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Long-term communication of aftershock forecasts: The Canterbury earthquake sequence in New Zealand

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A R T I C L E I N F O

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A B S T R A C T

On 14 February 2016, a magnitude (M)5.7 earthquake struck in Christchurch New Zealand (Aotearoa in the Maori language). The shaking caused damage to historic facades, power outages, cliff collapses, rock falls, and liquefaction but no reported injuries or fatalities. This Valentine's Day earthquake was an aftershock in the Canterbury earthquake sequence (CES), which began on 4 September 2010 with the M7.1 Darfield Earthquake and included the destructive and fatal M6.2 Christchurch aftershock on 22 February 2011. This study, eight months after the Valentine's Day earthquake and six years after the initiation of the CES, is the first to explore long-term aftershock forecast information and communication needs. The exploratory study also aimed to gather feedback on aftershock scenarios, an alternative form for communicating the forecast.

The qualitative study involved workshops with emergency managers, public health officials, and members of the public in Christchurch. Key findings for long-term communication throughout an earthquake sequence include: 1. divergent earthquake experiences affect aftershock communication response and information needs; 2. understanding aftershock sequence behavior is foundational to sense-making when large aftershocks occur; 3. strategic earthquake sequence updates from the trusted science agency and local agencies could serve as important reminders for earthquake preparedness; 4. communication of aftershock forecast uncertainty could aid with both the credibility of the information and living with uncertainty, and 5. inclusion of impact information and preparedness advice into aftershock forecast scenarios could provide links to actionable information. The paper derives implications for research and practice of long-term communications during an aftershock sequence.

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1. Introduction

In 2016, the 14 February "Valentine's Day" magnitude (M)5.7 earthquake in Christchurch, New Zealand (Aotearoa in the Maori language) occurred as part of the Canterbury earthquake sequence (CES) that began on the 4th of September 2010. Since the initiation of the sequence, scientists at the Institute of Geological and Nuclear Sciences Limited (GNS Science) in New Zealand forecasted the likelihood and number of aftershocks of various magnitudes occurring within time periods (for example, a day, month, year) to inform affected populations about what to expect. In this study, we aimed to investigate long term communication of aftershock forecasts six years after the initiation of the CES and get feedback on aftershock forecast scenarios.

Aftershock forecasts provide critical information because following a large earthquake the frequency of earthquakes increase markedly before the rate decays with time although a large aftershock can re-energize the sequence (e.g., Fig. 1A). Aftershock forecasts use empirical relations of:

(1) the number of aftershocks scales with the magnitude of the mainshock, on average 10 times more aftershocks for each unit of mainshock magnitude increase (Table 2 in Ref. [1], p. 420–427) and
(2) the number of aftershocks is, on average, 10 times more aftershocks with each unit drop in magnitude considered; for example, on average, 10 times more M5 aftershocks than M6 aftershocks (Table 3 in Ref. [2]).

Although aftershock forecasts have been in development since Reasenberg and Jones [3], the effectiveness of the content and communication of the forecasts had received little evaluation except following the 1989 Loma Prieta earthquake in California (Mileti and O'Brien, 1993). Twenty years later, the seismology community became nervous about communicating forecasts after the events of the L'Aquila earthquake sequence in Italy and its controversies and litigation; scientists and public officials were criticised for not communicating a clear and strong enough warning of heightened earthquake likelihood during an earthquake swarm [4–6].

Recognizing the communication research gap for aftershock forecasts, two and half years after the initiation of the Canterbury Earthquake Sequence (CES) a 2013 study explored aftershock forecast communications with various publics, reporters, information officers, and decision-making bodies (e.g., politicians, emergency managers, structural engineers) [10–12]. A series of focus groups

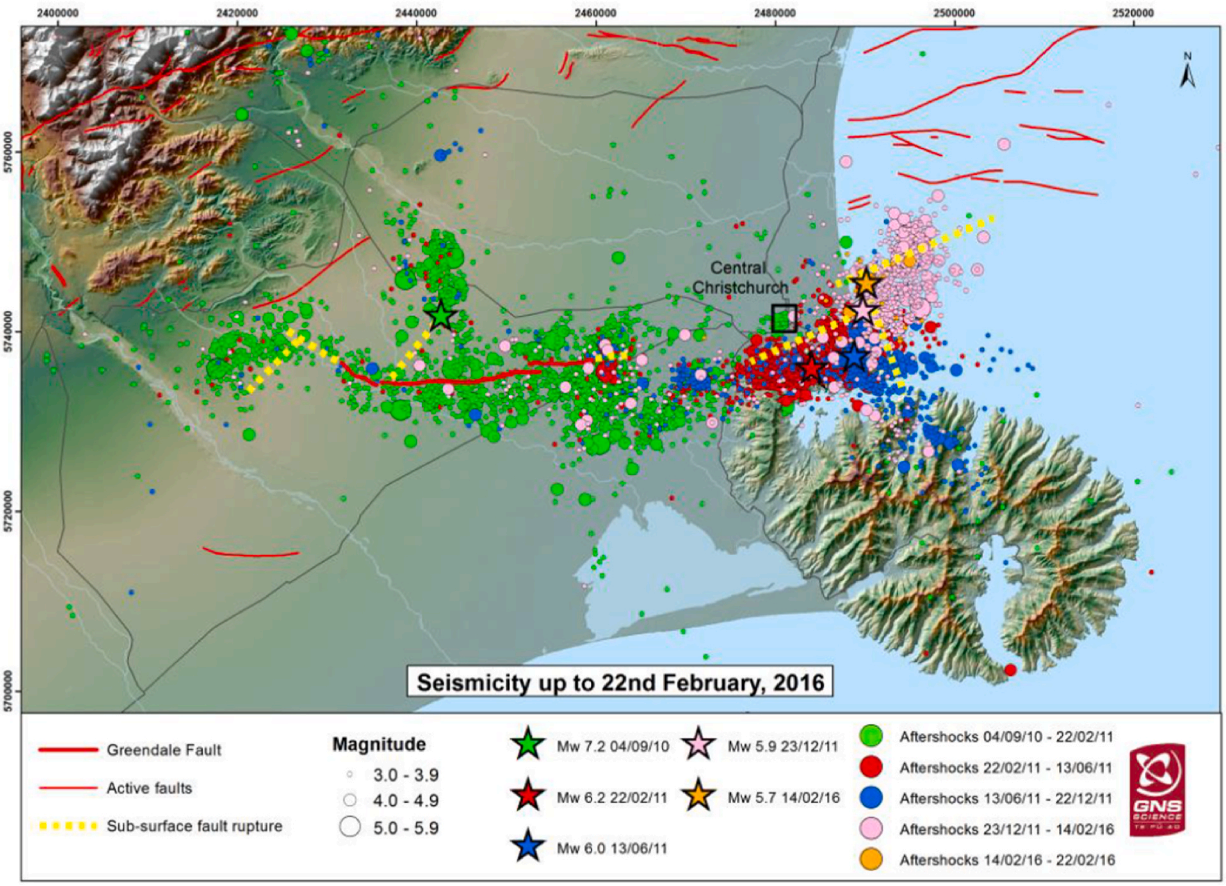

Fig. 1. A. Map of large earthquake epicenters and subsequent aftershocks. Source: [7].
B. Cumulative number of aftershocks annotated by earthquakes larger than M5. Sources: [8,9].

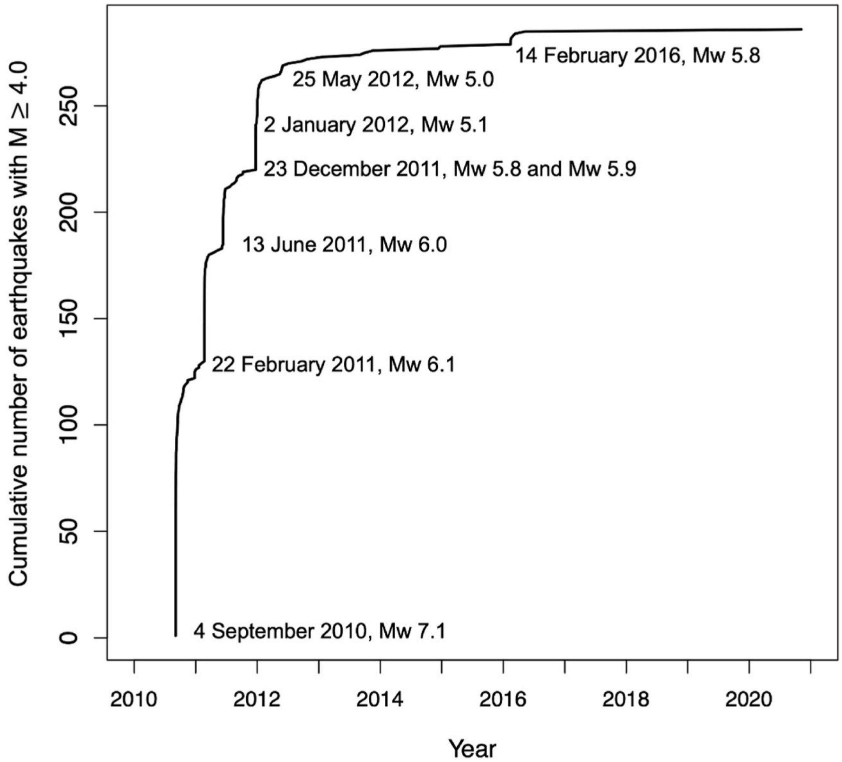

Fig. 1. (*continued*).

and interviews with scientists and staff from agencies and the public gathered perspectives and needs for aftershock information during the first few years of the Canterbury earthquake sequence. The study found that communication of aftershock information can be improved by:

a) providing aftershock forecasts information in various formats (e.g., text, table, graph, map) and channels for different professions, agencies, and publics to cater for different decision-making needs during response, recovery, and hazard mitigation;
b) the development of simpler and accessible messages that incorporate local/regional context;
c) coupling forecasts with preparedness actions to reduce risk and with empathy for psychological support;
d) developing coordinated messages between trusted agencies and translators of earthquake information and aftershock forecasts;
e) providing access to progressively more technical information for those who seek it; and
f) communicating risk to convey the concept of lower likelihood and greater impact earthquakes as well as greater likelihood and lower impact earthquakes.

To understand the evolution of aftershock forecast information needs in the long term, we extended the previous study by revisiting experiences and information needs in the sixth year of the sequence, eight months after the 2016 Valentine's Day aftershock. In workshops with public health officials, emergency managers, and members of the public, we aimed to understand how exposure to earthquakes and information about these events related to changes in attention to and retention of aftershock information, risk perceptions, sense-making, and levels of preparedness over time throughout the earthquake sequence. The study also presented the opportunity to get feedback on aftershock scenarios that were developed to address the 2013 study findings of needing to improve risk communication of low probability and high impact earthquakes and provide a narrative form of aftershock forecasts (points a, b, and f above from Ref. [13]).

Risk communication strategies and frameworks have largely focused on singular disasters (e.g., tornados, flash floods, hurricanes); risk communication throughout an evolving hazard situation is less understood and studied [14]. At the initiation of the research in 2013 [11,12], there were only a few studies of risk communication during a protracted hazard event (primarily volcanic unrest, e.g., Ref. [15]) and none for the duration of an aftershock sequence. Since collecting the data in 2016, the COVID-19 pandemic has spurred study of long-term risk communication. The nature of elevated risk and intermittent crises during an earthquake sequence has similarities with periods of volcanic unrest and waves of the COVID-19 pandemic.

Early in the COVID-19 pandemic, Sutton et al. [14] reviewed literature of relevance to longitudinal risk communications. Their framing of knowledge gaps under the topics of attention, motivation, longitudinal communication in a fragmented environment, trust in information sources, and communication sustainability provided structure for our analyses along with further literature review spurred by our findings. Attention knowledge gaps include waning attention, recapturing attention, and effects of uncertainty on sustaining attention of recipients throughout a protracted hazard. Related, is the theory of psychological adaptation when earlier experience with a hazard decreases concern at a later time [16]. In the case of fluctuating COVID-19 pandemic risks, Schneider et al. [17] found that risk perception levels were under- or over-estimated at different times and higher levels were associated with psychological predictors (e.g., of being female, trusting science and medical professionals, and having direct experience with the hazard, greater prosocial tendencies, and higher personal efficacy).

Sutton et al. [14] identified knowledge gaps in the motivation and maintenance of protective behaviors during a protracted event. The desire to move on during the COVID-19 pandemic and feeling protected (e.g., by a vaccine) are reasons people stopped taking protective behaviors [18]. Sutton et al. [14] refer to the theory of atrophy of vigilance in preparedness that identifies causes including complacency and boredom, non-productive status of safety measures, and shifts in focus back to normal operations [19]. Atrophy of vigilance has recently been observed and investigated in the context of the COVID-19 pandemic [20].

Sutton et al. [14] identified knowledge gaps of sustaining trust in credible voices and effects of media, political scrutiny, and stress. During volcanic unrest, Haynes et al. [15] found scientists were among the most trusted sources for authorities and members of the public, and that trust in information sources is dynamic and influenced by political factors, change in and uncertainty of volcanic activity, and translation of scientific information by the media and other intermediaries. Recent studies of the COVID-19 pandemic investigated trust in information sources and communication channels over time. Although trust in scientists to have the best interests in society declined over time, they remained the most trusted source [21,22]. Furthermore, trust in the United States Center for Disease Control was associated with levels of concern and was most critical for support of and compliance with interventions in the first year of the COVID-19 pandemic [23]. Notably, throughout the COVID-19 pandemic, trust in local health organizations and providers was elevated above trust in state and federal organizations [23].

However, the levels of trust in scientists differed by political party preference, education, and race; tensions developed over the scientific bases for health and safety policy versus personal choice, business and economic activity, and schooling [22]. In a fragmented communication environment, [24] showed that misinformation perceptions accumulated over time, especially for people exposed to false storylines and refuted statements on social media platforms where users receive information in their feeds compared to seeking information. Furthermore, persistent users of social media during the pandemic were identified as lower income and less educated compared to the population at large [25].

Sutton et al. [14] also identified knowledge gaps in adapting risk communication frameworks and models to dynamic, evolving, and protracted hazard contexts. They suggest that the Social Amplification (and Attenuation) of Risk Framework (SARF) [26] may be insightful for understanding the effects of information channels, organizations, and networks on the transfer of and response to risk communications over time. Other frameworks provide additional considerations such as the importance of timing and use of different communication techniques (specifically humor) for science agencies when responding to on-going natural hazard events [27]. Sutton et al. [14] also highlighted inequities in accessibility of information and provision of culturally relevant information for diverse populations in a longitudinal communication setting.

There are implications for organizational forms and strategies of science information providers that are conducive to sustaining communicative capacity and effectiveness over extended and intensive periods of time, and what can be realistically achieved in low-resourced environments [14]. For example, Brantley et al. [28] emphasizes that personal engagement with scientists is a crucial part of volcanic eruption response even with digital dissemination of warnings for observatories. Similarly, Haynes et al [15] documented dissatisfaction with time-limited capacity for deliberation of prolonged volcanic eruption uncertainties and implications among scientists, authorities, and groups making their own decisions. The need for deliberation of the aftershock forecasts among critical infrastructure providers and the effectiveness of in-person interactions between scientists and decision-makers was also evident in the earlier study of CES aftershock forecast communications [11]. A formal recognized structure or procedures within a science organization to facilitate such interactions may help address the dynamic needs for information and communication (including in-person) during a protracted event (Oral communication, Kelvin Berryman, Hazards Platform Lead during the CES, 2013).

In terms of communication products, Sutton et al. [14] identify that research is needed to understand the effectiveness of media-rich messaging (i.e., using narratives and visual imagery) in capturing attention over the long term and effects on risk awareness and protective action behaviors. Regarding our aim to gather feedback on aftershock scenarios, there appears to be few examples of real-time development of protracted hazard scenario forecasts. COVID-19 pandemic scenarios were generated by Charumilind et al. [18] that spanned the multitude of possible future COVID-19 pandemic outcomes with three scenarios. The visual component was line graphs of hospitalization patterns for each scenario. Fagerlin and Peters [29] endorsed the use of line graphs for the purpose of showing risk over time. Furthermore, Padilla et al. [30] found that perceived risks were greater when using a cumulative scale of COVID-19 deaths than an incident scale of death. The above literature is representative of what we were able to bring to bear on the analyses of the long term communication of aftershock forecasts using data that was collected before many of these studies were published.

We proceed by setting the scene of the CES and aftershock forecasts around the Valentine's Day earthquake, followed by the workshop design and participant roles. From listening to workshop discussions and analyzing transcripts, three themes are: (1) surprised (or not) reaction to a damaging earthquake that occurred in the sixth year of the aftershock sequence; (2) dynamics of risk communications and preparedness behaviors over time; and (3) feedback on aftershock scenarios and their uncertainty. Study findings and literature are integrated to offer interpretations of needs for and provision of long-term communication of aftershock forecasts in research and practice. The conclusion consolidates contributions, study limitations, and future research.

2. The CES aftershocks and forecasts

The Canterbury earthquake sequence was initiated by the M7.1 Darfield earthquake on 4 September 2010 [31], which ruptured several faults, including surface rupture of the Greendale fault (Fig. 1A, red line). The epicenter (Fig. 1A, green star) occurred about 50 km east of the city of Christchurch while aftershocks in the following months (green dots) extended as far as Christchurch. Within the first year, two aftershocks greater than M6.0 occurred and the M6.3 Christchurch earthquake on 22 February 2011 resulted in 185 fatalities [32]. Fig. 1B shows the cumulative number of earthquakes larger than M4 from the Darfield earthquake until the end of 2020, using data from a revised earthquake catalogue [8,9]. Annotations highlight earthquakes that reinvigorated the aftershock sequence. The seismicity in Canterbury exhibited an eastward trend (Fig. 1A) and a decay in the overall frequency of earthquakes (Fig. 1B). The impacts of the 2010-2011 earthquakes are described in Potter et al, 2015, By 2016, the Canterbury region had experienced an active earthquake sequence for more than five years with aftershocks still occurring. By the morning of 14 February 2016, there had been no earthquakes larger than a M5.0 since January 3, 2012.

Throughout the sequence, GNS Science continued to update and publish aftershock forecasts on the GeoNet website.[1] Table 1 shows an updated forecast based on international expert elicitation [33,34]. Forecasts for various magnitudes and time periods, start on 1st October 2015 and are for the region from 171.6 to 173.2° East and 43.3–43.9° South (Fig. 2). For example, within the next 1 year (October 1, 2015 to September 30, 2016 - covering the time in which the 14 February 2016 earthquake occurred), there was a 50 percent probability of one or more earthquakes of magnitude 5.0 to 5.9 occurring in the region (shown in the box in the map) and between 0 and 3 events of this magnitude were expected during the same period. The M5.7 Valentine's Day earthquake occurred at a shallow (8 km depth) 2 km from the shore of New Brighton beach ([7]; Fig. 1A, orange star). The shaking caused damage to historic facades, power outages, cliff collapses, rock falls, and liquefaction but no reported injuries or fatalities [35]. The larger earthquake temporarily increased the probability of a magnitude 5–5.9 earthquake in the region from 50 percent to 63 percent within the next year starting February 15, 2016 [36].

3. Methods

For an exploratory study of a long-term communication perspective (6 years into the CES), workshops were used to collect qualitative data and we conducted a thematic analysis to understand and explore in greater depth and detail how participants understood and interpreted aftershock information over time. This method is similar to that used in the original study, as outlined in Becker et al. [12]. The analytical approach is inductive, a bottom-up approach that starts with the data, rather than testing hypotheses given the scant literature on long-term communications and minimal study of communications during a protracted aftershock sequence. This type of approach is commonly used by qualitative researchers and is different from quantitative research that seeks statistical validity of generalizable results for a representative population. Data comprise open free responses that can be quite different from participant to participant (unlike a closed set of options in a quantitative survey). The workshops were facilitated using an unstructured interview guide, as compared to a structured guide, reflective of the method described in [37]. We also discussed a set of communication examples, including aftershock scenarios (Table 2).

3.1. Workshops

In October 2016, three workshops were conducted in Christchurch and one in Wellington, New Zealand. The meetings in Christchurch assembled different groups constituting of Christchurch residents (N = 3), local and regional emergency managers (N = 7), and local and regional public health officials (N = 6). The Wellington workshop included key disaster researchers from Christchurch who were visiting to attend a professional conference and a national-level official who had worked locally during the Canterbury earthquake sequence (N = 5).

The recruitment process involved inviting previous study participants via email and an additional advertisement for new participants circulated via the Canterbury Civil Defence Emergency Management Office. Consequently, the largest respondent group were emergency managers, and the smallest group were residents. Notably, public health officials, who were absent from our initial 2013 sample, were recruited via the invitation from the Canterbury Civil Defence Emergency Management Office. Most of the 2013 study participants did not choose to participate again in 2016. Reasons for reduced repeat participation for our study included reported job turnover since the earthquakes and less concern about aftershocks that had decreased with the decay of the sequence. The Christchurch disaster researchers were recruited by announcement at a conference in Wellington, New Zealand. The study had open enrolment so any respondents that signed up for a workshop were welcomed.

Workshops opened with the same introductory information and framing for consistency. Each group discussion was conducted separately. As the emergency manager and public health official workshops were held at the same time and place, these groups broke out into two discussion rooms. An interview guide of three sets of predetermined unstructured prompting questions, listed in Table 2, was used to explore various aspects in the workshop discussions. The first two sets of questions in Table 2 focused primarily on information needs, information exposure and receipt, information sources and uses, and provision of information after the 2016 Valentine's Day earthquake, as well as the evolution of information needs over time since the 2010 Darfield earthquake. In the public

[1] https://www.geonet.org.nz/earthquake/forecast/canterbury.

Table 1
Aftershock probability table for the periods of one month and one year from October 1, 2015 for the Canterbury region defined in Fig. 2. For each time period, the number of earthquakes (expected and range) and probability of least one are provided for three earthquake magnitude ranges.

	1 Month			1 Year		
Magnitude	Expected number	Range for number	Probability (at least 1)	Expected number	Range for number	Probability (at least 1)
5.0–5.9	0.06	0–1	6 percent	0.7	0–3	50 percent
6.0–6.9	0.005	0–1	1 percent	0.06	0–1	6 percent
7.0–7.9	0.0004	0–1	Less than 1 percent	0.005	0–1	Less than 1 percent

Table 2
Interview guide for the 2016 workshops relating to earthquake information over time, including for the Valentine's Day earthquake. Questions were not asked directly or prescriptively, as is study protocol for unstructured workshops, but used by the researchers to consider whether all topics had been covered during discussions.

Thinking of the Valentine's day earthquake on 14th February:

- Was the Valentine's Day earthquake a surprise (or not)?
- Following the event, did you want to know anything about aftershocks or earthquakes?
  - o If so, what?
- What kinds of aftershock information were you exposed to after the February earthquake? (e.g. environmental cues, type, format, where from, etc)
  - o What did you think about the information? (your reactions to the information)
  - o Good/bad/liked/disliked/scared/too much/not enough/useful/not useful
  - o Did you do anything/need to do anything in response to the information (if so, what)?
  - o Was the information useful/not useful for response?
- Were you a 'provider' of aftershock-related information?
  - o If so, what was it?
  - o Any comments on it? (Good/bad/liked/disliked/scared/too much/not enough/useful/not useful)

Thinking of the earthquake sequence over time:

- Do you think information needs for aftershocks have changed over time, from Sept 2010, to 2011, to present?
  - o If so, how have they changed? (e.g., less/more info, different sources, different types of info, different uses of info (e.g. response vs psychological vs planning, etc.))
- What other information needs might have changed related to aftershocks?

Considering scenarios for the aftershock sequence:

- What do you understand from these scenario descriptions?
- How does uncertainty affect your decision-making?
- Do you prefer the single probability or a range for the probability of each scenario?

Table 3
The Canterbury Earthquake Sequence: What we think will happen next.

(Note: the following scenarios were based on the February 15, 2016 probability table. However, this story was developed for the 2016 research conducted by GNS Science and is for research purposes only.)

We've developed three scenarios based on what we know so far. There are very different probabilities for each scenario, some of these are more concerning than others. We recognize that while these scenarios may increase anxiety in people living in this area of New Zealand, the best thing is to be prepared.

Scenario One – Very likely (70 percent within the next year)

The sequence will continue to decay, behaving like a typical aftershock sequence with numerous felt earthquakes, but none larger than M 6.0 or greater. The earthquakes will be scattered throughout the Canterbury plains and many will be felt in Christchurch.

Scenario Two –Unlikely (27 percent or less within the next year)

A large aftershock of M > 6 to occur. Given the recently increased activity in Canterbury and near Christchurch and what we know of the sequence to date, the possibility for such an event is highest around the location of the M7.1 mainshock and the Christchurch region.

Scenario Three – Very unlikely (3 percent within the next year)

A much less likely scenario than the previous two scenarios is that recent earthquake activity will trigger a similar size or much larger earthquake than the September 2010 7.1. The most likely location for an event of this size is on the Porter's Pass fault to the northeast of Christchurch and at the base of the Southern Alps. However, as with the Greendale fault which ruptured in the September M7.1, there are likely to be other faults around the region which we are not aware of but that are capable of producing an earthquake of M7 or greater.

About our scenarios

After reviewing and watching carefully, we've developed these scenarios based on our understanding of the tectonics in the region, data from the current quakes, historical observations, and statistical models. The likelihood of these scenarios will change over time, based on the activity over the coming days. Be aware there is always a level of uncertainty in our models.

health group, the questions diverged to explore issues of psychosocial health of the communities impacted by the earthquakes in Christchurch. The third set of questions invited feedback on aftershock forecast scenarios (Table 3) including communication of uncertainty.

Extensive notes were taken during the workshops, which were also audio recorded and transcribed for analysis. All data were collected and stored according to Massey University's Code of Ethical Conduct for Research (low risk notification 4000016747). At the

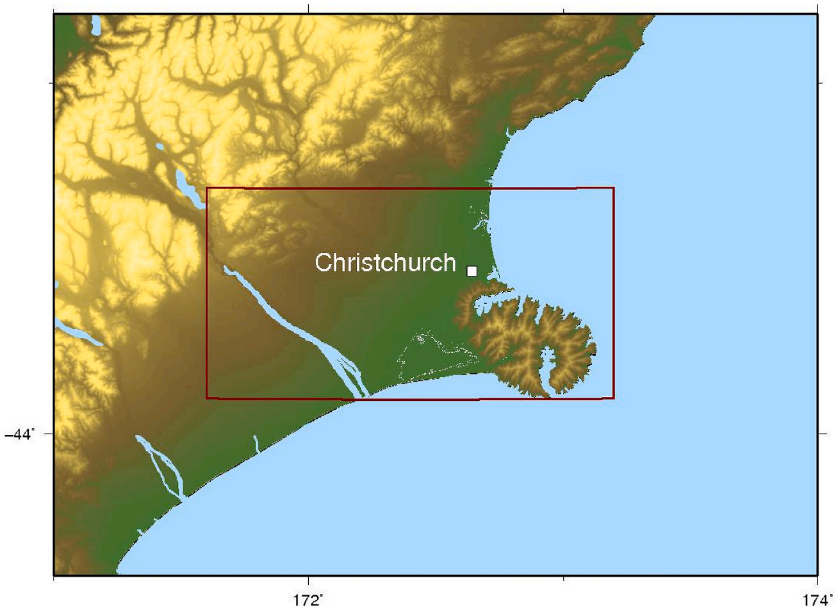

Fig. 2. Map of the central Canterbury area (New Zealand) showing the rectangular zone covered by the aftershock forecast model (171.6–173.2° east and 43.3–43.9° south).

end of the workshops, all participants were provided with information for additional sources of personal support, due to the experiences they may have encountered throughout this sequence of earthquakes.

3.2. Data analysis

After the workshops, the researchers collaborated to collectively familiarize ourselves with the data [38]. Subsequently, we used interpretive thematic analysis (ITA) of the transcripts, which is conducted to identify patterns of meaning, following the approach of Braun and Clarke [39]. We developed codes, labels for organizing themes and relationships between those themes [40]. Two researchers independently developed and analyzed codes using technological and manual approaches [41]. The coding schemes were integrated to build a comprehensive set for the purpose of the analysis. Researcher one's code development was informed by our previous research findings and the risk communication literature (Appendix A) and analysis was performed using NVivo [42]. Researcher two developed codes to capture dynamics of time and earthquake experience while relating to long term communication literature and performed the analysis manually. The coding moved between data driven (from participant descriptions) and concept driven (from theory and study of risk perceptions, trust, and behaviors during protracted hazard events) [43]. Researcher two then cross-checked researcher one's codes for consistency, crossover themes, and additional codes to arrive at the codebook in Appendix B. A fourth round of analysis assessed whether the breadth of the participants responses and feedback had been accommodated. In Appendix B coding is summarized for the three groups of participants (health officials, emergency managers and informed members of the public). The Wellington group contained one emergency manager, otherwise those participants represented informed members of the public. All groups touched on most of the subthemes. Notably, members of the public uniquely raised living with uncertainty over time and did not address communication response shortfalls, strategies to maintain preparedness/response, and need for interagency coordination that were in the domain of responsible public health officials and emergency managers.

The themes identified are not mutually exclusive, and any one portion of a participant's comment could have been coded and assigned to multiple themes, reflecting the depth, complexities, and inter-dependencies of processes. As stated by Braun & Clarke (2013, p. 261), we also have no way of interpreting what is not reported in qualitative data, and if people did not raise an issue in their comments that does not mean it is not important. Additionally, to conduct a quantitative analysis on the frequency of identified themes as an indication of value would be inappropriate and misleading [44].

4. Results and discussion

The three themes that follow from the lines of enquiry and collective analyses of the transcripts are: *the element of surprise*; *time dynamics;* and *aftershock scenarios and uncertainty*. Following the presentation of each theme, findings are discussed in context of the previous study [11,12] and the literature.

4.1. The element of surprise

The CES continued for a decade after the first M7.1 Darfield earthquake [45]. The M5.7 Valentine's Day aftershock occurred in the sixth year of the CES [7]. Our results from the workshops suggested that this aftershock generated "surprise" for some residents and agency staff. The code "surprise" outlines how people viewed and the media portrayed the event as expected or not. The 'surprise' theme also incorporates sub-themes of how people coped with the Valentine's Day earthquake, why organizations responded as they did, and strategies to mitigate communication gaps.

4.1.1. Surprise

There were a range of responses that related to the concept of 'surprise'. A general response was surprise about earthquake sequences. A member of the public stated:

> "One thing that surprised me, I did not realize about aftershock sequence[s]. [That earthquakes were] not an event. [The]… numbers of earthquakes were astonishing." (Member of the public).

Specific to the Valentine's Day earthquake, participants expressed surprise about the occurrence, magnitude, or impacts of the Valentine's Day earthquake. Expressions of surprise about a M 5.7 earthquake occurring more than five years into an earthquake sequence related to four characteristics of the affected population: 1. people who had heard and retained the concept of an earthquake sequence with degradation and spikes of activity or the rule of thumb of how many earthquakes of each size to expect in a sequence; 2. people who had become less attentive to earthquake risks and wanted to "*get on with their lives*"; 3. people still recovering psychologically from the sequence experience; and 4. young children or new residents in the area who were inexperienced with the earthquake sequence. With regards to the first category of people, a participant who was not surprised and considered the Valentine's Day earthquake "*absolutely expected*", recalled a scientist's description of an aftershock sequence:

> "I remember …..he [scientist] outlined it quite clearly about the fact that the degeneration of earthquakes [occurs], but you will get a spike, and I always remember that, so when February [2011 Christchurch] happened I thought, he's right, that's what's happening. I'm not sure that the general public actually understood that" (Emergency manager).

However, the actual time and the magnitude of the M 5.7 aftershock was a surprise. For example,

> "It was unexpected at that exact time. It was certainly part of the aftershock sequence ….." (Emergency manager).

Furthermore, a response official recalled they were surprised by the impacts of the earthquake reported by the media and further disseminated via social media:

> "I had no idea that the cliffs had fallen until I saw it on the news" (Emergency manager).

Additionally, participants who retained awareness of the ongoing earthquake sequence expressed surprise that other people were surprised by the Valentine's Day earthquake. An emergency manager was frustrated by a media report that conveyed surprise:

> "'I can't remember any specifics but I can remember being slightly disappointed in the way the media reported it in that 'oh no, it's another earthquake' when it wasn't necessarily unexpected" (Emergency manager).

Another participant was reassured by GNS scientists being surprised by some people's surprise:

> "I remember hearing that you guys [GNS Science] were surprised at the public response to Valentine's Day cos you thought it [the Valentine's Day earthquake] was quite normal, which was really reassuring actually" (Public health official).

Participants surmised that people were surprised by the Valentine's Day earthquake because they had not stayed attuned to potential aftershocks and had moved on with their lives. For example,

> "I think that people respond differently to earthquakes, …there's the hypersensitivity but then there's also the wanting to push it away, and I think when you've not had one for a long time you get into the really "don't want to know, don't want to know, I just don't want to know anymore. I just want to get on with my life!" and then you set yourself up for that surprise to come, and I think there's a …. that's one of the difficult ones to get around when you're trying to communicate hazards" (Emergency manager).

A public health participant expressed surprise about how many people were shaken up – about half of the hospital staff. Another public health member noted that some people were still suffering emotionally and mentally from the stresses of aftershocks or vulnerable to flashbacks:

> "It showed a really big difference between the people who were genuinely okay and the people who were just okay cos the ground wasn't shaking" (Public health official).

Indeed, a member of the public who had to relocate multiple times after prior earthquakes reported having flashbacks. In addition, young children and new residents or visitors to Christchurch who had not experienced the first few years of earthquakes or understood much about earthquakes, did not cope as well.

> "A UK guest was scared out of his wits by the earthquake, am I going to die?" (Member of the public).

4.1.2. Communication response

Our findings suggest that the state of not being surprised and initially unaware of others' surprise and *"how shook up people were by it"* resulted in underestimating communication needs and missing an education opportunity by professionals. A Public health participant noted that the local government did not activate their Emergency Operations Centre (EOC) for response, and they interpreted this as the event not being that serious:

> "We always look to [redacted organization and local government] for information so we can gauge our response in respect to the public, and because the [redacted local government] didn't stand up the EOC that day – and they accepted that was a mistake, I think they will if there's a future event" (Public health official).

An emergency manager explained that under-activation of the response was affected by assumptions that there would be no major damage to buildings and unawareness of the cliff collapses:

> "I felt, yeah, that's a rather large earthquake, but there's not many buildings left in town ….when we saw that sort of damage [referring to cliff collapse] happening I thought, well, okay, there's still some stuff going down here, so that was quite a significant thing to see … so we weren't aware of it straight away" (Emergency manager).

Later, they realized that they could have communicated more, both in terms of immediate response-related earthquake messaging and educational information:

> "when I say that we missed an opportunity for education … I don't think it needed to be a major thing, but just a small thing to follow up so people could go to the website or (social media platform) or something and I think that's where I could have done a bit more." (Emergency manager).

Earthquake information was received from reporters and schools, and GNS Science was recognized by our participants for covering a large part of the communication gap. Otherwise, participants noted that social media, facilitated by a health board and mental health foundation, filled a communication void for 88,000 people with:

> "a significant post about nine o'clock that night with some advice about how to manage the adrenaline and what to do and how you might want to negotiate that within your family" (Public health official).

Social media provided a forum for people with diverse experience with earthquakes:

> "people who'd been through it all talking to people who it was their first ever earthquake" (Public health official).

4.1.3. Communication strategies

Participants offered communication strategies to address aspects related to surprise about aftershocks and the Valentine's Day earthquake; divergent communication needs after an aftershock more than five years into an earthquake sequence; and communication network breakdowns. First, participants advised communicating about earthquake sequences rather than a single earthquake would help to address surprise:

> "I think we can do a lot with very simple changes like for example, people still talk about an Alpine Fault earthquake. Stop It! Start talking about an Alpine Fault sequence of earthquakes and you're already planting seeds before you get there, and then you can start painting what that sequence looks like" (Emergency manager).

None of the participants reported to have sought out the aftershock forecast around the time of the Valentine's Day earthquake; some indicated that if the aftershock had been more damaging, they would have gone to look for the forecast. However, professionals in the workshops called on the leading science agency to remind them about earthquake sequences after significant aftershocks:

> "there's your opportunity to get in and say 'guys, this is not unusual. It's going to happen again……Guys, this is going to happen for the next ten years. Just brace yourselves and be aware" (Emergency manager).

In practice, reinforcing earthquake sequence behavior after the Valentine's Day aftershock helped people make sense of the Valentine's Day earthquake:

> "GNS Scientists on [redacted media outlet] the next day talking about the natural degradation of the sequence, and I remember that phrase because I don't think I'd heard it before and so it was really helpful because the media were driving us to say "will this be the final straw for your population?" which is a very unhelpful question to have to answer" (Public health official).

In between, large aftershocks in a sequence, there was recognition of tension between people getting on with lives and keeping them alert with available knowledge:

> "maybe we are not doing our job properly, that this has come as a surprise. I know people want to push it away and put it behind but we really need to be in, no, we're still in this thing and we're still going to get some pretty good shakes, and we also knew when it shakes pretty good that the cliffs are going to come down" (Emergency manager).

Public Health Officials and Emergency Managers raised concerns about "*crying wolf*" or "*the proverbial fire hose [of earthquake information]*". Over the long term of an earthquake sequence, participants looked to GNS Science to periodically (e.g., six monthly) remind people, including policy makers, that the aftershock sequence continues:

> "a six monthly update or whatever it might be, just to say actually we're still in the process, this is what's happening ….., and it is a constant reminder, cos otherwise, you know, a year is too long, is six months long? I don't know what works, but it is about keeping it up in front and central. ….[Central government in] Wellington overreacted because they hadn't heard anything for a year" (Public health official).

Some participants endorsed providing reminders in the form of aftershock forecasts:

> "I personally like the probability forecast. I find them reassuring, and from a professional point of view it's good too because lots of people in public life are busy people, they've got other totally different aspects to their work, and it's sometimes difficult to keep them on track for emergency responses, so if that information's coming out regularly it's easier, it makes it easier for me to keep their minds attuned you know, they might have to operate in the EOC again" (Public health official).

Public health officials also suggested that aftershock forecasts could be accessed as part of readiness events and provide context for realistic exercises.

Workshop participants identified the need to communicate with two types of audiences: people that are earthquake seasoned and people that are inexperienced with earthquakes and perhaps don't understand aftershocks:

> "having it [communication] in a context, which for those people that have experienced and for those people that haven't …. … so that you've kind of covered both camps" (Public health official).

Some participants concurred with prior study findings about the importance of multiple and coordinated communications (Wein et al., 2016):

> "I also think the point you raised in your two research papers are excellent as well and I would fully agree with these findings … Different types of information at different stages.… not just putting up a scientific message but coordinating that with the public messaging from all the other agencies, I think that's the main thing" (Public health official)

A suggestion was made for forming a group of community leaders for the purpose of consistent communications:

> "But I wonder if there's some kind of, you know, growing a group of communicators who are also important community leaders like, ….. Ministers and some journalists potentially, and you know, so that there is a consistency of message so that we don't lose our nerve" (Public health official).

4.1.4. Discussion of insights about countering surprise

In the literature about psychological adaptation to previously experienced hazards, Loewenstein and Mather [16] define surprise as "when events deviate from previous expectations". Merz et al. [46] identify two sources of surprise (for flood risk) as limits of predictability and cognitive biases (including recency bias). During the CES, unpredictability pertained to the timing, location, and size of the aftershocks and unawareness of residual risks (e.g., cliff collapse). A recency bias is plausible from participants comments about the time lapse of the large Valentine's Day earthquake, compounded by the drop in environmental cues of aftershocks with the decay of the sequence. However, a message that had stuck for some participants from earlier in the sequence and resonated for those hearing it for the first time, was the graphical language of a decaying earthquake sequence with spikes of activity over time. The concept served both purposes of reducing the surprise of the Valentine's Day earthquake for those who had seen and heard it prior and making sense of the aftershock afterwards.

The surprise theme relates to Sutton et al. [14]'s topic area of attention with elements of waning attention and ways to recapture attention while avoiding message fatigue. The question of how often scientists could remind populations about an ongoing earthquake sequence was raised. At the stage of the sequence in its sixth year, a participant guessed six monthly to find a balance between crying wolf and the one year since the central government had been informed. Message fatigue appeared to be less of a factor six years into the earthquake sequence compared to the weariness of frequent earthquake probability messages earlier in the sequence [11]. It is possible that messages could have been provided more frequently to remind people about the on-going sequence to counter the effect of 'surprise' about the Valentine's Day aftershock. Our findings suggest that increased messaging, more often than annually, could be considered for future earthquake sequence communications when large aftershocks have not occurred for a year or so and the probability of a magnitude 5 earthquake within a year is 50 percent, as was the case prior to the Valentine's Day aftershock.

Some participants suggested that aftershock forecasts could be used to remind populations about the ongoing sequence. The forecast could be more easily found by linking the forecasts to the earthquake notification (e.g., GeoNet's Valentine's Day earthquake page) that people are more likely to seek out. After the 2018 Anchorage earthquake, local media referred to USGS aftershock forecasts for five months (Michael et al., 2020; [47]). In the longer term, aftershock forecasts could provide context for readiness events and exercises.

When using aftershock forecasts as a reminder, the time window (e.g., x percent probability of occurrence within the next day, week, month, year, etc.) is another balancing act. A longer forecast time window will make the chance of occurrence seem more probable, but if the time window is too long, the event will seem too far away or irrelevant [48,49]. Michael [50] proposed adjusting forecast windows to the relevant disaster stage decision-making time frames. Beyond the initial response, emergency manager participants indicated that one month time window provides actionable information while the forecasts are appreciably changing. Guidelines for aftershock forecast time window and communication frequency commensurate with earthquake risk and preparedness requires further study. These aspects add depth to the research question of adapting risk communication models to address protracted, dynamic, and evolving disasters [14].

It is also possible to communicate the expected duration of an aftershock sequence. U.S. Geological Survey scientists have calculated ranges for the forecasted time a sequence might take to decline to baseline annual probability levels for M 5, 6 and 7 earthquakes [51,52]. Duration information has been requested by various professions in three countries [53] and the uses in decision-making and sustaining attention could be studied further.

When it comes to the communication response to a large aftershock occurring years later, gaps to consider are the accessibility of messages for vulnerable populations (e.g., those inexperienced with or re-traumatized by earthquakes), the potential for emergency management and health agencies to under-activate communications, and a continued need for coordination of communications. In the workshops, emergency managers and public health officials recognized that messages needed to accommodate the divergent experience and different types of coping with earthquakes within the population as time had passed. During the earthquake sequence, the affected population in Christchurch and the central Canterbury region had shifted, with a number of new residents having moved to the city to assist with the reconstruction [54]. Between 2013 and 2018 the population of Christchurch grew by 8 percent and diversified; the Asian population increased by about 25,000 (79 percent growth) [54]. Consequently, in February 2016, there were new residents and visitors who may have heard of the earthquakes but not experienced the damaging earthquakes. Meanwhile, other residents who experienced the earthquakes had moved away from Central Christchurch and the Eastern Suburbs including those that were forced to move out of the red-zoned areas that were deemed uninhabitable land [55]. Based on reports of people inexperienced with earthquakes or re-traumatized by the Valentine's Day earthquake, the prior recommendations to provide messages about coping, taking safety precautions, and where to find psychological support (Becker et al. 209) likely still applied, as evidenced in the interactions on social media.

At the national level, GNS Science communicated comprehensively by not only providing scientific information and what to expect for aftershocks but by also referring to other authorities about what to do and how to cope [36]. A lack of local activation muted communications in the networks of emergency management and public health organizations, reportedly owing to a lack of surprise about the aftershock, feeling safe in the recovered built environment, and initial unawareness of physical and social impacts of the Valentine's day earthquake. The various dynamics affecting social attenuation of risk communications could be considered within the SARF framework as Sutton et al. [14] suggest.

Endorsement of message coordination harked back to the earlier study finding [11] consistent with social science research to couple hazard information with behavioral and psychosocial advice and confirmation of messages from multiple authorities and channels (e.g., Ref. [56]), and in particular by local entities that are similarly impacted by the earthquakes (e.g., Ref. [11]). However, a complementary approach is necessary as too much similarity in messaging between agencies can be construed by various publics as evidence of conspiracy rather than partnership [57].

4.2. Time dynamics

Surprise about the Valentine's Day earthquake was a product of time dynamics of experience with and knowledge gained about an earthquake sequence, residents getting on with their lives, psychological recovery, and new residents settling in the area including young children. Other time dynamics during the earthquake sequence pertained to establishing scientists as trusted sources of information, diminishing earthquake preparedness, shifting concern about earthquake sources, increasing tolerance for uncertainty, and changing information needs in the informed population.

4.2.1. Trust in scientific information providers

As noted above, participants looked to GNS Science as the trusted source for communications about aftershock sequences after a large aftershock and periodically throughout the sequence. For some participants, it was apparent that, since the initiation of the earthquake sequence in 2010, GNS Science had gained trust as a credible source of information over prior misinformation of earthquake predictions by an alternate theorist:

> "We have the experience of watching the forecast come true. Better than [alternate theorist]" (Emergency manager).

4.2.2. Earthquake preparedness

Reportedly, items were not secured for the strongest shaking of the Valentine's Day earthquake:

> *"Parklands where there were bookcases over every, literally every, house in the cul-de-sac"* (Emergency manager).

In terms of preparedness to respond, new people living and working in the Christchurch area alongside waning attention to aftershock risks contributed to lapses in earthquake response procedures at a hospital:

> "we've got new people who haven't experienced earthquakes so their response in the Hospital in the [redacted regional entity] wasn't as sharp as it was previously, and our procedures weren't followed. It was kind of like they've forgotten and maybe they didn't think about it. So a good example of that was from the discussion we would actually activate our Hospital plan, and it became pretty evident quite quickly that the staff were unsettled, the patients were unsettled, so they activated, but they didn't follow procedures properly so there was gaps. That wouldn't have happened during the earthquake sequence even up to 2012 …" (Public health official).

Public health officials and emergency managers noted that maintaining a state of readiness in the tail of an aftershock sequence is challenging:

> “I think it is about keeping alert because we might not have something for five to ten years now, of any main significance nationally, but keeping it, and that’s a challenge for all of us” (Public health official).

4.2.3. Shift in concern

While there are indications that risk perceptions regarding impacts from an earthquake in Canterbury had lowered due to a stronger built environment and decay of the sequence, all workshop participant groups - public health, emergency management, and members of the public – referred to the Alpine Fault, a long fault in the South Island that is further away from faults underlying the area affected by the CES. First, they acknowledged that they had normalized the earthquake risk in Christchurch compared to risks from the Alpine fault and faults in Wellington:

> “I think back then, because it was new, like you know Christchurch, we didn’t, you know, we were all expecting Wellington to go or expecting the Alpine to go, we never thought there was going to be a new fault that was going to go off like a major fault” (Member of the public).

In turn, the Canterbury earthquake experience had become a reference point for a larger Alpine Fault rupture:

> “the Alpine Fault’s going to be however many times bigger than Christchurch, but for those people who hadn’t experienced Christchurch they’ve got no meter for what that actually means” (Public health official).

Additionally, some people were now more curious about the possibility of an Alpine Fault earthquake:

> “it’s more intriguing now because we’ve learnt so much about the Alpine Fault and stuff like that …. I don’t want it to happen but I’m kind of intrigued to see what will happen, cos we’ve learnt so much about it” (Member of the public).

4.2.4. Coping with uncertainty

Participants expressed reassurance from knowing that scientists understand what is happening during an earthquake sequence. Members of the public revealed changes in how they coped with uncertainty after living with aftershocks for multiple years:

> “It can get frustrating because there is so much uncertainty [about day, time, location of earthquake] but I think that’s something I’ve just come to deal with because you can’t change it” (Member of the public).

Essentially, it was expressed that despite the uncertainty of what could happen from an earthquake, and where and why, residents came to accept and cope with the ongoing earthquakes. This was partly due to all that they had experienced, or what they had learned about earthquake faults and behavior. People got used to living with the uncertainty of earthquakes, and better understood them, so they were less bothered by them. Notably, some explicitly stated that their fear of earthquakes had diminished:

> “over time I adjusted a little bit, got a little bit more immune to them. I don’t mind them as much anymore” (Member of the public).

And, their fear had transitioned to intrigue:

> “I want to learn about them [earthquakes] because I just know that the media can twist things and that’s why I always get frustrated …, so I actually want to learn how these things work and the mechanisms behind them so I can feel a lot safer” (Member of the public)

4.2.5. Information needs

Information needs later in the sequence were presented as needing less than earlier in the sequence now that people were more educated about earthquakes and coping better:

> “I think now, because we experienced so much we don’t need as much information because we’ve sort of been through that initial information overload cos we needed it and now that we’ve got it” (Member of the public).

However, being more educated about earthquakes led to the perception that Canterbury residents wanted more details than people in other parts of New Zealand:

> “I think that in general the public is, in Canterbury, is probably more educated now than what it used to be as well, so they’re seeking a bit more information, whereas if you live in Nelson, you know, earthquakes, yeah, shakes the building, who cares? People who have actually lived it now want to know a little bit more” (Emergency manager).

As an example, a public health official would want to know if the Valentine’s Day earthquake was part of the degradation of the sequence or starting up something on a *new* fault line.

4.2.6. Discussion of implications for long-term communication

The dynamics of trust and credibility of information sources is a knowledge gap in Sutton et al [14] and has been considered in earlier aftershock and recent COVID-19 communication studies. The 2013 study of the CES, three years into the earthquake sequence, detected trust issues related to frustration with scientists for changing aftershock forecast probabilities, tensions around alternative theorists predicting when the next large earthquake would occur, and government leaders withholding information for fear of causing panic [11]. These findings highlighted the importance of transparency throughout the scientific process of learning about an evolving situation and delivering nontechnical forms (e.g., analogies) of aftershock forecasts [12] and by local experts [11]. Becker et al. [12] also reported on trust built from the credibility of the number of aftershock occurrences within forecasted ranges and empathetic messages. The 2016 workshops then shows that trust continued to evolve over time in a positive way among the affected participants, with more trust in the agency presenting the science, due to ongoing reliable and consistent communication efforts.

In other literature, COVID-19 pandemic studies of trust in scientific organizations show nuance in the dynamics in terms of political party preference, education, age, ethnicity, and race [22] that could be investigated in an earthquake sequence setting. As for accumulation of misinformation on social media platforms over time [24,25] it is difficult to know whether marginalized and immigrant population experiences and trust in GNS Science were similar to what was expressed by workshop participants.

Another question is whether level of concern about risk is strongly associated with the evolution of trust in government [23] during an aftershock sequence. It is unclear given other influences. For example, at the initiation of the earthquake sequence in 2010 aftershock risks were of low concern owing to lack of damage, knowledge, and experience [12]. After the fatal 2011 Christchurch earthquake, decision-making about the built environment was risk averse for some time [12,58]. In 2016, participants reported less concern when living in a safer building environment than earlier in the earthquake sequence. In addition, decreasing level of concern or risk perceptions are valid as the rate of earthquakes decline during the aftershock sequence (e.g., Fig. 1B). In 2016, earthquake risk perceptions may have been below the objective risk, in terms of the likelihood for a large (e.g., M5.7) earthquake to occur and lack of awareness of seismically induced cliff collapse risks (as the rate of rockfalls had diminished within 1–5 years of the February 22, 2011 Christchurch earthquake [59]). In the 2016 workshop, concern had shifted to larger earthquakes from distant faults (i.e., the Alpine Fault, a longer fault than the Canterbury faults) supported by scientific information about it.

Trust in scientists could be a positive influence for earthquake preparedness over time as shown during the COVID-19 pandemic [21], but there is little study of it. Becker et al. [60] are tracking earthquake preparedness before, during and after the CES and monitor trust in local, community and media organizations, but not scientists. Health providers and others that had not maintained their earthquake response and readiness could be researched for possible causes (e.g., Ref. [14]). More deeply understanding lapses in preparedness during an earthquake sequence could be informative to long term communications.

Reminders or cues can be helpful for prompting protective actions [61]. In the workshop with public health providers, they proposed that reminders every six months from scientists could motivate the exercising of emergency procedures and coordination of science, emergency, and public health communications. Seeking reminders was a shift from needing more education about aftershocks and training prior to the initiation of the sequence and earlier in the sequence [12]. An additional consideration is the transition back to baseline seismicity and people digesting risk from sources beyond the immediate sequence. This could be part of the continuum of communication about earthquakes that maintains engagement between exposed populations and scientists [47]. Another example is expanding communications of seismic activity into periods of quiescence for a focus on mitigation of risks, similar to a transition from communications about volcanic unrest to eruption risks [62].

Public workshop participants shared about coping with the uncertainty of earthquake sequence behavior. Becker et al [12] reported that learning about earthquakes and aftershocks aided with coping earlier in the CES. However, information needs were polarized by two forms of coping: monitoring (information seeking to help understand and make meaning of what was happening) or blunting (information avoidance because it caused anxiety) [11,12]. In the workshops, a participant reported that with time her mother had been able to shift from avoiding earthquake information to knowing about it. Overall, participants' reported learning to live with change and uncertainty in alignment with Berkes' [63] factors of building a memory of past events, abandoning the notion of stability, expecting the unexpected, and increasing the capability to learn from crisis. Participants recalled past earthquake experience, they had abandoned deterministic earthquake predictions of alternate theorists, had accepted they couldn't know when the next earthquake would occur, and were curious about even larger Alpine Fault earthquakes. Related is the finding that positive learning outcomes can result from being able to "sit with uncertainty" [64].

4.3. Aftershock scenarios and uncertainty

The third theme encompasses feedback about aftershock sequence scenarios (Table 3), pertaining to their structure, probability expression, and content and use.

4.3.1. Aftershock scenario structure and hazard content

The forecast scenario structure included three possible future aftershock sequences that cover the range of possibilities for (1) a decaying earthquake sequence, (2) an earthquake sequence that is reinvigorated by at least one large aftershock that is smaller than the mainshock, and (3) an earthquake sequence with an aftershock larger than the original mainshock, each with an estimated probability of occurring. Several participants stated that three scenarios was a good number. An initial problem with the comprehension of the set of scenarios was that some participants reported reading the aftershock sequence forecasts as three independent and unrelated future scenarios, rather than as a set of three mutually exclusive alternate future possibilities for the current sequence. An emergency manager participant offered suggestions to "*push out that one of three could happen*". Independently, in another breakout group, a public health official offered a visual betting opportunity:

> "I can see a cartoon coming up. 'Oh, place your bets [on which scenario will eventuate] here'"(Public health official).

Another participant reported misunderstanding the source of the earthquakes in the forecast scenarios and whether it included long faults further away.

A participant expressed concern about "*too much reading*" and the complexity of the earthquake sequence scenario forecasts.

> "I'm looking at the words and I'm thinking some of this would put off the public ….. they kind of want one or the other" (Emergency manager).

An alternative suggestion was made for a single encompassing description.

> "As it's written I would just pick out the common stuff. I would say there are going to be continuing earthquakes, …, on the whole they're likely, most likely to get less and further apart, smaller and further apart, but we could still get, we don't know exactly where they're going to be, we could still get a significant larger one, and so I wouldn't necessarily paint the three different scenarios, I'd just paint the full range in one sentence …..and then people don't have to sit down and work out what the differences are. They've got the information they need" (Emergency manager).

The public health workshop discussed the meaningof "typical" in the first aftershock sequence scenario. An analogue for what is typical was recommended. There was also interest in a worse-case earthquake sequence scenario:

> "Yes, yes. I'd rather have a worst-case scenario and have some idea of what's going on, if and when it ever happens, than to have it come out of the blue" (Member of the public).

Independently, an emergency manager also acknowledged they would want to know about a worse case aftershock sequence with a 3 percent chance of occurring, which was the probability of the third scenario in the example provided.

A member of the public was interested in the scientific backing of the aftershock sequence scenarios, as in how and where the aftershocks could occur including which fault lines could be involved within the fault system. Additional hazard information was also of interest in terms level of shaking (by member of the public) and potential for a tsunami (by all three participant groups).

4.3.2. *Aftershock scenario probabilities*

Targeted discussion about the expression of the probabilities for the three aftershock sequence scenarios confirmed that communication of uncertainty is necessary for credibility of the information; overly precise probability statements would be met with distrust. Preferences for communicating the uncertainty of probability estimates varied. One person from the public provided support for having one approximate number:

> "*No difference to me to have the range; Appreciate it is hard to forecast; Looking at overall relative number. Keep it simple for us" (Member of the public*).

Other participants expressed preference for a probability range:

> "I want to know if it's in a high range" (Emergency manager).

> "I want to know how much they [scientists] don't know" (Member of the public).

It was noted that when no range is communicated, a single point estimate is considered "not real" and leaves it open for people to extrapolate around the number inferring their own uncertainty range. A member of the public expressed a belief that the certainty of the probabilities had improved with more knowledge of the earthquake sequence.[2]

Emergency managers endorsed the use of wording (for example, 'unlikely') alongside the numerical probabilities of the scenarios:

> "I like that you use the words and not just the percentages" (Emergency manager).

They noted two caveats: 1) The words (like the probabilities) are tied to forecast time windows:

> "the use of very likely or very unlikely is also proportional to the timeframe you are talking about" (Emergency manager),

and 2) the verbal and numerical associations requires consistency across hazards:

> "I think the range is useful but across hazards I think it needs to develop some consistency" (Emergency manager).

4.3.3. *Aftershock scenario use*

Some participants appreciated the potential use of the three earthquake sequence scenarios as a planning tool. An emergency manager summarized the scenarios by noting that the *"confidence to maneuver go[es] up as probabilities go down"*. In other words, when the situation is more dire, it is clearer that emergency managers need to act. Some participants reiterated that it is important to know what might be expected from future earthquake activity, but they needed further consultation and discussion on the potential impacts and their implications for decision-making. For example, an emergency manager concerned with public safety and employing human

[2] This comment about accuracy of probabilities increasing with time and knowledge, suggests that over the longer timeframe of a sequence people may believe forecast and probability information to be more certain and potentially useful. However, the perception of increased accuracy is not necessarily true for long duration forecasts that depend on the accuracy of decay parameters ([72], p. 159).

resources described:

> "in 1st scenario. if I have a cordon zone, would be wary……Want to know if we should be ready for egress, would want consultation with engineers with this.
>
> 2nd scenario – good to know – need to know, how are people reacting? Are they leaving home? Stronger powers for preparedness.
>
> 3rd scenario, it is hard – where are these [earthquakes] going to be? What are the effects and safety of buildings?" (Emergency manager).

Public health and public participants wanted to know what they should do within their control.

In contrast to identifying impacts, in the public health workshop discussion, a participant offered a message about reduced building risks since the beginning of the earthquake sequence owing to demolition of unsafe buildings and building back stronger:

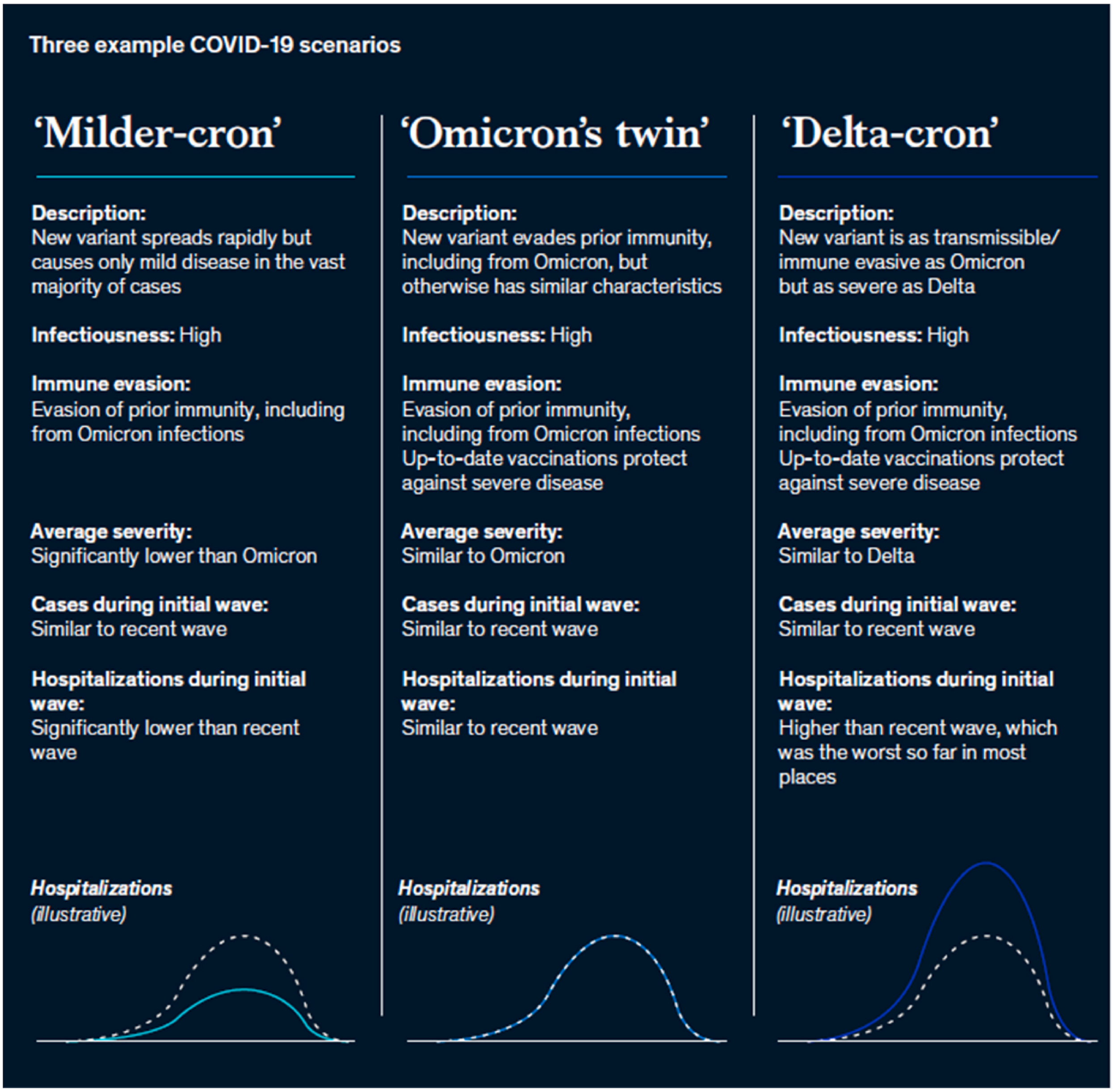

Fig. 3. Exhibit from "When will the COVID-19 pandemic end?", July 2022, McKinsey & Company, www.mckinsey.com.

> "One of the key messages I think is that Christchurch is a sacred place, so our buildings that have been built are a lot better" (Public health official).

Participants identified scientific sources of impact information as credible, which then helped them when communicating with the public about earthquakes:

> "For me, with my Civil Defence hat on, I feel far more comfortable going to public consultation showing them here's the science, cos other than that when I talk to people about the assessment I'm talking about my best guess based on my experience, and I don't have a science background, so I wouldn't call my assessment credible" (Emergency manager).

Some participants acknowledged that local governments in New Zealand have varying scientific capabilities, with smaller regions relying on national level sources for impact information. The need for multiple credible sources of information about implications and impacts echoed earlier discussion about coordinated communications soon after the earthquake.

4.3.4. Discussion of improving aftershock scenarios

Aftershock scenarios are a novel communication product that can bring attention to the protracted nature of earthquake sequences. In summary, we heard that three aftershock scenarios with verbal/numerical probability ranges adequately cover the potential outcomes of an aftershock sequence while conveying unknowns. There is also a place for more concise descriptions of the range of forecasted aftershock scenarios. Participant feedback suggests that the scenarios could be improved by (1) clearly presenting that one of the three scenarios will occur and the likelihood of each one, (2) identifying levels of shaking intensity and other hazards (e.g., tsunami, liquefaction) that could be triggered, (3) describing impacts for each scenario in support of decision-making, (4) providing preparedness advice, and (5) explaining fault behavior underpinning each of the three scenarios (e.g., [65]).

The second item seeks a comprehensive description of all the hazards that might occur, which could help to bear in mind the potential for further cliff collapse in the case of the Valentine's Day earthquake. The fourth item is supported by risk communication advice to couple hazard information with recommended actions (e.g., [13,66,67]). The fifth item expresses curiosity about understanding earthquake processes to gain knowledge that may help with living and coping with uncertainty.

On the first point, there appear to be few examples of real-time protracted hazard forecast scenarios. Charumilind et al. [18] presented three future coronavirus pandemic scenarios consisting of a description of virus behavior, measures of severity, impacts of cases and hospitalizations in context of what has occurred, and a comparative visual representation (Fig. 3). This scenario construction aligns with feedback received on aftershock scenarios: that is, three future scenarios is a good number; explain underlying behavior (e.g., of the fault zone) for each scenario; convey potential impacts; and present a worse case.

Although, the likelihood of each of the COVID-19 scenarios occurring was not, or could not, be assigned, communicating uncertainty has been found to be critical to fostering trust [68]. With or without technical training, people can comprehend earthquake forecast uncertainty (Schneider, 2022). When people know uncertainty exists, they want to be informed about how certain the scientific findings are [69] and if not provided, make their own assessment of how low or high the uncertainty may be [70]. Furthermore, use of numbers and words to convey probabilities for events has been shown to improve comprehension of the information, although different time periods and different hazards present a challenge for verbal descriptions [48]. Our workshops gathered evidence to the same effect.

While some people wanted to keep it simple by using 'about' or 'approximately' before a single probability number, others wanted to know the range of the uncertainty around the probability mean. However, the communication of probability ranges comes with challenges. McBride et al. [71] reported that the media rarely reported the lower end of an earthquake magnitude probability range, only the pessimistic top end of the range. Requests for ranges of probabilities may reflect an increased level of sophistication gained from experience with an earthquake sequence in addition to technical users of the forecasts.

Alternatively, ranges of expected numbers (rather than probabilities) of earthquakes were found to be successfully communicated in the media for the M.7.1 Anchorage Earthquake, with the media communicating the range more frequently than previously [72]. In a prior study, participants also endorsed communication of the range of expected number of earthquakes and found a comparison with actual outcomes validating and reassuring [12].

On the fifth point, the need for forecast impact information could be informed by development of impact-based forecasts by Meteorological Services (e.g., Ref. [73,74]) at the encouragement of the World Meteorological Organization [75]. A key finding on the effectiveness of the forecasts has been that while the provision of impact information improves risk perceptions, it has not necessarily translated into taking action [73,76]. Some of the perceived challenges in providing impact-based forecasts include lack of impact data to draw from, the need to understand vulnerability and capacities of affected populations and designing for individual use rather than community scale use [74]. In a study of multiple hazards, Merz et al. [77] conclude that the effectiveness of impact-based forecasts for various uses could increase from understanding their use in decision-making and developing them collaboratively, consistent with the approach of Schneider et al. [53].

In the case of earthquakes, there may be more data to draw from to develop impact forecasts for use in decision-making. For example, after the 2016 Kaikoura, New Zealand earthquake, the aftershock forecast was translated into risk-based forecasts to satisfy user-demand for estimates of temporal risks of fatalities, masonry falling onto streets, and exceedance of shaking design levels for structures [13]. The risk-based products were developed iteratively with engineers and used to inform government response for mandatory retrofitting or official assessment of unreinforced masonry buildings in central New Zealand. Additionally, Merz et al. [77] summarize capabilities for Operational Earthquake Loss Forecasts (OELF) in Italy and the United States including a spatiotemporal earthquake cluster model [78] that underpins a prototype loss model [79].

Impact assessment tool capabilities used in developing hypothetical but plausible earthquake sequence scenarios for disaster exercises and mitigation planning could also assist with real-time scenario development [77]. For example, Prompt Assessment of Global Earthquakes for Response (PAGER) has the capability to estimate population exposure, fatalities and economic losses [47]. In depth, the HayWired earthquake sequence scenario [80] considers repeat liquefaction, cumulative building and water utility damages, waves of population displacement, and evolving uses of earthquake early warning during response and recovery phases of an earthquake sequence [81]. The HayWired Scenario Toolkit (https://www.earthquakecountry.org/haywired/toolkit/) includes a discussion-based exercise tool for incorporating aftershocks (and afterslips) into recovery planning.

Another technique is a qualitative approach to describing impacts as demonstrated by the Department of Interior Strategic Sciences Group (https://www.doi.gov/strategicsciences/publications)This is a process that assembles experts to identify chains of consequences – social, environmental, and economic – to help support longer-term strategic planning (i.e., for recovery rather than response). Such deliberation among multi-disciplinary experts could benefit the development of aftershock sequence impact information that is specific, credible, and actionable. Overall, an extension of impact information within forecasts would add another layer of analysis and need for meaningful communication of those uncertainties [64].

4.3.5. Implications for research and application

Table 4 encapsulates the thematic analyses and key insights about aftershock forecast communications that inform user needs research and capacity planning for the science agency. As highlighted in our previous research, organization capacity and resources are critical considerations for successful communication of aftershock forecasts [12] and additional implications are identified from this study. This falls under the umbrella of organizing for communication sustainability in Sutton et al. [14]. The table presents the key insights from the analysis and literature, integrating the relevant themes and subthemes of surprise of the Valentine's Day earthquake, time dynamics and utility of aftershock forecast scenarios.

5. Conclusion and future directions

The workshops conducted by GNS Science and Massey University with emergency managers, public health officials, and members of the public, provided a long-term perspective on the communication of aftershock forecasts six years into the Canterbury earthquake sequence that initiated in 2010. In this conclusion, we summarize study findings, research and knowledge gaps, and implications for science organizations. Details are provided in Table 4. We also discuss limitations of this exploratory study of long-term hazard communication and a need for broader participation.

The workshop discussion highlighted aspects of surprise around the 2016 M5.7 Valentine's Day earthquake. Knowledge of earthquake sequence behavior helped reduce the surprise of a large earthquake six years into the sequence and make sense of damaging aftershocks throughout the sequence. This indicates potential long-term effectiveness of risk communication about the aftershock sequence behavior (e.g., potential spikes of seismic activity) when affected populations and decision-makers are paying attention (e.g., after large earthquakes or during exercises).

Participants conveyed evolving trust in scientific sources of information, shifting earthquake risk perceptions, increased coping with uncertainty of aftershocks, desire of the affected population to get on with their lives, as well as lapses in preparedness. There is more to understand about the dynamics of trust including among users of different communication channels and transparency about uncertainty in an evolving situation. How people cope with uncertainty over time could involve greater reflection, specifically in relation to public education. For example, whether the following components of aftershock forecasts contribute to coping with uncertainty (after [63]).

- explaining earthquake sequences;
- showing earthquake sequence events that have occurred;
- conveying uncertainty in earthquake forecasts;
- explaining the physical processes of stress redistribution in the crust following a fault rupture.

Workshop participants recognized that earthquake information needs diverged depending on prior exposure to earthquakes and the need for tailored communication for new and young, as well as re-traumatized, residents. Furthermore, risk communications coordinated through agency networks would help fill the gaps that occurred around the Valentine's Day earthquake. Retrospectively, participants reported looking to the trusted science organization for reminders about the hazards and risks of an ongoing earthquake sequence and motivation to maintain preparedness and response communications. A strategic consideration to explore further could focus on issues like frequency of aftershock forecast communications and decision-relevant timeframes and products to help maintain appropriate levels of concern and preparedness while earthquake risk is changing and overall declining to the baseline earthquake risk. Another consideration is maintaining coordination of science advice, emergency management, and public health messages.

Participants largely endorsed three aftershock scenarios that could be improved with visual representations to reduce reliance on text and clearer presentation that one of the three scenarios will occur and the likelihood of each one. Additionally, they wanted descriptions of fault zone processes underpinning each scenario; information about potential hazards including shaking, ground failure and tsunami; preparedness advice; and understanding of potential impacts for decision-making. Regarding the latter need, aftershock forecast scenarios are an example of the emerging area of impact forecasts in research and practice to provide actionable information to users. Qualitative and quantitative multi-disciplinary methods and processes could be explored and evaluated to describe aftershock scenario impacts and residual risks (e.g., forecast shaking intensity maps [53], collaboration with engineers [13], and hypothetical

Table 4
Thematic analyses and key insights to inform research, implementation, and communication plans.

Themes and Subthemes	Insights from Participants and Literature	Implications for User Needs Research and Application	Communication Capacity Planning Considerations
Element of Surprise			
People informed about earthquake sequence behavior; not surprised	Concepts of aftershock sequence behavior (spikes of activity) and magnitude distribution sustained sense-making over time. Line graphs of cumulative risk have been found to be effective [29,30].	Investigate effective ways and timings for providing periodic aftershock information, including specific products, e.g., use of line graphs of sequence behavior and duration reports in aftershock forecast communications.	Communicate earthquake sequence behavior prior to, early in the sequence, and periodically, particularly after large aftershocks when people are paying attention. Link aftershock forecast to the notification of a large aftershock. Implications of smaller aftershocks could also be communicated.
People informed about earthquake sequence behavior; not surprised *and under activated*	Risk perceptions decrease with decay in aftershock activity, demolition of unsafe buildings, stronger rebuilding. Concern about a hazard decreases with time [16]. Residual risks may be overlooked (e.g., cliff collapse).	Collaborate to develop tools or mechanisms for ongoing hazard and risk assessments and communication of risk during earthquake sequences.	Communicate about residual risks and potential impacts from these risks.
	Organizations take cues from each other and a lack of response in one part of the network may socially attenuate risk communications] [26].	Explore effective ways to develop relationships, networks and shared mental models for response, ahead of an event, so that organizational responses are agreed upon, coordinated, and effective.	Develop relationships, communication networks and planning before an event. Develop, maintain and practice coordinated messaging during an earthquake sequence.
People “getting on with their lives”; setting up for surprise	Over time affected populations may psychologically adapt[16], resulting in decreased attention to earthquake risk, reduced concern.	Conduct research on factors affecting risk perceptions during an earthquake sequence.	Use balanced messaging over time - to support people wanting to get on with their lives, while also helping them understand ongoing risks.
Re-traumatized or new residents or visitors inexperienced with earthquakes; surprised and upset	Over time, experience with earthquakes diverges in the population, leading to different information needs.	Develop communication tailored to populations with widely divergent earthquake experience and backgrounds.	Communicate tailored information with populations that have ranges of earthquake experience including empathetic messaging for new, young, or re-traumatized residents.
Time Dynamics			
Atrophy of vigilance [19]	As risk decreases and earthquake experience diverges, organizations may fail to execute earthquake response protocols executed earlier in the sequence. Challenge is to balance message fatigue [14] or cry wolf with reminders to maintain preparedness [61]. Emergency managers and health officials may look to the lead science agency for aftershock reminders and risk information.	Understand the factors leading to reduced vigilance. Investigate how particular types of trusted information or communication might assist in keeping attention on risks e.g., frequency, regularity, and time window of decision-relevant aftershock forecasts to prompt practice and preparedness relative to risk and the transition back to the baseline risk.	Communicate throughout a sequence with effective types of information to support preparedness and risk mitigation. Incorporate active aftershock forecast information into regular readiness activities (e.g., the international ShakeOut drills at shakeout.org).
Evolution of trust in lead science agency for aftershock information	The evolution of trust in scientists may be differentiated by population characteristics [22] and channels [24,25], and local vs national government providers [23]. Communication of uncertainty instills trust [68].	Understand the dynamics that affect trust in scientists by audience characteristics during an earthquake sequence including information providers and products (e.g., estimations versus observations), communication channels, empathetic messaging, communication of uncertainty.	Develop strategy and products for building and maintaining trust with various audiences on various channels for long term communications, which includes monitoring misinformation and providing accessible information on social media.
Coping with the uncertainty of earthquake sequence behavior in affected population	Building memory, communicating uncertainty, and aiding learning about aftershocks may help people cope with it (aligns with [63]).	Investigate aftershock information/ forecast content that can be communicated and that can assist people to live with uncertainty of the earthquake sequence behavior.	Acknowledge that experience over time can help people accept there is some uncertainty in earthquake sequences, while also continuing to communicate the uncertainties involved.
Expanded information needs for affected and informed populations	Informed populations experienced with earthquakes may continue to seek deeper and broader scientific understanding (follows from Ref. [12])	Develop communication products with layers of technicalities and scientific depth (including fault systems) and breadth of baseline seismicity.	Respond to increasingly sophisticated audiences, by providing more detailed information for those who seek it.
Shifts in risk perceptions in the affected population	Increased appetite for risk communication about larger earthquake sources or risk from different locations, may present. Or, as above, risk perception may lessen as the aftershock sequence decays, or there is less perceived risk to the built environment.	Understand how risk perceptions shift over time, including with respect to hazards from other earthquake sources/ locations.	Present the aftershock forecast in context of baseline risks. Provide information or mechanisms to engage about broader earthquake risks affecting the region.

(*continued on next page*)

Table 4 (*continued*)

Themes and Subthemes	Insights from Participants and Literature	Implications for User Needs Research and Application	Communication Capacity Planning Considerations
Aftershock Scenarios			
Structure and hazard content of aftershock scenarios	Three forecast scenarios including an extreme case could be presented in a more accessible layout (e.g., Ref. [18]), alongside the fault behavior underpinning each of them and expected shaking and triggered hazards.	Investigate effective scenario structures and content including visual components that make it clearer (e.g., visually) that 1 of 3 scenarios will occur and the communication is less reliant on text alone. Also, consider developing an all-encompassing summary of aftershock sequence behavior.	Continue to use and improve scenarios. Streamline process for quickly constructing aftershock scenarios to complement earthquake probability table information. Underlying fault behavior for the scenarios may be of interest, while also acknowledging the possibility of unknown faults.
Aftershock scenario probability and uncertainty	Verbal likelihoods of forecast scenarios may supplement probability numbers [48] while being conscious of inconsistency across hazards and variations in forecast time window decision needs. Some decision-makers may seek confidence intervals for the probabilities.	Address representation of uncertainty for clearly stated time windows and geographical area of the source of aftershocks as appropriate for the forecast and ability of users to interpret them.	Educate on forecast capabilities. Be prepared to provide and explain uncertainty of aftershock scenario probabilities for informed decision-makers that seek them (e.g., as probability ranges).
Utility of aftershock scenarios	Multi-hazard and impact information may be needed for actionability of aftershock forecast scenarios by decision-makers. Members of the public also wanted relevant preparedness information.	Develop tools and processes for real-time forecasting of hazards (shaking, ground failure and tsunami) and scenario impacts including uncertainty, linking to actions and decisions. Investigate the efficacy of impact-based aftershock forecasts.	Maintain long term collaborations to support developing and communicating scenarios with multiple hazards and impacts, including uncertainties and links to coordinated preparedness actions.

earthquake sequence scenarios [81]. Evaluations of impact-based meteorological forecasts and warnings may be informative to incorporating impacts into aftershock scenarios.

A study limitation is that qualitative data are gathered from a subset of decision-makers: emergency management professionals, public health providers, or interested and informed members of the public. In some cases, our participants speculated on the perceptions and information needs of others. We did not access other groups that participated in the earlier 2013 study [11,12] including scientists, geotechnical and structural engineers, critical infrastructure providers and business owners, public information officers, media reporters, and politicians. Furthermore, a recovery decision-maker with a long-term perspective was absent from the discussion of aftershock scenarios. As described in the methods sections, very few of the previous participants that were invited by email re-engaged. New participants were invited through civil defence management agency advertisement and a disaster conference announcement.

Intentional engagement with members of racial and ethnic groups (including recent migrants) and other under-represented communities would improve accessibility and cultural relevance of information for broader applicability of risk communications during a protracted earthquake sequence. Future research could expand the study of long-term risk communications with populations that are particularly vulnerable to aftershock sequence impacts including new incoming populations during a protracted (e.g., 5–10 years) earthquake sequence. Such investigations of aftershock experiences would be valuable for science agencies to develop better information products for on-going hazard and risk communication.

Overall, our research highlights experience with an aftershock sequence and forecast information to understand factors and dynamics of long-term risk communication and implications for research and practice. It is a continuation of the research program started in 2013; representing an ongoing initiative to study the communication of aftershock forecasts and ways science agencies can make improvements to the critically important informational products and communication processes.

CRediT authorship contribution statement

Anne M. Wein: Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Sara K. McBride:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Julia S. Becker:** Writing – review & editing, Writing – original draft, Project administration, Investigation, Data curation, Conceptualization. **Annemarie Christophersen:** Writing – review & editing, Writing – original draft, Software. **Emma E.H. Doyle:** Writing – review & editing, Writing – original draft, Resources. **Matthew C. Gerstenberger:** Writing – review & editing, Writing – original draft, Resources. **Sally H. Potter:** Writing – review & editing, Resources.

Declaration of competing interest

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Commission (presently Natural Hazards Commission), GNS Science, Land Information New Zealand, National Emergency Management Agency, Ministry of Business, Innovation & Employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Earthquake date and location data for the Canterbury earthquake sequence are available at https://quakesearch.geonet.org.nz/. The workshop data contain information that could compromise the privacy of research participants and thus, these GNS Science/ Massey University data cannot be publicly released. For more information, please contact Julia Becker at Massey University.

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Disclaimer: Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Appendix A. Codebook from Researcher 1

Codes

Name	Files
Critical information	3
— blunting - not wanting to hear info - fatalism	1
— Emotional wellbeing	1
— Misinformation	1
— mislocation	1
— Uncertainty	1
Mag gaming	3
Other earthquakes	1
Perceived panic by officials	2
Preferred channels	4
Sequence recall	3
Suprise	2
USGS Nepal and Pawnee product	4
— Scenarios	4

Table A. Initial code book developed for qualitative analysis.

Appendix B. : Final Codebook from Researcher 2

Table B
Final code book for analysis of long-term communication and contributions to themes by participant groups of Health – Christchurch public health workshop participants; Public – Christchurch public and Wellington (except for one emergency manager) workshop participants; EM – Christchurch emergency manager workshop and Wellington emergency manager participants.

Themes	Subthemes	Codes	Health	EM	Public
Surprise at time of Valentine's day earthquake	Expression of surprise	Yes, no, set up for surprise	X	X	X
	Surprise about what?	Sequence, aftershock (Valentine's Day) 6 years later, magnitude/time, people's reactions	X	X	X
	Experience with sequence	Time living in affected area, experience with earthquake sequence individual events	X	X	X
	Knowledge of earthquake sequences	Degradation, spikes of activity, magnitude frequencies	X	X	X
	Attention to forecasts	If and when would consult forecast	X	X	X
	Risk perceptions	Buildings, cliffs, Alpine and Porters Pass Faults	X	X	X
	Coping	Signs of distress	X	X	X
	Response and communications	Responsiveness of organizations (emergency responders, hospitals, science agency, news and social media, schools), factors affecting amplification/attenuation of risk communications	X	X	
	Strategies to maintain preparedness	Reminders about sequence to prompt exercising of procedures and coordination of communications	X	X	
Changes over time	Psychological adaptation	Relative concern with experience of the earthquake sequence	X	X	X
	Atrophy of vigilance	Preparedness/response relative to earlier in the earthquake sequence	X	X	
	Living with uncertainty	Coping with uncertainty of earthquakes with experience and knowledge			X
	Trust in Science Agency	Evolution of trust in science agency	X	X	X
	Information needs	Information needs (frequency and content) compared to earlier in the sequence and other parts of the country.	X	X	X
Aftershock forecast scenarios	Scenario structure and hazard content	Number and scope of scenarios, misunderstandings of the structure, fault lines underpinning the scenarios, other related and triggered hazards	X	X	X
	Probability and Uncertainty	Credibility of communicating uncertainty, needs for number ranges and verbal descriptions	X	X	X
	Other information needs	Impacts of scenarios, preparedness advice	X	X	X

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