Title of research (EQC grant reference number)
Social and sector-based benefits of an earthquake early warning system (EEWS) for New Zealand (EQC grant reference number: 18/750)

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Key words
Earthquake early warning, behavioural response, public response, sectoral response, New Zealand

Summary
This project sought to investigate the societal and sector-based benefits of an Earthquake Early Warning System (EEW), with a view to providing recommendations on future EEW development for Aotearoa New Zealand.

Introduction
Earthquake Early Warning (EEW), whereby sensors are used to detect earthquakes and provide advanced warning of anticipated shaking to distal locations, is becoming more utilized around the world. To detect and warn for such earthquakes, some countries have national systems of sensors, some use stand-alone alerting devices (which are often networked), and others rely on a combination of both. Systems are designed to either detect earthquakes at source or detect the arrival of P-waves before shaking from the S-waves arrives. After detection has occurred, advance notifications are sent out to locations further afield that can expect strong shaking. Such notification allows organizations to take either automated or procedural actions to counter the impacts of the shaking (e.g. slowing trains, stopping surgeries, turning off dangerous equipment) (Johnson et al., 2016; Allen and Melgar, 2019), and gives the public opportunity to take protective actions such as 'drop, cover and hold', or moving away from windows and objects which may fall.

In Aotearoa New Zealand, EEW is still in its infancy with only limited thought given so far to its viability. Consequently we undertook a study to better understand the geographic regions most likely to benefit from an EEWS; and the potential societal benefits for New Zealand (including automated and procedural responses by key sectors and behavioural responses by the public).

Identification of regions most likely to benefit from an EEWS
To identify regions that could potentially utilise an EEW we developed EEW maps for three earthquakes (see Becker, Potter, Prasanna et al., for submission). The earthquakes included an event on the potential southern Hikurangi Margin (M9.0) and southern Alpine Fault (M7.9), and the real past November 2016 Kaikoura M7.8 earthquake. The maps were based on a "'rapid earthquake source determination"' EEW approach. They included warning times and shaking intensities (New Zealand Modified Mercalli Intensity, MMI) for various locations though out New Zealand. Maps were produced for two different GeoNet sensor configurations of 30 s and 60 second timeframes between detection and warning (i.e. six maps in total).

Potential automated and procedural responses by key sectors

To collect data on how representatives from different sectors anticipated using EEWs we undertook focus groups and interviews. Eight multi-sector focus groups were held in Wellington on 17 July 2018 (6 attendees), Christchurch on 23rd July 2018 (Group 1: 9 attendees; Group 2: 10 attendees), Napier on 6 August 2018 (6 attendees) and Auckland on 28 August 2018 (Group 1: 6 attendees; Group 2: 5 attendees). Interviews were held with six additional agency representatives from 12 April 2018 to 13 August 2019. Finally, two additional single-agency focus groups were held in Wellington on 25 March 2019 and 26 March 2019. Interviews were held with six additional agency representatives from 12 April 2018 to 13 August 2019. Sectors represented included the three waters , electricity, gas, road, rail, port, telecommunications, education, health, building, security, event management, emergency management, emergency services (police, ambulance, fire), geotechnical engineering (with a recovery focus) and local government.

We asked participants how they thought their organisation might respond to a warning for the three map scenarios prior to shaking starting. We focussed primarily on discussing the maps that provided a warning after 30 sec, but also had all three 60 sec maps available for viewing. We also asked questions related to how an EEW system might operate in New Zealand, including preferred shaking intensity thresholds, what kind of alert they'd like to receive and useful minimum and maximum warning timeframes. Our final questions focussed on participants' reactions to false and missed alarms, and the benefits and challenges of having an EEW system.

We digitally recorded or took detailed notes at each focus group session and interview, and transcribed any digital recordings. Transcriptions and notes were analysed for any themes. The key themes that emerged are reported in Becker, Potter & Prasanna et al., (for submission), and aligned with previous research where applicable.

Understanding of behavioural responses by the public

In terms of understanding public response to EEW, as New Zealand has limited experience of such technology, we looked to Japan, where a national system has been officially operated by the Japan Meteorological Agency (JMA) since 2007 (Fujinawa and Noda, 2013). This system uses sensors to detect earthquakes and send advanced notification of shaking to provinces that may be affected. Both agencies and the public receive these notifications. Given many years of public exposure to EEWs and limited research on aspects of public response to actual warnings we sought to understand how the public of Japan react to warnings by undertaking two public surveys following earthquakes in Gunma and Chiba Prefectures in 2018 (Nakayachi, et al., 2019). While the aim of this survey was to better understand how the Japanese public responds to EEWs, it also had a second purpose of developing questions for a survey in New Zealand.

Using the questions used in Nakayachi et al. (2019) we created a public survey for the New Zealand context. These questions were developed based on previously published theoretical research on understanding people's behaviour to warnings (e.g. Lindell and Perry, 2012; Mileti and Sorenson 1990; Wood et al., 2017). We adapted some questions for relevance to the cultural context and added a few extra related to warning content and timeframes. The survey contained 20 questions in total, both quantitative (single response, multiple response, and Likert scale) and qualitative (free-response). The questions focused on previous earthquake experience, anticipated behavioural response to EEWs, perceived usefulness of EEWs, feelings about false alarms, preferred attributes of a warning system (i.e., warning thresholds, timeframes, channels, and messages), earthquake preparedness, and demographics.

The survey ran online via SurveyMonkey from 22 March 2019 to 30 April 2019. The survey was promoted via an EQC press release (resulting in a newspaper article in a national paper and radio interviews) and social media (e.g. Facebook, twitter). We received a total of 3084 responses from across New Zealand. Frequencies were calculated using the software packages IBM SPSS and Microsoft Excel. The results from the analyses are presented in full in Becker, Potter & Vinnell et al. (for submission).

Conclusions and key findings

Potential automated and procedural responses by key sectors

From the sectoral-focus groups and interviews, we found that participants supported the idea of EEW in general but noted the challenges of applying it within their sectors. Primary benefits were perceived to be (1) life safety and/or health & safety; (2) psychological preparedness; (3) activation of emergency plans and situational assessment; and (4) organisational and site-specific actions to reduce damage impacts and aid response and recovery. Participants were more enamoured with automated or procedural actions that caused minimal description disruption for both their sector and the public, and were easy to turn on and off again. Given participants' lack of experience with EEW some struggled to think of exact applications within their sector and it was noted that more detailed thinking needed to be done to work out exactly what actions might be beneficial.

Participants suggested it would be ideal would be to have a nationally integrated EEW system, including a network of sensors, notification and messaging, earthquake mitigation and preparedness, and interaction across perils (e.g. tsunami). People wanted to have confidence in the system, which would come from it being technologically robust, and producing as few false or missed alarms as possible. While this project discussed the warnings that might be generated from a GeoNet-type sensor system, many participants had experienced using in-house sensors capable of alerting and saw the potential in networking these sensors both for EEW and ground motion detection for post-earthquake assessment.

There was support for having a two-tiered threshold system for sending nationwide warnings similar to Japan, with specific sectors alerted at lower thresholds (e.g. MM4-6) and the public alerted at a higher threshold (e.g. MM6-7). However, some participants also saw utility in having adjustable warning thresholds within their sectors (e.g. they might want to be alerted at a lower threshold if undertaking a dangerous activity such as post-earthquake building assessment).

In terms of warning notification channels, most participants suggested Emergency Mobile Alert cell broadcast as the key channel for notification, but also felt warnings needed to be propagated across a variety of other channels to ensure reach (TV, radio, mobile texts, computer notifications, control room/network centre notifications, public announcements, social media, staff supervisors).

Participants generally agreed any messages should be simple, clear, easily digested, universally understood and directive, so as to promote appropriate action. Suggested message content included notification about earthquake shaking, intensity information (e.g. strong shaking, MM6 shaking) and actions that should be taken (e.g. with 'drop, cover, hold' suggested as the primary message). We note that some countries are not specific about what actions to take, as actions could vary depending on the context (Johnson et al., 2016; Wood 2018), which this study also highlights. However, if the primary purpose is for psychological preparedness and life safety/health & safety, a message to drop, cover and hold might be considered appropriate in the first instance. Planning, training, education and exercising were all considered essential to supporting EEW message comprehension and action, so these components should be undertaken well in advance to ensure the most effective responses.

There was strong support for thinking carefully about how tsunami messages might be integrated into the EEW messaging process, whether these should be part of an initial message or a follow-up message. Participants noted that 'stand-down' messages after the shaking had passed might also be useful, but again careful thought about the context would need to be considered before developing such messages.

Intended behavioural responses by the public

Japan surveys

Our Japan surveys (Nakayachi et al., 2019) examined the effectiveness of Earthquake Early Warning (EEW) in Japan based on experiences of residents who received warnings before earthquake shaking occurred in two earthquakes. In Study 1, a survey (N = 299) was conducted to investigate residents' experiences of, and reactions to, an EEW issued in Gunma and neighbouring regions on June 17, 2018. The main results were as follows: (a) People's primary reactions to the EEW were mental, not physical, and thus motionless. Most residents stayed still, not for safety reasons, but because they were focusing on mentally bracing

themselves. (b) Residents perceived the EEW to be effective because it enabled them to mentally prepare, rather than take physical protective actions before strong shaking arrived. (c) In future, residents anticipate that on receipt of an EEW they would undertake mental preparation as opposed to physical protective actions. In Study 2, a survey (N = 450) was conducted on another EEW issued for an earthquake offshore of Chiba Prefecture on July 7, 2018. Results were in line with those of Study 1, suggesting that the findings described above are robust. The research highlighted people's lack of impetus to undertake protective action on receipt of an EEW, and suggested that many were optimistic that that there would either be no shaking or light shaking, and that they wouldn't be harmed. This gave us good insight into understanding response in a real situation before undertaking our New Zealand survey.

New Zealand Survey

As mentioned previously we adapted the questions from the Japan survey for a New Zealand situation and the findings from the New Zealand survey are as follows. Overall, the New Zealand public supported the concept of EEW and deemed it potentially useful for the purposes of being able to take action to protect themselves and others (e.g. family, friends, and pets). The majority (91%) of participants indicated that they would use early warning as an opportunity to mentally prepare themselves for imminent shaking. This finding aligns with mental preparedness for actual warning instances in Japan (Nakayachi et al., 2019), suggesting that the value of this aspect may be transferable across contexts.

In terms of other actions, people also optimistically suggested they were likely or extremely likely to tell other people shaking was coming, move a few steps to safety, or take protective action (all over 80%), a much higher anticipated level of action than reported in studies of actual EEW responses (Nakayachi et al., 2019). While intended actions are often a good predictor of real action (e.g., hurricane evacuation; Kang et al., 2007) in such a situation one wonders whether this would hold true given that intention-behaviour gaps can exist in other contexts (e.g. in the health risk context or for pro-environmental behaviours). The low rates of physical actions undertaken in Japan suggests that the results presented here should be interpreted with caution.

Participants shared perspectives on their preferred attributes of an early warning system which included having MM Intensity thresholds of MM5-6 (moderate-strong shaking) and a preferred channel of mobile phones (supported by other channels). Results show alignment with other systems in the world, where cell broadcast technology is often used to deliver EEW text messages to mobile phones in the first instance, with support via channels such as television, radio and public announcements (including sirens), and even social media where time allows (Steed et al., 2019).

Participants suggested that along with receiving a brief warning message about "strong shaking expected soon" they were interested in receiving supporting information about: (a) the earthquake that had occurred, (b) additional geohazards such as tsunami, and (c) what actions to take in response to the warning. Given this interest, and the preference for some participants to seek further information as a response to the warning, EEW messages should be integrated with other important information to help with decision-making and response. However, given the timeframes available for EEW response, such information provision should be thought out carefully (e.g. see examples from Potter, 2018; Wood, 2018). For example, an initial EEW might provide a short message ("Earthquake early warning, strong shaking expected soon, drop cover hold" or "Earthquake early warning, strong shaking expected soon, take protective action"). After the shaking has occurred this could be followed by another short message to coastal areas who received the EEW, stating that if the earthquake shaking felt 'long or strong' (this is official guidance from emergency management, with a supporting public education programme, National Emergency Management Agency, n.d.), then evacuate immediately in case of tsunami. Subsequent messages could also provide links to further information about the earthquake that has just occurred, the impacts, and what to do. This information could come from the same source or channel or from separate sources or channels, as long as this integration is identified and addressed, as exemplified in the JMA system.

People's anticipated actions differed over varying timeframes with people more likely to intend undertaking quicker and easier actions for shorter timeframes of less than 10 seconds (e.g., stop, mentally prepare, take protective action), and more likely to move to a nearby safe area, help others, look for more

information, or take safety actions as timeframes increased. Mapping these actions out over time provides interesting insight into behaviours for short-fuse warnings and support for the idea that people likely need time to process the warning message and mentally prepare before acting (Wood et al., 2017). However, some anticipated being able to move through this process relatively quickly and to take reasonably immediate physical action. Actions most readily anticipated included quick and easy protective actions, such as drop, cover, and hold. Free-response answers suggested that participants would take these actions because they saw benefit in terms of safety or because experience of prior earthquakes and participation in exercises had helped people understand the value of these actions.

Given that anticipated actions differed over varying timeframes, those developing EEW messaging should consider whether the priority is to focus on getting people to undertake quick protective actions or whether additional information like a countdown timer should be included to allow people to move around and undertake further safety actions. Either way, alert messages and educational and exercise initiatives should be aligned, to allow for consistency in understanding and response. Education and exercising comprises an important part of success in responding to an EEW. Educating people on how to respond to EEWs is an important component of the work being carried out for ShakeAlert in the US. Further, This suggestion is supported by the differences between the Japan and New Zealand data; countries new to EEW might need to focus on training people how to respond to an EEW in the first instance while countries with an advanced system, may need to focus on reducing optimism and normalization biases.

Concluding comments

Our final comment would be that EEW is not going away anytime soon. There is already significant international development and application of EEW, and high interest within New Zealand about how such technology and warnings could be applied. Indeed, sectors are already using in-house alerting devices for their own purposes. Given our findings that both organisations and the public (in both a hypothetical (New Zealand) and existing (Japan) EEW context) support having an EEW system, we recommend that further investigations are made to establishing such a system in New Zealand. Our recommendation is to keep the societal benefits of an EEW in mind as discussions continue in developing the sensors and warning network, to ensure those benefits are realised, and that investment in the system is appropriately placed.

Impact *(ie, how this research reduces the impact of natural disaster on people and property)*

This research has helped us understand the key benefits of EEW to New Zealand sectors, which include life safety/health and safety, mental/psychological preparedness, improvements in response times and reduction of economic damage. Similarly there is both a life safety/ health & safety benefit to the public if they take protective action on receipt of an EEW. The research has also highlighted some challenges in response to EEW, which with a better understanding we can address – such as the limits of EEW for some sectors and the potential lack of impetus by the public to undertake an effective response on receipt of a warning. This has highlighted the need for support in planning, training, education and exercising.

Additionally the impact of this research has not been within New Zealand only, but is help informing EEW planning in places like the United States (for ShakeAlert). Our public survey is currently being replicated in two additional countries (USA x2 and Italy) to assist with EEW understanding and implementation in those countries.

Future work

This project did not consider benefit-cost analyses (BCA), as it was beyond our scope. However, we note that BCA have been undertaken in other countries, and have shown that despite significant economic outlays in funding and maintaining outlays in systems, there can be significant benefits in terms of economic savings. For example, there is a proposed savings of $289 million savings over a 50-year period is proposed for a BCA undertaken for Washington State (Bouta et al., 2020). However, this BCA was for a location that has greater population and infrastructure than New Zealand. Therefore there remains a gap in this type of understanding for New Zealand, which may be worthy of future investigation.

Additionally, given the high costs of installing and maintaining a large national sensor network, it would be prudent to investigate other lower cost options, such as the feasibility of using a network of in-house/stand-alone or mobile sensors to perform the same function for nationwide warnings. Such a

network might be useful particularly in remote locations, where, as seen in this project, there are often difficulties with warnings reaching isolated places. However, given the appetite for nationally integrated warnings, there are also additional challenges to consider, such as how these devices might link to national notification channels and consistent messages, and the influence of official mandates on earthquake notification and warnings.

Finally, we have only begun to understand the nuances of human response to EEWs. It is essential to continue to investigate the reasons why people might or might not respond to earthquake warnings, and how this can be supported effectively through EEW infrastructure, education, training and exercises.

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Outputs and Dissemination

Peer reviewed publications:

Nakayachi, K., Becker, J. S., Potter, S. H., & Dixon, M. (2019). Residents' Reactions to Earthquake Early Warnings in Japan. Risk Analysis. doi:10.1111/risa.13306 (Published)

Becker, J.S., Potter, S.H., Vinnell, L.J., Nakayachi, K., McBride, S.K., Johnston, D.M (for submission) Earthquake Early Warning in Aotearoa New Zealand: A survey of the public's perspectives to guide warning development. Nature Communications.

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Outreach

Deguara, B., "Scientists consider earthquake warning system to help Kiwis prepare for tremor", Stuff, Apr 01 2019, https://www.stuff.co.nz/national/faultlines/111712316/scientists-consider-earthquake-warning-system-to-help-kiwis-prepare-for-tremor

Newstalk ZB radio interview with Chris Lynch, "Earthquake early warning system, worth it?" Tuesday, 2 April 2019, 12:31p.m. https://www.newstalkzb.co.nz/on-air/christchurch/canterbury-mornings-with-chris-lynch/audio/earthquake-early-warning-system-worth-it/

EQC press release: "New Zealanders keen for an earthquake early warning system https://www.eqc.govt.nz/news/new-zealanders-keen-for-an-earthquake-early-warning-system" (29 August 2019) https://www.eqc.govt.nz/news/new-zealanders-keen-for-an-earthquake-early-warning-system

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Feature in the Whakatane Beacon: Carlsson, S., "National Warning Systems", Whakatane Beacon, 8 October 2019

EEW project Featured on Prevention Web: 'New Zealanders keen for an earthquake early warning system' on PreventionWeb: https://www.preventionweb.net/news/view/67419

Earthquake early warning and social media/crowdsourcing

https://www.stuff.co.nz/national/nz-earthquake/111813587/social-media-could-be-key-to-warning-people-when-the-next-earthquake-hits

Presentations

- Presentation to the 2018 Lifeline Forum: Julia Becker, Sally Potter, Ben Payne (2019) "Sectoral and Social Benefits of Earthquake Early Warnings (EEW) for New Zealand", Lifelines conference: Research Day, 17 Oct 2018.
- Presentation to representatives undertaken via QuakeCoRE platform: QuakeCoRE seminar series: Julia Becker (2019) "The potential for Earthquake Early Warning in New Zealand: Investigating the social benefits", 10am Friday 17 May 2019
- International presentation to the University of Washington in Washington State: "The potential for Earthquake Early Warning in New Zealand: Investigating the social benefits", University of Washington seminar, 10 June 2019
- International presentation to the 10th conference of the international society for Integrated Disaster Risk Management (IDRiM) (18 October 2019). Kazuya Nakayachi, Julia Becker, Sally Potter, Maximilian Dixon (2019) "How residents respond to Earthquake Early Warning: An empirical study of the effectiveness of EEWs in Japan".

List of key end users

- Earthquake Commission
- Local and international Science agencies: GNS Science, United States Geological Survey. We are currently invited members of two advisory groups for ShakeAlert (David Johnston for ShakeAlert Steering Group; Julia Becker and Sally Potter for ShakeAlert social science research groups)
- Sectors: water, electricity, gas, road, rail, port, telecommunications, education, health, building, security, event management, emergency management (National Emergency Management agency, local civil defence emergency management groups), emergency services (police, ambulance, fire), geotechnical engineering (with a recovery focus), local government and insurance.
- Local and International researchers: Japan (Doshisha University, Japan; Japan Meteorological Agencies; University of Washington; INVG, Italy)
- Private earthquake early warning providers (e.g. sensor providers).

Abstracts for the website

Scoping the potential for Earthquake Early Warning in Aotearoa New Zealand: A sectoral analysis *(for submission)*

Julia S. Becker, Sally H. Potter, Raj Prasanna, Marion Tan, Ben Payne, Caroline Holden, Nick Horspool, Ryan Smith, David Johnston

Earthquake Early Warning (EEW) can be used to detect earthquakes and provide advanced warning of strong shaking, allowing pre-emptive actions that benefit life safety or infrastructure. We undertook focus group discussions and interviews with representatives from a range of sectors in New Zealand to scope whether they thought earthquake early warning (EEW) might be of use. We found that participants supported the idea of EEW in general but noted the challenges of applying it within their sectors. Primary benefits were perceived to be (1) life safety and/or health & safety; (2) psychological preparedness; (3) activation of emergency plans and situational assessment; and (4) organisational and site-specific actions to reduce damage impacts and aid response and recovery. Participants were more enamoured with automated or procedural actions that caused minimal description disruption for both their sector and the public, and were easy to turn on and off again. Given participants' lack of experience with EEW some struggled to think of exact applications within their sector and it was noted that more detailed thinking needed to be done to work out exactly what actions might be beneficial. Participants were supportive of a nationally integrated EEW system, including a network of sensors, notification and messaging, earthquake mitigation and preparedness, and interaction across perils (e.g. tsunami). There was support for having a two-tiered threshold system for sending nationwide warnings similar to Japan, with specific sectors alerted at lower thresholds (e.g. MM4-6) and the public alerted at a higher threshold (e.g. MM6-7). In terms of warning notification channels, most participants suggested Emergency Mobile Alert cell broadcast as the key channel for notification, but also felt warnings needed to be propagated across a variety of other channels to ensure reach (TV, radio, mobile texts, computer notifications, control room/network centre notifications, public announcements, social media, staff supervisors). Participants generally agreed any messages should be simple, clear, easily digested, universally understood and directive, so as to promote appropriate action.

Key words: Earthquake early warning, sectors, New Zealand, behavioural response

Residents' Reactions to Earthquake Early Warnings in Japan *(Published in Risk Analysis)*

Kazuya Nakayachi, Julia S. Becker, Sally H. Potter, and Maximilian Dixon

This paper empirically examines the effectiveness of Earthquake Early Warning (EEW) in Japan based on experiences of residents who received warnings before earthquake shaking occurred. In Study 1, a survey (N = 299) was conducted to investigate residents' experiences of, and reactions to, an EEW issued in Gunma and neighbouring regions on June 17, 2018. The main results were as follows: (a) People's primary reactions to the EEW were mental, not physical, and thus motionless. Most residents stayed still, not for safety reasons, but because they were focusing on mentally bracing themselves. (b) Residents perceived the EEW to be effective because it enabled them to mentally prepare, rather than take physical protective actions before strong shaking arrived. (c) In future, residents anticipate that on receipt of an EEW they would undertake mental preparation as opposed to physical protective actions. In Study 2, a survey (N = 450) was conducted on another EEW issued for an earthquake offshore of Chiba Prefecture on July 7, 2018. Results were in line with those of Study 1, suggesting that the findings described above are robust. Finally, given people's lack of impetus to undertake protective action on receipt of an EEW, this paper discusses ways to enhance such actions.

Key words: Earthquake Early Warning, effectiveness of warning, earthquake

Earthquake Early Warning in Aotearoa New Zealand: A survey of the public's perspectives to guide warning development *(for submission)*

Julia S. Becker, Sally H. Potter, Lauren J. Vinnell, Kazuya Nakayachi, Sara K. McBride, David M. Johnston

Earthquake Early Warning (EEW) can be used to detect earthquakes and provide advanced warning of strong shaking, allowing pre-emptive actions that benefit life safety or infrastructure. New Zealand EEW is in its infancy, so we undertook a study to better understand the social benefits. We surveyed the public's perspectives (N=3084) on the usefulness of EEW, preferred system attributes, and what people anticipated doing on receipt of a warning. We found strong support for EEW, and participants believed they could use a warning to mentally prepare for shaking and take physical protective actions, in contrast with Japanese data which shows low levels of real physical action. We found that people's actions can be affected by knowing the time available from the warning to arrival of shaking, and the type of messages and information received. We suggest careful thought be given to message content development, supported by education and exercises.

Key works: Earthquake early warning, public survey, New Zealand