International Journal of Disaster Risk Reduction 50 (2020) 101713

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: http://www.elsevier.com/locate/ijdrr

Developing post-alert messaging for ShakeAlert, the earthquake early warning system for the West Coast of the United States of America

S.K. McBride [a,*], A. Bostrom [b], J. Sutton [c], R.M. de Groot [a], A.S. Baltay [a], B. Terbush [d], P. Bodin [e], M. Dixon [d], E. Holland [f], R. Arba [g], P. Laustsen [a], S. Liu [a], M. Vinci [h]

[a] USGS, USA
[b] University of Washington, USA
[c] University of Kentucky, USA
[d] Washington Emergency Management Division, USA
[e] PNSN/USGS, USA
[f] California Governor's Office of Emergency Services, USA
[g] California Public Utilities, USA
[h] California Institute of Technology, USA

ABSTRACT

As ShakeAlert, the earthquake early warning system for the West Coast of the U.S., begins its transition to operational public alerting, we explore how post-alert messaging might represent system performance. Planned post-alert messaging can provide timely, crucial information to both emergency managers and ShakeAlert operators as well as calibrate expectations among various publics or public user groups and inform their responses to future alerts. There is a concern among the scientists and emergency managers that false alerts may negatively impact trust in the system, so quickly disseminated post-alert messages are necessary. For a new early warning system, such as ShakeAlert, this is particularly relevant given that the potentially affected population is likely to be unfamiliar with this system. We address this concern in six steps: (1) assessment of ShakeAlert performance to date, (2) characterization of human behavior and response to earthquake alerts, (3) presentation of a decision tree for issuing post-alert messages, (4) design of a critical set of post-alert messaging scenarios, (5) elaboration of these scenarios with message templates for a variety of communication channels, and (6) development of a typology of earthquake alerts. We further explore methods for monitoring and evaluating ShakeAlert post-alert messaging, for continuous improvement to the system.

1. Introduction

As the U.S. Geological Survey (USGS) and its partners allow for broader access to the earthquake early warning system, ShakeAlert, on the West Coast of the United States (Washington, Oregon, and California), there is increasing recognition that its effectiveness depends on the expectations, trust, and responses of West Coast communities to the system [1]. Post-alert messaging is messaging that is sent after an initial alert has been distributed via various channels. Distribution of post-alert messaging may be critical to building trust and appropriate expectations of ShakeAlert from various publics. Publics is a term that refers to the key groups and individuals, whether by locality or interest, which a specific communication is intended for and with whom a communicator interacts [91]. 'Publics' is the umbrella term for receivers, audiences, and communities [92]. Developing this messaging pre-event is important for fast and effective dissemination. Successful post-alert messages are best designed by identifying likely alert system performance scenarios, within post-alert messaging capabilities, and examining the likely expectations and information needs of alert recipients based on findings from the social and behavioral science disciplines. This paper addresses those needs as they apply to ShakeAlert. Planning ahead for post-alert response will support efficiencies during crisis, clearer communications, and therefore more effective responses to alerts and earthquakes. This is particularly relevant for ShakeAlert, as the public becomes more familiar with this new earthquake early warning system in the western U.S.

Post-event reports on the 2018 Hawai'i Ballistic Missile False Alert [2,3] confirmed decades of crisis communication research by illustrating the need for fast communication by agencies if a warning system performs outside expectations of users, including false alerts [3–10]. Even if details of the situation are not available in the early minutes after a false or otherwise potentially confusing alert, organizations cannot afford to wait to communicate something to the public [11–15]. By communicating quickly, organizations engender trust in capabilities to manage

* Corresponding author.
E-mail address: skmcbride@usgs.gov (S.K. McBride).

https://doi.org/10.1016/j.ijdrr.2020.101713
Received 9 September 2019; Received in revised form 28 May 2020; Accepted 5 June 2020
Available online 27 June 2020

the situation during times of crisis or perceived failures [5,6,12,16,17,80,83]. “All-clear” messaging,[1] meaning that the situation is no longer dangerous, could be useful and appropriate in some situations [18]. Further, we argue that there is a need for better post-alert messaging that addresses users’ experiences and expectations in the specific context of ShakeAlert. Issuing post-alert messaging within minutes of alerts requires advance consideration of message content and how it may be perceived and acted upon by an anxious public.

The remainder of this introduction sets the stage for developing a ShakeAlert post-alert messaging strategy, by characterizing the current state of early warning systems and the widely used signal-detection alert types. Subsequent sections present our research methods, our results (presented in six steps), then discussion of limitations and conclusions.

1.1. Early warning systems

Early warning systems are implemented globally [19,20,93]. Those for earthquakes, lahars, and tornadoes rely on near-instantaneous warning, which is a unique challenge of these systems, because it affords little time for scientific interpretation and validation by humans [21–24]. While our study is about earthquake early warning systems, the tornado literature offers relevant insights on how people respond to alarms (“alerts” for this paper) and how false alerts can negatively impact the credibility of the organization issuing the alert [22,25–27]. False alert tolerance is a product of trust in warning systems; too many false alerts can lead to reduced trust in an alert system, which can endanger people if and when alerts are correctly sent, and protective actions are not taken [26,27]. If people lose trust in the system, they may no longer take protective actions, or they may disable alert delivery devices altogether [28]. Further research themes to be explored in future for early warning systems, generally, are described in Tan et al. [94].

Lahar warning systems also are automated and provide important warning messages with very little time [24,95]. In New Zealand, a lahar warning system exists on the Mt. Ruapehu ski fields and relies on sirens [21,24]. As lahars provide little natural warning, alert systems have been placed in areas where people are at greatest risk from lahars to signal the need for immediate evacuation [21]. However, we found little useful evidence regarding how people responded to false alerts for lahars.

Different countries use diverse communication channels for their largely automated warning systems. Sirens and prerecorded messages broadcast on a public address (PA) system are used in many countries to warn people of lahars and tornadoes, and, in the case of Mexico City, earthquakes [29]. Mexico City has long used sirens as the primary warning channel, with the sirens emitting a characteristic sound to alert residents when earthquake shaking is imminent [30]. In Central Java, Indonesia, on the Merapi Volcano, traditional methods (drums) combine with the modern broadcast warning system [23]. Critical to the successful use of sirens and broadcast messages is that the community be informed about what they mean before they are used, that unique sounds are used for alerting for different hazards, for drills or tests rather than for actual alerts, and that the community is prepared to take appropriate protective actions when they sound [20,28,31].

For the U.S.-based ShakeAlert system, public alerts are being provided, as of October 2019, to publics in California via the MyShake app as explored in Strauss et al. [32] and Wireless Emergency Alerts (WEAs) [33]. Other alerting delivery apps exist or are under development. For example, Los Angeles County residents were the first publics to receive the alerts through a smartphone app, which was made available in January 2019 and developed by the City of Los Angeles [34]. Thresholds for this app were lowered in July 2019, so people in Los Angeles County who download the app can receive alerts when a magnitude (M) 4.5 earthquake occurs and ground shaking is predicted to be at least a Modified Mercalli Intensity (MMI) of III at the user’s location [34]; this shaking level is considered “Weak” [35].

Overall, we found that experiences and expectations of warning systems vary depending on the type of hazard, the population affected, and the system used.

1.2. Types of alert outcomes

Different warning performance typologies can result from alert systems. For example, Trainor et al. [36] uses the warning typology with false, hit (correct), miss, and all clear (correct no alert). Fig. 1 [37] illustrates four types of alert outcomes that are acknowledged in earthquake early warning systems and are based on the presence or absence of an event (e.g., an earthquake), and whether or not the system issued an alert: false, correct, missed, or correct no alert [38]. A false alert occurs when an event is not observed, but an alert is sent; a correct alert occurs when an event is observed and an alert is sent; a missed alert occurs when an event is observed, but no alert is sent; and a correct no alert when there is no event observed, and populations are not alerted [38].

Many warning systems adopt this quadrant classification—whether for tornadoes, volcanoes, or for air traffic control—to describe missed or false alerts [26,40–43]. In weather and other warning contexts, these classifications are based on the dimensions of occurrence (e.g., was there a tornado or in this circumstance, did an earthquake occur) and detection (e.g., did the system detect the event) which is based on signal detection theory [44].

Perceptions of systems are also a critical factor. Trainor et al. [36] found that perceptions and definitions of false alerts vary, and that the variance largely depends upon whether or not the receiver believed the alert was justified, specifically if there was a perception that forecasters did not have a justifiable reason to send the message. An added layer of complexity is the concept of alerting thresholds, i.e., when to send alerts to users and when not to. For the ShakeAlert system, Minson et al. [38] noted that for earthquakes, the alerting threshold can be set to be lower or higher than the shaking level that might cause damage, depending on the user’s tolerance of false alerts. In response to the feedback received from users of the app, developed by City of Los Angeles to alert residents in the county following the 2019 Ridgecrest, California, M 6.4 and 7.1 earthquakes, alerting thresholds were lowered. Residents were not warned because the shaking levels were not forecast to be sufficient to cause damage, but some people expressed the desire to be alerted in the future for lower levels of potential felt shaking, not just those thought to be damage-inducing [96].

The concept of a false alert is complex; perceptions from various users can be nuanced and may include, for example, assigning blame for

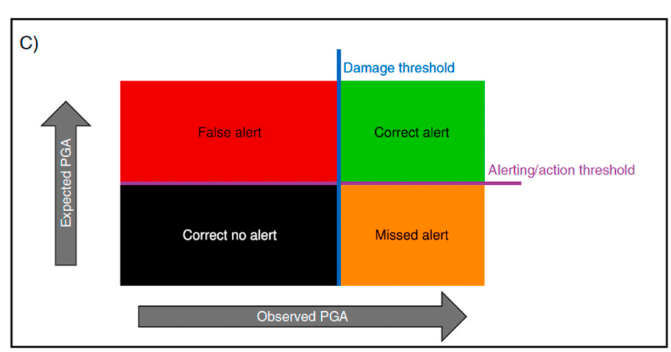

Fig. 1. Warning performance typology (reprint of Fig. 1c from Ref. [37]). PGA means Peak Ground Acceleration.

[1] An “all-clear” is “a signal that tells you that a dangerous or difficult situation has ended” (Cambridge English Dictionary definition).

error [36]. In the case of tornadoes, this is well understood by forecasters and the agencies issuing warnings. This group understands that high false alarm rates reduce recipients' tendency to respond to alarms [27]. This raises a concern about whether false alerts will decrease trust in an earthquake early warning system. From the alert or warning recipient's perspective, at least three additional dimensions are important: Did they personally feel it, did they receive an alert, and was there a risk? Warnings for near misses, for example if a tornado occurred nearby but not close enough to cause damage at individual's location, have not been regarded as false alerts by the warning recipients [45]. Therefore, for earthquake early warning even if someone is alerted but does not feel shaking, they may not perceive this as a false alert.

One counterargument is that people may not be so forgiving of earthquake early warning systems built on seismic networks that are sensitive to and register the seismic signals caused by other events, such as quarry blasts, heavy road traffic, and even exuberant dancing [46,47]. The potential for false alerts to decrease trust in the system, together with the discrepancies between what warning issuers and recipients define as false alerts, suggest that the issuers of alerts may be concerned with the reputation risks of issuing false alerts, more so than those receiving false alerts. Importantly, this balance depends on a more nuanced view of false and missed alerts than the standard 2×2 warning performance typology (Fig. 1) permits. In this paper, we develop a framework for post-alert messaging based on the nuanced ways in which alerting systems may behave and be perceived by end users, as noted in Minson et al. [37].

2. Methods and results

To evaluate potential post-alert messaging strategies for ShakeAlert, the USGS convened an interdisciplinary working group of seismologists, social scientists with expertise in risk communication and decision making, emergency managers, and communication practitioners. The working group assessed the needs and possibilities for post-alert messaging, with this article representing the process and outcomes of this group. This assessment was both iterative and integrative, and included the development of six products: (1) a summary of ShakeAlert performance to date using data from ShakeAlert testing and certification, (2) a characterization from the literature of what is known about human behavior and response to earthquake alerts, (3) a decision chart representing the decisions required to issue a post-alert message, (4) a critical set of post-alert messaging scenarios developed by the working group, (5) a typology of earthquake alerts informed by (1–4), and (6) a scenario matrix that includes message templates for various communication channels developed by the authors using the messaging and human behavior literature.

The next sections describe the methods and results for the multiple methods that were used to develop each of the six products.

2.1. Products and their development method and results

1) ShakeAlert detection performance and alerting status

The seismic detection system used in ShakeAlert includes two seismic networks: the Pacific Northwest Seismic Network (PNSN) and the California Integrated Seismic Network (CISN) [39] which are both part of the Advanced National Seismic System (ANSS). The seismic detection system is still being expanded; with increased instrumentation the proportion of successful detections are expected to improve.

It is a challenge for seismic networks to locate and characterize damaging earthquakes and predict impending shaking quickly and accurately enough for EEW on the U.S. West Coast, and the ShakeAlert system requires continual testing, research and development to improve its effectiveness [1,48]. Earthquakes in this region are geographically dispersed and tectonically varied; the amount of shaking that an earthquake produces is affected by a number of factors, including the details of the earthquake source itself (e.g. Ref. [49]), the distance from the earthquake source, and the particulars of seismic wave propagation through the region. Both on-land and nearby offshore earthquakes, which the system is designed to detect and alert for, and remote earthquakes affect the seismic signals that ShakeAlert uses to issue messages. For an earthquake to be detected and alerted for in the current ShakeAlert system, four seismic stations within ShakeAlert networks must trigger on the P-waves (primary wave) from the event. A P-wave is the first seismic wave generated by an earthquake. S-waves (secondary) are slower than the P-Wave and generally cause stronger shaking. The ShakeAlert system registers that an earthquake has occurred. The earthquake's location and its magnitude are then rapidly estimated. Next, the system predicts the shaking based on the estimated earthquake magnitude. Lastly, the alerting area is determined and alerts are sent to users, alert distributors, and infrastructure operators (Fig. 2 [39]). The accuracy and timeliness of alerts are dependent on many factors, including the accuracy of the earthquake location and magnitude estimated by the system, uncertainties in prediction of the resulting ground motion, and how much time elapses between the arrival of the initial P wave, which sometimes cannot be felt, and the more intense S wave [37,38]. It is important to note that with every earthquake there is a late alert zone near the epicenter where people will experience shaking before an alert can be delivered because of the time it takes to detect the earthquake, produce the alert, and deliver it.

System performance varies, and depends on location and magnitude of the earthquake, whether or not multiple earthquakes are occurring close in space and time, the density and locations of the seismic stations, and the data transmission latency or other processing delays. For 2018 more than half of the earthquakes of magnitude (M) 4.5 and above were detected successfully across the ShakeAlert system in Washington, Oregon, and California (Table 1 [1,78]). This was true even though the system was evolving and incomplete at the time [1]. Different earthquakes produce diverse alert latencies, population impacts, and ground shaking. Understanding past performance is critical for knowing how the system may behave in the future and what the potential for public protective actions may be. For example, the system, when fully developed, could detect a Cascadia subduction zone earthquake off the Washington or Oregon coast of magnitude 9 and issue an alert in time for many people to take protective actions. It is more likely, however, that the system will be alerting for more frequent and smaller earthquakes, for which many of those in the alerted area will receive very short alert times. Also likely are situations where alerts are received after shaking has arrived, as explored in Minson et al. [38], or alerts that are incorrect about the exact timing, location, or intensity of the earthquake.

The seismic network detection system is foundational to ShakeAlert, but so is the alerting system. The network of telecommunication channels that distributes alerts to end users makes it possible for messages to reach people and technical systems rapidly. As of the publication of this article, the ShakeAlert public alerting system is available only in California, where public alerts are sent through Wireless Emergency Alerts (WEA) and smartphone apps. WEAs are emergency messages sent by authorized government alerting

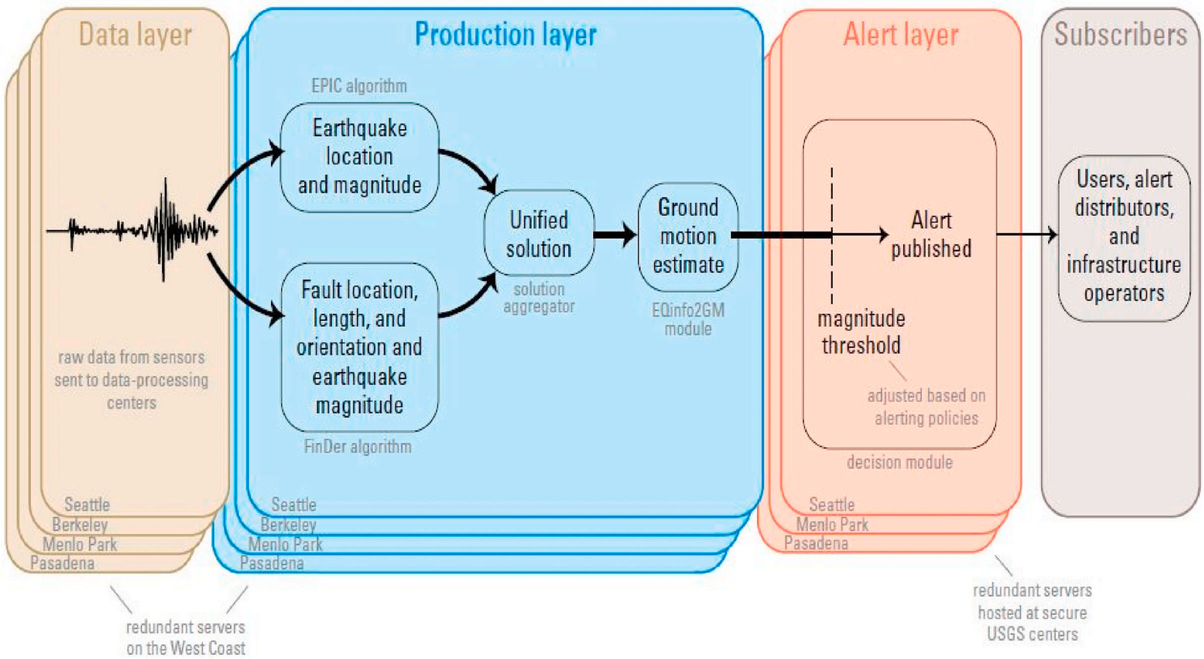

Fig. 2. From Given et al. [39]: schematic flowchart illustrating the architecture of the ShakeAlert system.

Table 1
ShakeAlert detection system performance. Data from the ShakeAlert Testing and Certification platform (TCP) from 2014 [48]. Successful events were detected correctly and alerts were distributed to test users. Missed events were either not detected or an alert was not issued even though the system should have produced an alert. Late events were detected by the system, but certain locations did not receive the information in advance because they were too close to the event to receive the alert before the strongest shaking arrived. Mislocated events were detected but their epicenters were incorrectly located. False alerts were not attributable to earthquakes and typically resulted from technical glitches. Note: This table uses terminology in the typology suggested in this article, explored fully in Table 2.

Earthquake Magnitude	Total Events	Successful	Missed	Late	Mislocated and false
M6+	11	8	1	0	2
M4.5-6	26	14	8	3	1

authorities through mobile carrier networks [98]. For alerts to be sent, both the earthquake magnitude and the predicted shaking at a user's location must exceed a pre-determined threshold that depends on the alert distribution pathway (see Ref. [39]) and alerts are issued only when these thresholds have been met or exceeded. Specific thresholds and smart phone app names are not included in this article as these might change rapidly as the system continues to evolve within the next few years.

2) Human behavior and response to earthquake alerts.

There are three critical aspects to human behavior and response to earthquake alerts: how people interpret their experiences (e.g., shaking); how they interpret any alert (or absence thereof) as it relates to their experience; and what actions they take based on that interpretation. If people believe that the recommended action will protect them from harm, they are more likely to take that action [50]. This three-pronged approach informs the template for post-alert messages.

Evidence regarding how people respond to earthquake early warnings comes largely from Japan [51] and Mexico City [29]. In Mexico City, people interviewed described earthquake alerts as useful even when the alert was sent after the strongest shaking had arrived [29]. However, in a survey conducted for two earthquakes that struck Mexico City in 2017, the system was found to be useful in the first earthquake, where there were 90 s of warning but not as useful by respondents in the second earthquake, where there was little or no warning [52]. In Japan, while people's responses were mixed on late alerts, most respondents nevertheless found the alerting system valuable as it was a confirmation that the earthquake had occurred, and trust in the system did not seem to be negatively affected [51]. Notably, more recent research shows that alerts provide information about earthquakes that recipients appreciate, even if they don't feel the shaking [53]. Further, the Nakayuchi et al. [53] study revealed that only five percent of respondents were concerned about receiving false alerts.

Given the constraints of the system, exploring issues like system performance and suggested timeframes for responses to alerts, the drop, cover, and hold on (DCHO) suite of protective actions was deemed the best approach [38,54]. How false alerts may impact these actions is currently unknown, given the novelty of the system in the United States incorporating the DCHO protective actions. Overviews of the body of research relevant to understanding protective actions taken in response to early warnings suggest that false alerts do not necessarily hinder responses when the reasons for the false alert are communicated clearly, as argued in Mileti and Sorenson [55]. Lim et al. [56] explored the associated human behavior with false alerts for extreme weather, specifically around protective actions and found that respondents were generally not dissuaded by false alerts. However, Wogalter et al. [57] found that individuals' response tendencies depend on the false alert rate; the more false alerts, the more likely people will begin to not take protective actions. The literature is still in flux regarding the issue of false alerts. Yet more research is required on how people interpret and react to false alerts [58].

How people experience an earthquake and align this understanding with an alert received (or not) will vary from person to person, depending on their location, situation, and characteristics, as well as on the earthquake. Understanding human receiver characteristics (e.g., gender, age, culture, race, locus of control) is a critical component in developing any post-alert messaging brief. Receivers' characteristics determine how they make sense of warnings; gender, age, and ethnicity are associated with levels of trust in information (see the review by Ref. [59]). False-alert-tolerant users or risk tolerance may also be a critical issue in terms of developing messaging [38]. Trust in communication channels can also vary by demographic group, as explored in Phillips & Morrow [59]. There is further evidence that psychological characteristics, such as feelings of internal or external "locus of control," which is the degree in which individuals feel they have power over their lives, also influence the interpretation of alerts [60].

People with visual or auditory impairments, reading or learning disabilities, or those who cannot afford smartphones to download apps or receive WEAs, have diverse accessibility requirements [61]. Across the three states (California, Oregon, and Washington) involved in ShakeAlert, over 53 million residents and seven million visitors annually may experience ShakeAlert when it becomes fully available (U.S. Census data,2018[2]). Further, approximately 9–20% of the population in these states, as of 2019, are new immigrants from other countries, suggesting that they may struggle with English as a language [62]. A further estimated 16 million adults who may encounter ShakeAlert, as residents of California, Washington, and Oregon, have learning disabilities and struggle with literacy [63]. Vermeulen [64] and Sellnow et al. [8] suggest that different publics may struggle with overly complex messaging. Given the constraints people may have in receiving and understanding post-alert messaging, it is better to use simple words and non-colloquial expressions to ensure that as many people as possible can understand the information provided to them.

Understanding that requirements for rapid mass transmission of graphics are prohibitive with current technologies, and reflected in the literature cited above, the working group concluded that ShakeAlert post-alert text messages should be simple and descriptive as well as delivered over trusted and accessible multi-communication channels.

3) Post-alert messaging decisions

A critical step in generating the scenarios for post-alert messaging is assessing what is known immediately after an earthquake or when the system has issued a ShakeAlert Message. Knowledge of the monitoring, detection, and alerting performance determine a set of post-alert messaging decisions. This process can be represented by a decision flow chart (Fig. 3), which maps directly to the scenarios (Table 2 in the next section) and alert typology (Table 3 [65]). Fig. 3 highlights the limitations and constraints that the ShakeAlert operational team will face for post-alert messaging. Further, Fig. 3 highlights opportunities for longer-form responses stemming from early assessments, based on which information the ShakeAlert operational team does or does not have available to them at the time the post-alert message is sent.

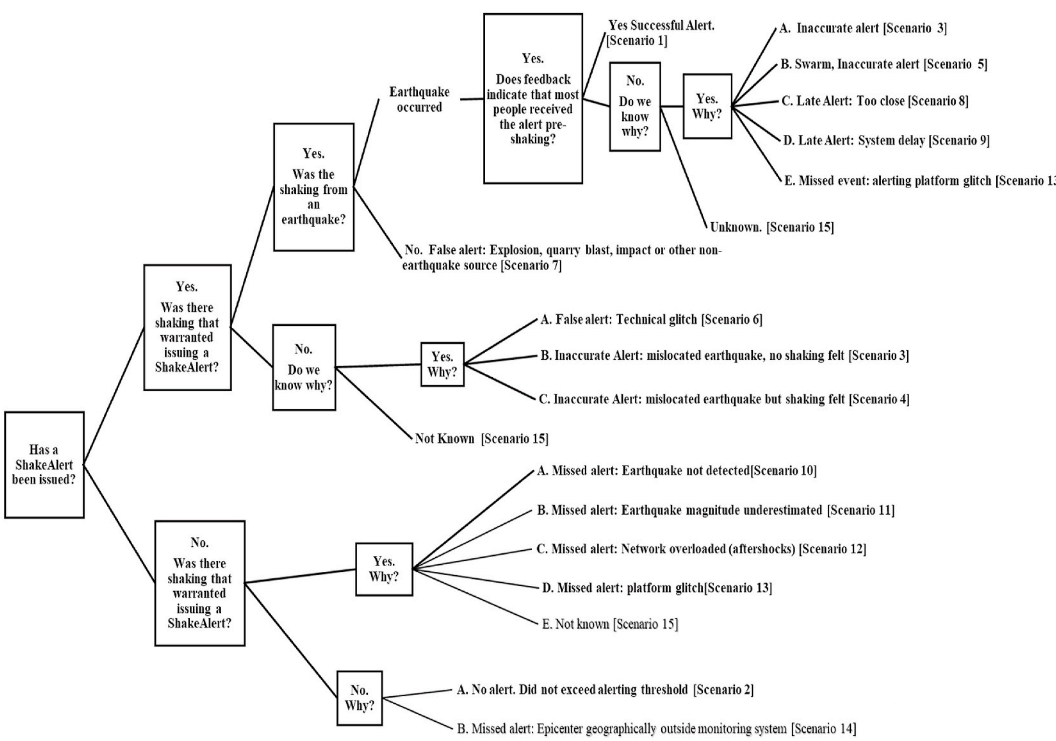

Fig. 3. Message decision flow chart.

Understanding the critical steps and decisions that the USGS staff operating the ShakeAlert system may have to make immediately after an earthquake occurs and/or a ShakeAlert Message is issued and then combining it with self-reflective questions allowed us to determine the

[2] Retrieved on 14 April 2019 from https://www.census.gov/quickfacts/fact/table/ca, US/PST045217#PST045217 (California), https://www.census.gov/quickfacts/fact/table/OR,US/PST045217%20(Oregon), https://www.census.gov/quickfacts/fact/table/WA, US/PST045217 (Washington).

Table 2
Earthquake alert scenarios, post-alert reasoning for communication, and potential messaging for various alerting platforms (WEA, Push Notification/Smartphone Apps, and Twitter).

A) Scenario	B) Response Reasoning	C) WEA Message	D) Push notification via Cell Phone App	E) Twitter/Broadcast Media
1. Successful Alert: A ShakeAlert Message was issued in time for people to take protective action. People felt shaking associated with the event.	Communicating our successes is a way to inform people about how the system works and that when people act when they receive an alert message, harm is reduced.	N/A. Initial alert message was distributed, no WEA follow up required.	N/A. Initial alert message was distributed, no follow up required.	A ShakeAlert Message was issued in response to the xx (name of earthquake) earthquake. If you took a protective action like Drop, Cover, and Hold On when you received an alert, you did the right thing (3).
2. No Alert: An earthquake has occurred and shaking may have been felt, but the alerting threshold was not met.	People may be concerned about why they felt the quake but didn't receive an alert message.	N/A, WEA not used as this channel is meant to only be used in times of emergency.	There was an earthquake, but its magnitude did not meet alerting thresholds (1). If you took a protective action like Drop, Cover, and Hold On when you received an alert, you did the right thing (3).	There was an earthquake, but its magnitude did not meet the threshold to issue a ShakeAlert Message (1). If you took a protective action like Drop, Cover, and Hold On when you received an alert, you did the right thing (3).
3. Inaccurate Alert: event mislocated offshore or outside network, no shaking felt in alerted area. An earthquake has occurred, but it is offshore and/or outside of ShakeAlert's monitoring area. A ShakeAlert Message was issued but the earthquake magnitude and/or location is wrong.	If an alert is sent incorrectly to a large urban center, particularly at night, it is highly likely to be a high-interest event.	ShakeAlert Message canceled due to mislocated earthquake (1). If you took a protective action like Drop, Cover, and Hold On when you received the alert, you did the right thing (3).	The ShakeAlert Message has been canceled due to a mislocated earthquake (1). If you took a protective action like Drop, Cover, and Hold On when you received an alert, you did the right thing (3).	The ShakeAlert Message has been canceled due to a mislocated earthquake (1). We are working to improve our system (2). If you took a protective action like Drop, Cover, and Hold On when you received an alert, you did the right thing (3).
4. Inaccurate Alert: event mislocated offshore or outside network, shaking felt in alerted area. An earthquake has occurred, but it is offshore and/or outside of ShakeAlert's monitoring area. A ShakeAlert Message was issued but the earthquake magnitude and/or location is wrong.	An alert delivered to these communities would likely not do much harm, as they did feel shaking. However, it would be advisable to explain the location issues.	ShakeAlert Message was issued in response to an earthquake (1). If you took a protective action like Drop, Cover, and Hold On when you received an alert, you did the right thing (3).	A ShakeAlert Message was issued in response to an earthquake (1). You might have felt shaking. If you took a protective action like Drop, Cover, and Hold On when you received an alert, you did the right thing (3).	We issued a ShakeAlert Message to people living in (area) (1). This alert message was in response to our network picking up (xxx) earthquake and mislocated it (2). If you took a protective action like Drop, Cover, and Hold On when you received an alert, you did the right thing (3).
5. Inaccurate Alert: Underestimated magnitude that impacts the predicted ground shaking due to multiple earthquakes or swarms, thus the thresholds for public alerting were not met.	The magnitude was underestimated.	ShakeAlert Message canceled (1). If you dropped, covered, and held on or protected yourself, you did the right thing (3).	A ShakeAlert Message was issued in response to an earthquake (1). You might have felt shaking. If you took a protective action like Drop, Cover, and Hold On when you received an alert, you did the right thing (3).	The USGS issued a ShakeAlert Message and people living in (area) could have received an alert (1). The alert was in response to our network picking up (xxx) earthquake and incorrectly assessing the magnitude (2). If you took a protective action like Drop, Cover, and Hold On when you received an alert, you did the right thing (3).
6. False Alert: One or more of the alerting delivery platforms (Apps, WEA, etc.) or the ShakeAlert system itself has experienced a technical issue which caused a ShakeAlert Message to be issued.	People may be curious as to why they received an alert when no shaking was felt and no earthquakes were reported.	ShakeAlert Message canceled due to false alert (1). If you took a protective action like Drop, Cover, and Hold On when you received an alert, you did the right thing (3).	ShakeAlert Message canceled due to false alert (1). If you took a protective action like Drop, Cover, and Hold On when you received an alert, you did the right thing (3).	ShakeAlert Message has been canceled due to false alert (1). The USGS is investigating (2). If you took a protective action like Drop, Cover, and Hold On when you received an alert, you did the right thing (3).
7. Late Alert: An earthquake occurred that met the alerting thresholds, but people were too close to the epicenter to receive a timely alert. Shaking was felt in the "late alert zone".	This type of alert message has human impact as it failed to alert people that shaking was coming. People may have been harmed or killed; this is a significant issue to acknowledge after a damaging earthquake.	A ShakeAlert Message has been issued late which might have delayed alert delivery. (1). If you took a protective action like Drop, Cover, and Hold On when you received an alert, you did the right thing (3).	A ShakeAlert Message was issued for xx earthquake. Some people may have been too close to the earthquake to receive an alert. If you took a protective action like Drop, Cover, and Hold On when you received an alert, you did the right thing (3).	A ShakeAlert Message was issued for xx earthquake. Some people may have been too close to the earthquake to receive a alert. If you took a protective action like Drop, Cover, and Hold On when you received an alert, you did the right thing (3).
8. Late Alert: System delay or technical delivery latency. An earthquake occurred that met the alerting thresholds, but it took the system too long to accurately characterize its magnitude. A ShakeAlert Message was issued but it was received after the shaking	A ShakeAlert Message was issued but it took too long to accurately characterize the earthquake's magnitude as it grew in size, so many people who felt significant shaking received the alert late.	A large earthquake occurred but the ShakeAlert Message was issued late. If you took a protective action like Drop, Cover, and Hold On when you received an alert, you did the right thing (3).	A large earthquake occurred but a ShakeAlert Message was issued late. If you took a protective action like Drop, Cover, and Hold On when you received an alert, you did the right thing (3).	A large earthquake was reported but the ShakeAlert Message was issued late. We are working to improve this part of the system. If you took a protective action like Drop, Cover, and Hold On when you received an alert, you did the right thing (3).

(*continued on next page*)

types of scenarios that the ShakeAlert operational team could face in the future. After we analyzed the decision flow chart, we then focused on the development of scenarios, using the decision flow chart as our guide.

4 and 5) Earthquake alerts and post-alert scenarios with messages templates

To develop a parsimonious but comprehensive set of scenarios, the working group closely examined the performance of the ShakeAlert system combined with earthquake behavior and performance of the telecommunications systems that ShakeAlert relies on for distribution. We then used a descriptive term to match the scenario described, as explored in Table 2.

Further, for Table 2, we provided sample messages. Each of the post-alert messages begins with a simple statement on the status of the preceding ShakeAlert Message or earthquake, consistent with findings that communication of "all-clears" is vital to the warning message process [65]. These are in sentences identified with a (1). We further utilized aspects of the Crisis and Emergency Risk Communication (CERC) model, developed by Reynolds and Seeger [6], by providing a short description of the actions the USGS is currently undertaking to address the situation, identified as sentence (2) [17]. We diverted from the CERC model to the Protective Actions Decision Model, developed by Lindell and Perry [66] for our next message which focuses on confirmation of and support for

Table 2 (*continued*)

A) Scenario	B) Response Reasoning	C) WEA Message	D) Push notification via Cell Phone App	E) Twitter/Broadcast Media
arrived at some/many locations.				
9. Non-earthquake shaking: A non-earthquake event (explosion, quarry blast, or other cause) is detected on the system and a ShakeAlert Message was issued. Shaking may or may not be felt.	If a ShakeAlert Message was issued due to this kind of shaking, the novelty factor will cause interest to be quite high. However, the actual cause of the alert may overshadow the alert.	ShakeAlert Message not issued for a an earthquake but another event (insert cause if we know quickly) (1). If you took a protective action like Drop, Cover, and Hold On when you received an alert, you did the right thing (3).	ShakeAlert Message not issued for an earthquake but another event (insert cause if we know quickly) (1). If you took a protective action like Drop, Cover, and Hold On when you received an alert, you did the right thing (3).	ShakeAlert Message not issued for an earthquake but another event (insert cause if we know quickly) (1). If you took a protective action like Drop, Cover, and Hold On when you received an alert, you did the right thing (3).
11. Missed Event: The event is detected by the ShakeAlert system, but the magnitude is underestimated and does not meet the magnitude threshold and no ShakeAlert Message was issued. Shaking may be felt.	Given some people may have felt shaking, some response should be provided.	N/A, as WEA was not used.	An earthquake was detected by the ShakeAlert system but its magnitude was underestimated and it did not meet the threshold for issuing a ShakeAlert Message (1,2). If you took a protective action like Drop, Cover, and Hold On when you felt shaking, you did the right thing (3).	An earthquake was detected by the ShakeAlert system but its magnitude was underestimated and it did not meet the threshold for issuing a ShakeAlert Message (1,2). If you took a protective action like Drop, Cover, and Hold On when you felt shaking, you did the right thing (3).
12. Missed Event: aftershocks. The ShakeAlert System may be unable to detect an aftershock that follows a main event within several minutes. No ShakeAlert Message is issued but shaking is felt.	Given some people may have felt shaking, some response should be provided.	N/A, as WEA was not used for initial alert message.	An earthquake has been reported as an aftershock to the xx earthquake; given the number of aftershocks, you may not receive an alert for all earthquakes (1,2). If you feel shaking, take protective action like Drop, Cover, and Hold On (3).	An aftershock has been recorded from the xx earthquake (1). Given the number of aftershocks, you may not receive and alert s for all earthquakes (2). If you feel shaking, take protective action like Drop, Cover, and Hold On (3).
13. Missed Alert: platform glitch. Technical issues mean that one or more of the alerting delivery platforms (APPs, WEA) has failed.	There will likely be interest and the alerting platform providers may have to account for why the alert message was not sent to everyone.	(if WEA fails, it is unlikely the problem can be addressed by sending a WEA a response to its non-response).	(same as WEA).	Dependent on the case and the alerting delivery platform failure.
14. No Alert: epicenter outside ShakeAlert reporting area. The epicenter of the earthquake was outside the detection area, so no ShakeAlert Message was issued. However, it was a large earthquake and light shaking or more may have been felt at the user's location.	There will likely be interest, particularly if this is a large, damaging event.	A large earthquake has been reported outside the ShakeAlert detection area (1). If you took a protective action like Drop, Cover, and Hold On when you felt shaking, you did the right thing (3).	A large earthquake has been reported outside the ShakeAlert reporting area that may have produced shaking at your location (1). If you took a protective action like Drop, Cover, and Hold On when you felt shaking, you did the right thing (3).	A large earthquake has been reported outside the ShakeAlert detection area that may have produced shaking at your location (1). Given the number of aftershocks expected for such an event, you may feel additional shaking without receiving an alert message (2). If you took a protective action like Drop, Cover, and Hold On when you felt shaking, you did the right thing (3).
15. Unknown. It has not yet been identified why the alerts failed to be sent to some people but shaking was felt.	People may be concerned as to why they did not receive an alert message, as they felt shaking but did not get an alert message.	(WEA may not be working).	(Push notifications may not be working).	The ShakeAlert system detected an earthquake but a ShakeAlert message was not issued (1). We do not yet know why this occurred however we acknowledge that this experience is upsetting for many people (2). The USGS is investigating this issue and will keep updating information as we learn more. If you took a protective action like Drop, Cover, and Hold On when you felt shaking, you did the right thing (3).

effective protective actions (Drop, Cover, and Hold On), as explored in McBride et al. [54]; identified as sentence (3). Different nations use diverse protective actions for earthquakes, as explored in Goltz et al. [67]. It is important to note that while messages may be similar, these represent distinct scenarios that technicians and scientists may find themselves faced with regarding the ShakeAlert detection system.

Table 2 is the basis for a situational typology for post-alert messaging, described in the next section. This typology provides a framework for ShakeAlert expectations about system performance and public response. These expectations stem from empirically grounded knowledge of earthquakes, of detection and monitoring system behaviors, human population exposures, situational interpretations, and responses.

The post-alert template messages proposed for ShakeAlert in the scenario matrix (Table 2) are based on what is currently understood as effective content for alerts and warnings from the literature reviewed on messaging and behavior specifically, and professional communication expertise in the working group. The use of these messages and their numbered elements are illustrated in Table 2. The template messages focus on what occurred, or might still be happening post-alert, and what personal protective action could be taken, as suggested by Bean et al. [4]. Additional information is offered about messaging for specific channels and reasoning for communicating the message, as described in the results.

In the development of the post-alert messages, the working group also considered what communications channels would be available—WEA, push notifications (mobile applications), Twitter, and broadcast media (radio, print, television, online)—and their limitations, such as character limits, speed, and audience reach. Therefore, messages were crafted with attention to specific channel requirements (such as restrictions to character length) as well as using simple terminology. Because different groups trust messages from some channels but not others, as explored in Phillips & Morrow [59], the template recommends the channels of WEA, push notifications (opt-in apps), Twitter, and broadcast media for post-alert messaging. However, these messages should be tested and refined iteratively as ShakeAlert develops.

We make several assumptions to develop the template messages. First, in the cases of late alerts, which occur because the earthquake origin is too close for an alert to be sent before the strongest shaking arrives, it is assumed that many telecommunications channels will likely be too oversaturated to send messages. Second, it may be difficult to determine exact scenarios of alerts (e.g., successful, false, missed, inaccurate) in the first five to 10 min, so in many instances, more generalized information will have to suffice for immediate post-alert messaging.

6) A fit-for-purpose earthquake alert typology

A typology is a classification scheme; ours is informed by research on the communication of uncertainty in the context of natural hazards [68]. Although empirically informed, the suite of scenarios defined by the working group (Table 3) is conceptual and can be described as a typology, rather than a taxonomy, as typologies are more conceptual than empirically based taxonomies [69]. Table 3 illustrates the resulting typology including the following types of system performance (types of alerts): successful, false (technical glitch or no earthquake), missed, inaccurate, no alert, and late. These terms extend the simpler typologies derived from signal detection theory, as explored in Meyer et al. [70], and used in weather warnings and other alerting systems. The terms are chosen to identify distinguishing features of situations of relevance to interpretation and action, to be as descriptive as possible but still accessible for non-technical audiences, and to reflect common usage. Whether the wording choices achieve these goals remains to be tested.

The typology in Table 3 is more extensive than the typical alerting quadrant (e.g. Fig. 1) and is required to account for the diverse scenarios that result from the physics of earthquakes, controls on ground shaking, the alerting and communication systems involved, and how these affect people. The detection subsystem can technically behave differently from the communication or alerting subsystem, especially if alerts are not sent for all detected events. Further, if there are technical glitches, alerts could be sent in the absence of detection. Detection of P-waves at multiple stations close to the epicenter, estimation of earthquake location and magnitude and the resulting ground motion, and activation of the alerting system are required to release a ShakeAlert Message [39]. Any of these systems could potentially fail or produce miscalculations leading to an incorrectly issued alert. Our development of the typology, along with the definitions in Table 2, combined with research on human behavior and communication channels led us to the development of a full suite of post-alert message templates.

Table 3
Typology of alerts. (**X** means that there was no occurrence and **✓** means that there was an occurrence.)

Alerting Type	Ground shaking detected	Earthquake Detected	Alerting Threshold met for alert	Public Alert Sent and received before strong shaking arrives
Successful Alert	✓	✓	✓	✓
False Alert (technical glitch)	X	X	X	**✓ (alert sent but no shaking)**
False Alert (shaking but not an earthquake)	✓	X	✓	✓
Missed Alert	✓	✓	✓	**X (no alert sent)**
Inaccurate Alert	✓	✓	**X Yes, but the detection was inaccurate.**	✓
No Alert	✓	✓	X	X
Late Alert	✓	✓	✓	X

3. Limitations and recommendations

There are limitations to our investigation and application of each of the three factors informing post-alert messaging: the earthquake, the ShakeAlert system, and human behavior. While we know much about earthquake hazards on the U.S. West Coast, new knowledge that is relevant to ShakeAlert performance in damaging earthquakes continues to emerge [38,71,72]. Performance of the ShakeAlert detection and monitoring system will change and likely improve as the earthquake monitoring networks that supportthe ShakeAlert system are built out. We further require more investigation regarding the initial message however, work has begun on this process, as explored by Sutton et al. [85]. The last factor, how people interpret and respond to post-alert messaging, is perhaps the most complex and least well understood or studied. We analyzed recommendations from the warning and crisis communication literature, with a focus on tornado and lahar research, given that time is a factor in both warnings and post-alert messaging for those hazards. The development of the messaging matrix in Table 2 relied heavily on this literature, but we suggest that next steps for this research include a monitoring and evaluation program tailored specifically for ShakeAlert, to help inform future development.

A related limitation is that the proposed message templates have not yet been translated into other languages or designed to be accessible for those with visual or learning disabilities. This research signals a starting point for future research and development, as user testing is key to determine what iterations to post-alert messaging could be made in the future [65]. Accounting for visitors from non-English speaking countries, immigrants, and those with literacy or learning disabilities, the number of people who may struggle to understand ShakeAlert content may be as high as approximately 25 million people in the West Coast states, at any given time. This bears consideration when developing future post-alert messaging, as language and literacy are critical components of understanding messages.

A critical component of needed post-earthquake information includes the potential severity of aftershocks, with their possible location, timing, magnitude, rates, and frequency [73]. The USGS has developed a first response template for aftershock forecasts that is intended to be released within 30 min of the event [74,82]. This template provides information about what could be expected in terms of numbers and sizes of aftershocks. Further, it is critical to contextualize ShakeAlert as part of a suite of information products the USGS provides shortly after an earthquake occurs. These products include ShakeMap, Did You Feel It?, the Origin product (magntitude, location, depth), PAGER, and others [97]. Future consideration could be given to adding brief messages about aftershocks forecasts and other available earthquake informational products as part of ShakeAlert's communication strategy.

4. Conclusions

The post-alert messaging framework presented here derives from observational data, the post alert messaging working group expertise with ShakeAlert system performance, earthquake behavior, reviewed literature on how people make sense of warnings for natural hazards, and information about how organizations communicate in crises. These factors are further informed and constrained by warning times (i.e., the amount of time between when an alert is received and strong shaking begins), accuracy and timeliness of ground motion prediction, and operator errors in the alerting system itself, as well as what people can and should do to protect themselves in response to alerts. Furthermore, we recommend that those responsible for communication refine this framework and the proposed messages iteratively, as evidence accumulates regarding their use. This paper offers recommendations that could be taken into account in developing effective communications strategies and post-alert messaging for ShakeAlert and other EEW systems around the world.

We argue that these messages represent the first response after an alert has been sent, not the last response from the USGS. Our post-alert messaging framework assumes and requires a comprehensive communication strategy that includes providing more information as the situation unfolds. Similarly, this article represents the beginning of our research on post-alert messaging rather than a final statement on the matter.

This work represents a first attempt to identify, constrain, and craft messages to communicate about a system that is not yet fully publicly available across the West Coast of the U.S. Given the nature of both the system within the U.S. and emergent information and communication technologies, it has provided a unique opportunity to combine social science with seismology and technical systems for the USGS, the federal agency responsible for issuing the ShakeAlert Message and post-alert messaging. As the technologies and sciences regarding ShakeAlert evolve, so will the need for approaches to evaluate and refine future post-alert messaging. Further, the performance and decision analyses and alert typology developed in this paper provide a framework for future research, including testing and evaluations of the message templates we propose.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. We thank our USGS internal reviewers, Dr. Anne Wein and Dr. Elizabeth Cochran, for their insights which greatly improved this article. We also thank Dr. Andrea Llenos, Dr. Stephen Hickman, and Shane Detwiler at the USGS for further contributions to this article. We also thank our external reviewers for their contributions to this work.

References

[1] E.S. Cochran, B.T. Aagaard, R.M. Allen, J. Andrews, A.S. Baltay, A.J. Barbour, P. Bodin, B.A. Brooks, A. Chung, B.W. Crowell, D.D. Given, T.C. Hanks, R. Hartog, E. Hauksson, T.H. Heaton, S.K. McBride, M.A. Meier, D. Melgar, S.E. Minson, J. R. Murray, J.A. Strauss, D. Toomey, Research to improve ShakeAlert earthquake early warning products and their utility, U.S. Geological Survey Open-File Report 2018– 1131 (2018) 17, https://doi.org/10.3133/ofr20181131.

[2] Federal Communications Commission, Report and Recommendations from Hawaii Emergency Management Agency's January 13, 2018 False Ballistic Missile Alert. Washington, D.C, 2018. Retrieved from, https://docs.fcc.gov/public/attachments/DOC-350119A1.pdf.

[3] S.E. DeYoung, J.N. Sutton, A.K. Farmer, D. Neal, K.A. Nichols, "Death was not in the agenda for the day": emotions, behavioral reactions, and perceptions in response to the 2018 Hawaii Wireless Emergency Alert, International Journal of Disaster Risk Reduction (2019) 101078.

[4] H. Bean, J. Sutton, B.F. Liu, S. Madden, M.M. Wood, D.S. Mileti, The study of mobile public warning messages: a research review and agenda, Rev. Commun. 15 (1) (2015) 60–80.

[5] V.T. Covello, Best practices in public health risk and crisis communication, J. Health Commun. 8 (S1) (2003) 5–8.

[6] B. Reynolds, M.W. Seeger, Crisis and emergency risk communication as an integrative model, J. Health Commun. 10 (1) (2005) 43–55.

[7] T.L. Sellnow, D.D. Sellnow, D.R. Lane, R.S. Littlefield, The value of instructional communication in crisis situations: restoring order to chaos, Risk Analysis 32 (4) (2012) 633–643.

[8] T.L. Sellnow, R.R. Ulmer, M.W. Seeger, R.S. Littlefield, Effective Risk Communication: A Message-Centered Approach, Springer Science & Business Media, New York, NY, 2008.

[9] J. Sutton, S.C. Vos, M.M. Wood, M. Turner, Designing effective tsunami messages: examining the role of short messages and fear in warning response, Weather, Climate, and Society 10 (1) (2018) 75–87.

[10] W. Whiting, Hurricane katrina: risk communication in response to a natural disaster, in: T.L. Sellnow, R.R. Ulmer, M.W. Seeger, R.S. Littlefield (Eds.), Effective Risk Communication: A Message-Centered Approach, Springer, New York, NY, 2009, pp. 77–89.

[11] R.L. Heath, J. Lee, L. Ni, Crisis and risk approaches to emergency management planning and communication: the role of similarity and sensitivity, J. Publ. Relat. Res. 21 (2) (2009) 123–141, https://doi.org/10.1080/10627260802557415.

[12] M. Lombardi, Communication about major accident hazards: credibility of qualified informers in an Italian city, Disaster Prev. Manag.: Int. J. 4 (2) (1995) 4–13, https://doi.org/10.1108/09653569510082641.

[13] L. Palen, S.B. Liu, Citizen communications in crisis: anticipating a future of ICT-supported public participation, in: Paper Presented at the Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, 2007.

[14] T. Perko, B. van Gorp, C. Turcanu, P. Thijssen, B. Carle, Communication in nuclear emergency preparedness: a closer look at information reception, Risk Analysis 33 (11) (2013) 1987–2001, https://doi.org/10.1111/risa.12048.

[15] S.C. Quinn, Crisis and emergency risk communication in a pandemic: a model for building capacity and resilience of minority communities, Health Promot. Pract. 9 (4 suppl) (2008) 18S–25S.

[16] K. Haynes, J. Barclay, N. Pidgeon, The issue of trust and its influence on risk communication during a volcanic crisis, Bull. Volcanol. 70 (5) (2008) 605–621.

[17] M.W. Seeger, Best practices in crisis communication: an expert panel process, J. Appl. Commun. Res. 34 (3) (2006) 232–244.

[18] I.I. Stoddard, W. Robert, J.P. Elm, J. McCurley, S. Sheard, T. Marshall-Keim, Wireless Emergency Alerts: Trust Model Technical Report (No. CMU/SEI-2013-SR-021), Carnegie-Mellon Univ Pittsburgh Penn. Software Engineering Inst, 2014.

[19] C. Garcia, C.J. Fearnley, Evaluating critical links in early warning systems for natural hazards, Environ. Hazards 11 (2) (2012) 123–137.

[20] J.H. Sorensen, Hazard warning systems: review of 20 years of progress, Nat. Hazards Rev. 1 (2) (2000) 119–125.

[21] J.S. Becker, G.S. Leonard, S.H. Potter, M.A. Coomer, D. Paton, K.C. Wright, D. M. Johnston, Organisational response to the 2007 ruapehu crater lake dam-break lahar in New Zealand: use of communication in creating an effective response, in: C.J. Fearnley, D.K. Bird, K. Haynes, W.J. McGuire, G. Jolly (Eds.), Observing the Volcano World. Advances in Volcanology (An Official Book Series of the International Association of Volcanology and Chemistry of the Earth's Interior – IAVCEI, Barcelona, Spain), Springer, Cham, 2017.

[22] J. Brotzge, W. Donner, The tornado warning process: a review of current research, challenges, and opportunities, Bull. Am. Meteorol. Soc. 94 (11) (2013) 1715–1733.

[23] F. Lavigne, J.-C. Thouret, B. Voight, K. Young, R. LaHusen, J. Marso, M. Dejean, Instrumental lahar monitoring at Merapi Volcano, central Java, Indonesia, J. Volcanol. Geoth. Res. 100 (1) (2000) 457–478.

[24] G.S. Leonard, D.M. Johnston, D. Paton, Developing effective lahar warning systems for Ruapehu, Plann. Q. 158 (6) (2005) 9.

[25] W.R. Donner, An Integrated Model of Risk Perception and Protective Action: Public Response to Tornado Warnings, ProQuest, 2007.

[26] J.T. Ripberger, C.L. Silva, H.C. Jenkins-Smith, M. James, The influence of consequence-based messages on public responses to tornado warnings, Bull. Am. Meteorol. Soc. 96 (4) (2015) 577–590.
[27] K.M. Simmons, D. Sutter, False alarms, tornado warnings, and tornado casualties, Weather, Climate, and Society 1 (1) (2009) 38–53.
[28] R.M. Stokoe, Putting people at the centre of tornado warnings: how perception analysis can cut fatalities, International Journal of Disaster Risk Reduction 17 (2016) 137–153, https://doi.org/10.1016/j.ijdrr.2016.04.004.
[29] R.M. Allen, E.S. Cochran, T.J. Huggins, S. Miles, D. Otegui, Lessons from Mexico's earthquake early warning system, Eos, Earth and Space Science News 99 (2018).
[30] E. Reddy, Crying 'crying wolf': how misfires and Mexican engineering expertise are made meaningful, Ethnos (2019) 1–16, https://doi.org/10.1080/00141844.2018.1561489.
[31] M. Couling, Tsunami risk perception and preparedness on the east coast of New Zealand during the 2009 Samoan Tsunami warning, Nat. Hazards 71 (1) (2014) 973–986.
[32] J.A. Strauss, Q. Kong, S. Pothan, S. Thompson, A. Mejia, S. Allen, R.M. Allen, MyShake Citizen Seismologists help launch dual-use seismic network in California, Frontiers in Communication 5 (2020) 32.
[33] D. Leonard, California Launches Earthquake Early Warning System 30 Years after Deadly San Francisco Tremor, 2019 October 19. The Washington Post. Retrieved from, https://www.washingtonpost.com/weather/2019/10/19/california-launches-earthquake-early-warning-system-years-after-deadly-san-francisco-tremor/.
[34] R.G. Lin, 2 Quakes in 2 Days, No Warning from ShakeAlertLA. Now the App Is Getting Reworked, Los Angeles Times, 2019, August 14. https://www.latimes.com/california/story/2019-08-14/earthquake-early-warning-app-shakealertla-released.
[35] H.O. Wood, F. Neumann, Modified Mercalli intensity scale of 1931, Bull. Seismol. Soc. Am. 21 (4) (1931) 277–283.
[36] J.E. Trainor, D. Nagele, B. Philips, B. Scott, Tornadoes, social science, and the false alarm effect, Weather, Climate, and Society 7 (4) (2015) 333–352.
[37] S.E. Minson, M.-A. Meier, A.S. Baltay, T.C. Hanks, E.S. Cochran, The limits of earthquake early warning: timeliness of ground motion estimates, Science Advances 4 (2018), https://doi.org/10.1126/sciadv.aaq0504.
[38] S.E. Minson, A.S. Baltay, E.S. Cochran, T.C. Hanks, M.T. Page, S.K. McBride, K. R. Milner, M.A. Meier, The limits of earthquake early warning accuracy and best alerting strategy, Sci. Rep. 9 (1) (2019) 2478, https://doi.org/10.1038/s41598-019-39384-y.
[39] D.D. Given, R.M. Allen, A.S. Baltay, P. Bodin, E.S. Cochran, K. Creager, R.M. de Groot, L.S. Gee, E. Hauksson, T.H. Heaton, M. Hellweg, J.R. Murray, V.I. Thomas, D. Toomey, T.S. Yelin, Revised technical implementation plan for the ShakeAlert system—an earthquake early warning system for the West Coast of the United States: U.S, Geological Survey Open-File Report 2018 1155 (2018) 42, https://doi.org/10.3133/ofr20181155 [Supersedes USGS Open-File Report 2014–1097.].
[40] S.R. Dixon, C.D. Wickens, J.S. McCarley, On the independence of compliance and reliance: are automation false alarms worse than misses? Hum. Factors 49 (4) (2007) 564–572.
[41] A. Jalooli, N. Hussin, R.M. Noor, J.J. Jung, Public alerts on landslide natural disaster using vehicular communications (retracted article. See pg. 23458, 2015), Int. J. Distributed Sens. Netw. 7 (2014), https://doi.org/10.1155/2014/969864.
[42] J. Lin, P. Szczurek, O. Wolfson, B. Xu, Observe-Driver-and-Learn platform for relevance estimation in safety warning applications from vehicular ad hoc network, Transport. Res. Rec. (2489) (2015) 49–56, https://doi.org/10.3141/2489-06.
[43] D.E. Whitmer, V.K. Sims, M.E. Torres, Assessing mental models of emergencies through two knowledge elicitation tasks, Hum. Factors 59 (3) (2017) 357–376, https://doi.org/10.1177/0018720816672117.
[44] J.A. Swets, The relative operating characteristic in psychology: a technique for isolating effects of response bias finds wide use in the study of perception and cognition, Science 182 (4116) (1973) 990–1000.
[45] K. Dow, S.L. Cutter, Crying wolf: repeat responses to hurricane evacuation orders, Coast. Manag. 26 (4) (1998) 237–252.
[46] S. Malone, K. Hall, L. Simmons, J.E. Vidale, How to recognize a "beast quake" and a "dance quake", Seismol Res. Lett. 86 (3) (2015) 1006–1008.
[47] J.E. Vidale, Seattle "12th man earthquake" goes viral, Seismol Res. Lett. 82 (3) (2011) 449–450.
[48] E.S. Cochran, M.D. Kohler, D.D. Given, S. Guiwits, J. Andrews, M.A. Meier, M. Ahmend, I. Henson, R. Hartog, D. Smith, Earthquake early warning ShakeAlert system: testing and certification platform, Seismol Res. Lett. 89 (1) (2018) 108–117.
[49] R.A. Harris, Numerical simulations of large earthquakes: dynamic rupture propagation on heterogeneous faults, Pure Appl. Geophys. 161 (11/12) (2004) 2171–2181, https://doi.org/10.1007/s00024-004-2556-8.
[50] S. Potter, Recommendations for New Zealand Agencies in Writing Effective Short Messages. (2018/2), Lower Hutt, New Zealand: GNS Science, 2018.
[51] Y. Fujinawa, Y. Noda, Japan's earthquake early warning system on 11 March 2011: performance, shortcomings, and changes, Earthq. Spectra 29 (s1) (2013) S341–S368.
[52] J. Santos-Reyes, How useful are earthquake early warnings? The case of the 2017 earthquakes in Mexico city, International Journal of Disaster Risk Reduction 40 (2019) 101148.
[53] K. Nakayuchi, J.S. Becker, S.H. Potter, M. Dixon, Residents' reactions to earthquake early warnings in Japan, Risk Analysis (2019), https://doi.org/10.1111/risa.13306.
[54] S.K. McBride, J.S. Becker, D.M. Johnston, Exploring the barriers for people taking protective actions during the 2012 and 2015 New Zealand ShakeOut drills, International journal of disaster risk reduction 37 (2019) 101150.
[55] D.S. Mileti, J.H. Sorensen, A Guide to Public Alerts and Warnings for Dam and Levee Emergencies, U.S. Army Corps of Engineers, 2015. Retrieved from, http://silverjackets.nfrmp.us/Portals/0/doc/WarningGuidebook_USACE.pdf?ver=2015-08-10-213008%20520.
[56] J.R. Lim, B.F. Liu, M. Egnoto, Cry wolf effect? Evaluating the impact of false alarms on public responses to tornado alerts in the southeastern United States, Weather, climate, and society 11 (3) (2019) 549–563.
[57] M.S. Wogalter, Handbook of Warnings, CRC Press, London, U.K., 2006.
[58] M.K. Lindell, H. Brooks, Workshop on weather ready nation: science imperatives for severe thunderstorm research, Bull. Am. Meteorol. Soc. 94 (12) (2013) ES171–ES174.
[59] B.D. Phillips, B.H. Morrow, Social science research needs: focus on vulnerable populations, forecasting, and warnings, Nat. Hazards Rev. 8 (3) (2007) 61–68.
[60] D.S. Mileti, L. Peek, The social psychology of public response to warnings of a nuclear power plant accident, J. Hazard Mater. 75 (2) (2000) 181–194.
[61] H.T. Sullivan, M.T. Häkkinen, Preparedness and warning systems for populations with special needs: ensuring everyone gets the message (and knows what to do), Geotech. Geol. Eng. 29 (3) (2011) 225–236, https://doi.org/10.1007/s10706-010-9363-z.
[62] C.P. Gambino, Y.D. Acosta, E.M. Grieco, English-speaking Ability of the Foreign-Born Population in the United States. Washington, D.C, 2014. Retrieved from, https://www.%20census.%20gov/prod/2014pubs/acs-26.%20pdf.
[63] P.N. Pastor, C.A. Reuben, Diagnosed attention deficit hyperactivity disorder and learning disability: United States, 2004-2006. *Vital and Health Statistics*, Series 10, Data from the National Health Survey 237 (2008) 1–14.
[64] K. Vermeulen, Understanding your audience: how psychologists can help emergency managers improve disaster warning compliance, J. Homel. Secur. Emerg. Manag. 11 (3) (2014) 309–315.
[65] National Academies of Sciences, Engineering, & Medicine, Emergency Alert and Warning Systems: Current Knowledge and Future Research Directions, The National Academies Press, Washington, DC, 2018.
[66] M.K. Lindell, R.W. Perry, The protective action decision model: theoretical modifications and additional evidence, Risk Analysis 32 (4) (2012) 616–632.
[67] J.D. Goltz, H. Park, G. Nakano, K. Yamori, Earthquake Ground Motion and Human Behavior: Using DYFI Data to Assess Behavioral Response to Earthquakes. Earthquake Spectra, 2020, https://doi.org/10.1177/8755293019899958.
[68] E.E. Hudson-Doyle, D.M. Johnston, R. Smith, D. Paton, Communicating model uncertainty for natural hazards: a qualitative systematic thematic review, International Journal of Disaster Risk Reduction (2018), https://doi.org/10.1016/j.ijdrr.2018.10.023.
[69] K.D. Bailey, Typologies and Taxonomies: an Introduction to Classification Techniques, vol. 102, Sage Publications, Thousand Oaks, CA, 1994.
[70] J. Meyer, Effects of warning validity and proximity on responses to warnings, Hum. Factors 43 (4) (2001) 563–572.
[71] A.D. Frankel, E.A. Wirth, N. Marafi, J.E. Vidale, W.J. Stephenson, Broadband synthetic seismograms for magnitude 9 earthquakes on the cascadia megathrust based on 3D simulations and stochastic synthetics, Part 1: methodology and overall results, Bull. Seismol. Soc. Am. 108 (5A) (2018) 2347–2369.
[72] E.A. Wirth, A.D. Frankel, N. Marafi, J.E. Vidale, W.J. Stephenson, Broadband synthetic seismograms for magnitude 9 earthquakes on the Cascadia megathrust based on 3D simulations and stochastic synthetics, Part 2: rupture parameters and variability, Bull. Seismol. Soc. Am. 108 (5A) (2018) 2370–2388.
[73] J.S. Becker, S.H. Potter, S.K. McBride, A. Wein, E.E.H. Doyle, D. Paton, When the earth doesn't stop shaking: how experiences over time influenced information needs, communication, and interpretation of aftershock information during the Canterbury Earthquake Sequence, New Zealand, International Journal of Disaster Risk Reduction 34 (2019) 397–411, https://doi.org/10.1016/j.ijdrr.2018.12.009.
[74] S.K. McBride, A.J. Michael, A.M. Wein, J.S. Becker, J. Hardebeck, N. Field, M. Gerstenberger, Developing Earthquake Forecast Templates for Fast and Effective Communication. Paper Presented at the 11NCEE, Los Angeles, C.A, 2018.
[78] M.D. Kohler, E.S. Cochran, D.D. Given, S. Guiwits, D. Neuhauser, I. Henson, R. Hartog, P. Bodin, V. Kress, S. Thompson, Earthquake early warning ShakeAlert system: West coast wide Production Prototype, Seismol Res. Lett. 89 (1) (2017) 99–107.
[80] P.H. Longstaff, S.U. Yang, Communication management and trust: their role in building resilience to "surprises" such as natural disasters, pandemic flu, and terrorism, Ecol. Soc. 13 (1) (2008) 3.
[82] A.J. Michael, S.K. McBride, J.L. Hardebeck, M. Barall, E. Martinez, M.T. Page, N. van der Elst, E.H. Field, K.R. Milner, A.M. Wein, Statistical seismology and communication of the USGS operational aftershock forecasts for the 30 november 2018 Mw 7.1 anchorage, Alaska, earthquake, Seismol Res. Lett. (2019), https://doi.org/10.1785/0220190196.
[83] B.L. Rawlins, *Trust and PR practice*. Institute for Public Relations–Essential Knowledge Project.Reynolds, B., & Seeger, M. W. (2005). Crisis and emergency risk communication as an integrative model, J. Health Commun. 10 (1) (2007) 43–55.
[85] J. Sutton, L. Fischer, L.E. James, S.E. Sheff, Earthquake early warning message testing: visual attention, behavioral responses, and message perceptions, International Journal of Disaster Risk Reduction 49 (2020) 101664, https://doi.org/10.1016/j.ijdrr.2020.101664.
[91] J.E. Grunig, F.C. Repper, Strategic management, publics, and issues, Excell. Public Relat. Commun. Manag. 73 (1) (1992) 117–157.
[92] S.K. McBride, The Canterbury tales: an insider's lessons and reflections from the Canterbury Earthquake Sequence to inform better public communication models: a

thesis presented in fulfilment of the requirements for the degree of Doctor of Philosophy in English and Media Studies at Massey University, Wellington, New Zealand (Doctoral dissertation), Massey University, 2017.
[93] I. Kelman, M.H. Glantz, Early warning systems defined, in: *Reducing Disaster: Early Warning Systems for Climate Change*, Springer, Dordrecht, 2014, pp. 89–108.
[94] Tan, M.L., Harrison, S., Becker, J.S., Doyle, E.E.H., Prasanna, R. (2020). Research themes on warnings in information systems management literature. Conference Paper in the Proceedings of the 17th ISCRAM Conference – Blacksburg, VA, USA May 2020.
[95] K.E. Allstadt, M. Farin, A.B. Lockhart, S.K. McBride, J.W. Kean, R.M. Iverson, D. George, Overcoming barriers to progress in seismic monitoring and characterization of debris flows and lahars, in: Association of Environmental and Engineering 28, Geologists; special publicationColorado School of Mines. Arthur Lakes Library, 2019.
[96] Del Rio, G.M.N. (2019, July 5). ShakeAlertLA will Drop Threshold for Earthquake Alerts, Amid Gripes People not Alerted. Los Angeles Times. https://www.latimes.com/local/lanow/la-me-ln-local-shakealert-lowers-threshold-20190705-story.html.
[97] E.M. Thompson, S.K. McBride, G.P. Hayes, K.E. Allstadt, L.A. Wald, D.J. Wald, A. R. Grant, USGS near-real-time products—and their use—for the 2018 Anchorage earthquake, Seismol Res. Lett. 91 (1) (2020) 94–113.
[98] Federal Communications Commission, Wireless Emergency Alerts, 2020. https://www.fcc.gov/public-safety-and-homeland-security/policy-and-licensing-division/alerting/general/wireless.