.5 | 0-4 | 78% | 0.15 | 0-1 | 15% |
| Within 30 Days | 290 | 257-324 | >99% | 27 | 17-38 | >99% | 2.5 | 0-6 | 92% | 0.26 | 0-2 | 23% |

*95% confidence bounds.

Table 2: Initial earthquake aftershock scenarios used to inform emergency management response activities [19].

| |
|--|
| Scenario One: Extremely likely (99% within the next 30 days) |
| The most likely scenario is that aftershocks will continue to decrease in frequency (and in line with forecasts) over the next few months to years. Felt aftershocks (e.g. > M5.0) would occur from the M7.5 epicentre near Culverden, right up along the Kaikōura coastline to the Cape Palliser/Wellington area. This includes the potential for aftershocks of between M6.0 and M6.9 (91% within the next 30 days). |
| Scenario Two: Unlikely (15% within the next 30 days) |
| An earthquake smaller than Monday's main shock and between M7.0 to M7.5 will occur. There are numerous mapped faults in the Marlborough or Cook Strait areas capable of such an earthquake. It may also occur on an unmapped fault. This earthquake may be onshore or offshore, but close enough to cause severe shaking on land. This scenario includes the possibility of an earthquake in the Hikurangi Subduction Zone. Such earthquakes have the potential to generate tsunami. |
| Scenario Three: Very unlikely (7% within the next 30 days) |
| A much less likely scenario than the previous two scenarios is that recent earthquake activity will trigger an earthquake larger than Monday's M7.5 main shock. This includes the possibility of an earthquake of > M8.0, which could be on the 'plate interface' (where the Pacific Plate meets the Australian Plate). This scenario is similar to what occurred in the Tohoku Earthquake in Japan in 2011. Although it is still very unlikely, the chances of this occurring have increased since the M7.5 earthquake. |

At 17:00 NZDT QuakeCoRE and GeoNet held a meeting with senior management of Wellington based engineering firms to ensure that research response activities were coordinated and informed by the most recent scientific findings.

Wednesday 16 November 2016

By Wednesday, regular science meetings were scheduled with the collation of summary information being documented in daily science status reports to regional Emergency Coordination Centres (ECCs). These reports covered a range of topics including earthquake activity, aftershock scenarios and probabilities, landslides, tsunami, liquefaction, imagery and LiDAR, engineering, social science and field activities. These reports were used by emergency management agencies to inform the event response activities.

By 12:00 NZDT, the online clearinghouse, including a website, geospatial portal and data portal, was live. Clearinghouse establishment was fundamental for the sharing of information and technical data across the complex national research structure and with international partners. Regular 'Kaikōura Earthquake Technical Clearinghouse' meetings were established with a focus on sharing data related to building performance with engineering consultants, and the

broader dissemination of data and science being captured by GNS Science.

QuakeCoRE, in collaboration with local engineering professionals, led geotechnical reconnaissance teams in Marlborough, Canterbury and Wellington to capture engineering field data. All research and data captured were available from the clearinghouse platform for the duration of the event.

At 18:00 NZDT, GNS Science revised the magnitude of the earthquake to M7.8 [20].

Thursday 17 November 2016

Structured science sector reporting, coordinated by the NHRP, commenced on this date. Reporting summarised findings across a vast range of research areas including aftershock probabilities (Figure 2), landslides and dams, tsunami, faults, liquefaction, engineering, social science, Wellington building response, LiDAR and imagery. Updates on field team deployments were also included to synergise field activities with the broader emergency management response. Science sector reports informed the development and content of the National Action Plan [20].

Probability of damaging shaking in the next 30 days

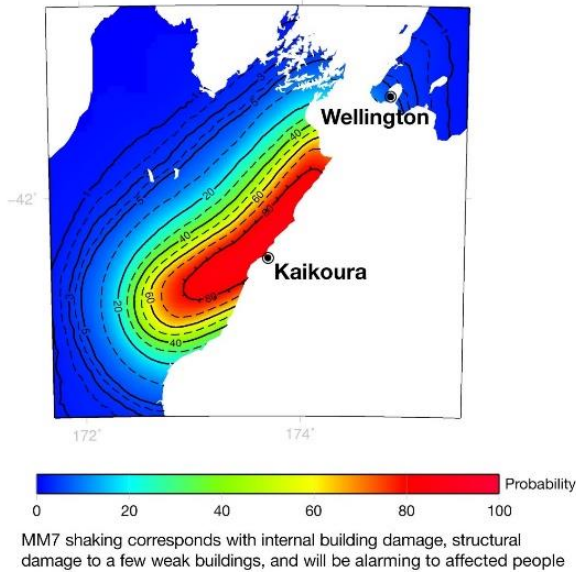


Figure 2: Example of aftershock probability graphics used to convey the probability of damaging shaking over the next 30 days.

At the 09:00 NZDT science briefing, social science experts provided insights into the concerns and questions of the community. An analysis of social media content was able to identify key thematic areas for which the public had particular concerns. Such questions included; What does the evolving understanding of M7.5 to M7.8 and the number of faults affected imply? What does it mean for the Alpine Fault? What does it mean for Wellington and/or the subduction zone? Initial analysis indicated that tsunami alerts and evacuations were a significant point of discussion. These were alarming to many, and a subsequent public discussion on the lack of a 24/7 monitoring system delivered by GeoNet, and the related vulnerability was concerning. There was public discussion on why some communities do not have tsunami warning sirens, and why they were late to be activated in some locations.

Building safety and security were also a point of discussion, especially as it is incumbent for employers to provide evidence of assurance. In relation to this, New Zealand's new health and safety legislation [21] and the ability for employers to ask employees to work from home, while attending to health and safety requirements, were also questioned. In this regard, employees also had concerns about income security if they were disallowed to work from home. It was apparent that there is a lack of alternative spaces for organisations to relocate to, and this is a potential threat to the Wellington region's ability to attract and retain talent and business.

In terms of psychosocial concerns for individuals, the fact that the earthquake impacted such a wide area means that the range of reactions was likely to be very widely spread. The rural and isolated nature of many of impacted communities means that they were hard to reach in terms of providing initial support. A key lesson from the 2010-2011 Canterbury earthquake sequence for psychosocial wellbeing was that most people affected by the events were resilient and self-healed [22]. However, psychosocial and mental health issues resulted not only from people's experience of the event itself, but also from the secondary stressors associated with recovery. Monitoring multiple psychological and social indicators after the Canterbury earthquakes helped to inform psychosocial recovery strategies [22, 23].

By this time, field observations confirmed as many as 50 landslide dams had formed as a result of slope failure into stream and river channels. Of particular concern was possible failure of the Hapuku River landslide dam should it fill and overtop [24]. In response, GNS Science established a process for assessing the risk to people from possible landslide dam failure while identifying all landslide dams in Marlborough and Canterbury districts.

To facilitate the transfer of science and risk information to the local emergency response, two science liaison staff were deployed to the Canterbury and Marlborough Emergency Coordination Centres [24]. For the duration of the response, science liaisons provided briefings to emergency management staff, district governance including Mayors and Councillors, and assisted or presented at a range of public meetings in affected communities. Where science liaison staff could not attend public meetings, scientists from the field often attended.

Coordination efforts continued including a charrette on 19 December 2016 in Wellington, convened by representatives of QuakeCoRE. Invited attendees included representatives from the Ministry of Building, Innovation and Employment (MBIE) Building Systems Performance Branch and from Wellington City Council (WCC), plus a multi-disciplinary group of researchers with backgrounds in engineering, planning, governance, social science and economics. The focus of the charrette was to explore options to address the risk of URM façade failure during the period of heightened aftershock activity in the lower North Island and upper South Island. Whilst the topic was already being considered by both MBIE and WCC, the charrette contributed to the subsequent announcement made in January about the emergency legislation associated with URM façade securing in response to the Kaikōura earthquakes.

CHANGES TO EMERGENCY RESPONSE AND RECOVERY LEGISLATION

Civil Defence and Emergency Management

The Civil Defence Emergency Management Amendment Act 2016 was due to come into force 180 days after Royal Assent on 15 November 2016. However, it was brought forward by the Civil Defence Emergency Management Amendment Act 2016 which was passed on 29 November 2016 under urgency to assist with recovery from the Kaikōura Earthquake in Wellington City and the Hurunui and Kaikōura Districts.

The Civil Defence Emergency Management (CDEM) Act already provided the ability for certain persons to require information that is reasonably necessary for the exercise of civil defence emergency management activities; provided the information is in the possession of the person asked (s76 and 94). The changes to the legislation addressed a gap that existed where there were no powers available to direct an owner to carry out an assessment to ensure that a building is safe after an emergency, or if things change after an emergency - for example, due to a significant aftershock.

Existing obligations on building owners, e.g. Health and Safety at Work Act 2015 and Residential Tenancies Act 1986 [25], require building owners to ensure that a building is safe. However, those obligations are wide-ranging and are not specific as to the type of building checks that may be required following a particular emergency event. The new assessment provision in the CDEM Act is consistent with the wide-ranging obligations of building owners or landlords under this legislation.

The Civil Defence Emergency Management Amendment Act amended the CDEM Act to:

- establish a legislative framework for recovery management, by providing a mandate for recovery managers and by strengthening the requirement to plan for recovery;
- support a seamless transition from response into the initial recovery phase, by establishing a transition notice mechanism that makes some emergency powers available for a specified period of time (local or national transition period); and
- makes some minor and technical amendments to improve the Act, and consequential amendments to other legislation and the National Civil Defence Emergency Management Plan Order 2015.

In Wellington, the emergency powers were enacted on 14 December, following the appointment of Wellington City Council's Chief Resilience Officer, Mike Mendonca, as the City's Recovery Manager. Two subsequent extensions of the 28-day transition period were sought, through until 8 March [26]. Wellington City Council utilised these emergency powers to establish a Targeted Assessment Programme to address public safety issues, and to provide confidence that appropriate engineering investigations of buildings most affected by this earthquake were being carried out. This is outlined in the accompanying paper by Brunson et al. [27].

Resource Management Act

Two other Acts to help facilitate response and recovery became law in early December 2016. The Hurunui/Kaikōura Earthquakes Emergency Relief Act gained Royal Assent on 5 December 2016, and the Hurunui/Kaikōura Earthquakes Recovery Act gained Royal Assent on 12 December 2016.

The Hurunui/Kaikōura Earthquakes Emergency Relief Act made changes to the Resource Management Act 1991 in order to facilitate recovery, as follows:

- Temporary changes to time periods and notice requirements for undertaking emergency works;
- Temporary removal of any resource consent requirements for emergency farming practices;
- Lessening of the resource consent requirements for restoring the Kaikōura harbours, including assigning a permissive activity status, removing the need to consider RMA planning documents, reduced consultation requirements and time periods, and removing objection and appeal rights.

Hurunui/Kaikōura Earthquakes Recovery Act

The Hurunui/Kaikōura Earthquakes Recovery Act set up an Order in Council process, similar to the one set up following the Canterbury Earthquakes (2010-2011) [28]. The purpose of this process is to short-cut modifications to legislation that is seen as necessary to "assist economic recovery, planning processes, rebuilding and recovery of land and infrastructure, and increasing safety and resilience, as these relate to people, buildings, and natural environments", as stated in the explanatory note to the Bill and reflected in section 3 (purpose) of the Act. The Act has a number of checks and balances included in it, which go beyond those included in the Canterbury Act. These include a finite list of Acts that can be modified with specific exclusions such as the Bill of Rights Act 1990; a review panel to provide advice to the relevant Minister on the order; requiring the Minister to publish his or her reasons for the order; providing draft orders to the Regulations Review Committee; and having a sunset clause for both the legislation and any orders (most orders are revoked on 31 March 2018).

DISCUSSION OF LESSONS FROM THE KAIKŌURA EARTHQUAKE

Coordination of Science Research and Activity

The coordination of science activity (in a collective sense, including social science, physical science, engineering, economics) after a disaster event has been established as challenging [15]. The existence of five large research entities, in addition to local government, all with post-disaster science coordination responsibilities increased these challenges after the Kaikōura Earthquake. In the absence of established, transparent, widely accessible collaboration pathways and structures, the distribution of tasks and responsibilities was not immediately clear. This put pressure on leaders of these groups to develop ad hoc coordination arrangements rapidly and under the pressures of the response environment. These arrangements seemed to work reasonably well given the circumstances.

Several factors are likely to have contributed here. Recent earthquake experience is likely to have increased capacity to draw on larger, more established and well-resourced research networks in short order. The recent drive from funders for programmes that aim to develop strong networks both within the research sector and with community, government and private sector stakeholders is also likely to have increased networking capability within these entities, making it easier to distribute research coordination tasks and responsibilities after the earthquake. One obvious result of this existing emphasis on network building, was that many of the scientists involved in the post-earthquake coordination had strong links to several of the large research entities. Another contributing factor was the use by GNS Science of a more structured system to coordinate research in response to the disaster. This was initially driven from within GNS Science, as custodian of the NHRP, to provide science support and advice to agencies responding to disaster events. This system deployed science liaisons directly into district Emergency Operations Centres (e.g. Marlborough) and regional Emergency Coordination Centres (e.g. Canterbury) as part of a series of more direct links into the national coordinated incident management system. This more structured and open approach provided all five research consortia with improved communication pathways, more collaborative activities, and a greater sense of shared mission.

However, concerns remained about the involvement of researchers outside these funding networks. A key lesson from the Canterbury Earthquake Sequence science response was to consider people who were not already networked into disaster research entities, and who lack experience in this field. The confusion of transparent coordination structures between existing research programmes could have made it more difficult to connect into larger research initiatives on the ground. This increased the risk of research duplication with consequent associated pressure on local communities, organisations and resources caused by increased research numbers. It also made it harder to identify and address where the research needs of response and recovery agencies were not being addressed, and in some cases the lack of a transparent coordination structure also limited the ability to grasp how many researchers and research projects were occurring in the disaster impact region. Another concern was the need to ensure that all those in the region (researcher and non-researcher) were aware of the issues associated with post-disaster research activity. It was obvious to those 'inside the camp' that the first priority should remain supporting the immediate response and recovery, and that minimising researcher demands on coordinating agencies was critical.

These concerns prompted the NHRP, who were taking the lead in this area, to arrange ethical briefings for those researchers involved in immediate assessments on behalf of the science response, before they went into the field. A request made at one of these briefings for ethical guidance for field scientists, led to the development of a one-page reference guide to take into the field, supported by emergency contact information and advice. These guidelines underwent rapid review by the Natural Hazards Social Science Panel before being formally endorsed by NHRP, QuakeCoRE and RNC and posted on all relevant websites, including the Kaikōura Earthquake engineering clearinghouse website. Hard and soft copies were also distributed to field teams and through EOCs and public outlets in the region.

Additionally, over the medium term there will be a tremendous focus on Kaikōura and the North Canterbury region, and we expect – as with the Canterbury earthquake sequence – that domestic and international researchers will focus their attention on affected areas which may create additional undue stress for affected communities, agencies and service providers.

One key lesson is that there needs to be a clear and transparent coordinating lead agency supported by an equally transparent and well communicated decision making structure. This could or should take the form of an open access portal (web) that explains the situation, ethical risks, and how anyone can get involved. Importantly, such a system would require a clear structure for how the science research can be integrated into the CDEM response and recovery structures so that it is of most benefit.

Communication of Aftershock Forecasts

GNS Science seismologists produce Operational Earthquake Forecasts [29] following New Zealand's larger earthquakes, to communicate the likelihood of further significant shaking during the aftershock sequence [30]. GeoNet uses a number of techniques to communicate these forecasts and their inherent uncertainty. These techniques have been developed since the 2010 Canterbury Earthquake Sequence began, as a result of ongoing social science research [31, 32] and lessons learnt during significant earthquakes. Social scientists from GNS Science took part in a collaborative approach with seismologists and GeoNet communicators throughout the Kaikōura Earthquake response to apply their research findings. The techniques used to communicate earthquake forecasts include:

- A probability translation table for all geological hazards used by GeoNet [33] to ensure probabilities (such as 30%) and likelihood terms (such as 'unlikely') are used consistently and in a way that matches the majority of the public's perceptions as based on psychological research [34].
- A table containing the probabilities and expected range (number) of various magnitude aftershocks for timeframes of 24 hours, 1 week, and 30 days; which then changes to longer time periods (30 days and 1 year) as the sequence dies down and fewer changes are made to the probabilities day-to-day. These tables are accompanied by a text description giving an example of how to read the table, a map showing the area that the forecast refers to, the confidence bounds, and the day on which the forecast was produced.
- Scenarios are used to help communicate three potential situations of varying likelihoods (e.g. as described in the timeline), which match the probability table, and link to the probability translation table. This technique is used to provide examples of what might happen, including

descriptions of historically similar situations and what the resulting impacts were.

- Maps of the forecasted shaking are included, with concentric rings generally centred on the epicentre of the mainshock and fault ruptures, and a gradational colour scale used to show areas with higher likelihoods of damaging shaking. These maps show the probability of MM7 shaking, which corresponds with internal building damage, structural damage to a few weak buildings, and whether this will alarm affected people.
- Graphs of the forecasted number of aftershocks are used to show the decreasing nature of the sequence over time. The number of aftershocks that occur are subsequently plotted as time goes on.
- Similarly, a table showing the number of expected aftershocks is sometimes used, and updated as aftershocks occur. This has been found to give reassurance that (usually) scientific forecasts are producing accurate results.

This information is made publicly available as news stories on the GeoNet website, <http://info.geonet.org.nz>. The described techniques predominantly appear together in one story, to meet the information needs of users. The stories are also accompanied by contact details of support services, and mitigation advice from EQC and MCDEM.

The already complex Kaikōura Earthquake sequence has been further complicated by three slow-slip events taking place at the same time to the west of the lower North Island, and near the tectonic plate interface on the eastern side of the North Island. This was a new situation that required researchers and communicators to work together to effectively communicate changes in forecasts as the situation evolved. Expert elicitation was used, where New Zealand scientists estimated (including uncertainties) the probability of a M7.8 or larger earthquake occurring in the lower North Island/upper South Island area within the next year. As a result, the likelihood of Scenario 3 was increased to 5% and was accordingly incorporated into GeoNet's communications. International experts were consulted throughout the process.

Communication using Social Media

Social media, through the use of Twitter and Facebook and to a lesser extent Reddit, proved useful as platforms to deliver scientific information to stakeholders and the public during the response. The social media platforms that GeoNet maintains, specifically Facebook and Twitter, were used extensively to publicise stories, relay information, and convey empathetic messages. Facebook followers of this channel increased from 60,000 to over 100,000 in the month following the earthquake, while Twitter followers grew from 40,000 to 60,000 over the same period. However, one gap identified was the lack of robust analysis of social media, in order to further inform communication strategies. Data trends were difficult to access, as were the most pressing information needs from the public in an analytical manner. Given the amount of data promulgated throughout social media channels, it was difficult to capture all the meaningful conversations and information regarding the Kaikōura Earthquake in a coordinated multi-agency manner. Currently, GeoNet is exploring the use of a social media monitoring tool to fill this gap.

CONCLUSIONS

The Kaikōura Earthquake's response challenges were numerous; it was a complex earthquake beset by logistical and geographical challenges as well as the science coordination of numerous institutions and disciplines. A science response of this size and scale is no simple task, however, through relationships, expertise, and trust in each other, those involved

worked together for the good of all New Zealanders. This experience, tempered by the memory of the tragic events that occurred during the Canterbury Earthquake sequence, allowed teams to quickly form, and coordinate constructive working environments. Further structures, including legislative reform and administrative arrangements, assisted the science response as the event progressed.

The event has highlighted the complexity of the current research funding landscape in New Zealand, potential for duplication and areas where collaboration might be improved. While not only beneficial for future earthquake events, the lessons learned are applicable for hazard events, such as a large meteorological or volcanic hazards, which may necessitate a large coordinated science response to inform the emergency management sector.

A special and heartfelt thank you to all the many researchers, practitioners and administrators involved in the Kaikōura earthquake response.

ACKNOWLEDGEMENTS

The authors would like to extend thanks to the people of Kaikōura, Hurunui, Wellington and Marlborough Districts for their assistance in progressing scientific activities during a time of great adversity. Thanks are extended to Marion Schoenfeld and Helen Jack of Environment Canterbury and Maureen Coomer of GNS Science, for their valued reviews. The authors would also like to acknowledge the Natural Hazards Research Platform, QuakeCoRE and the Resilience to Nature's Challenges science challenge for their support both during and following the earthquake response. This is QuakeCoRE publication number 0173.

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