Practical Limitations of Earthquake Early Warning

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Earthquake early warning (EEW) entails detection of initial earthquake shaking and rapid estimation and notification to users prior to imminent, stronger shaking. EEW (ShakeAlert Phase 1, version 2.0) went operational in California in Oct, 2019, and is coming to the rest of the U.S. West Coast. But what are the technical and social challenges to delivering actionable information on earthquake shaking before it arrives? Although there will be tangible benefits, there are also limitations. Basic seismological principles, alert communication challenges, and potential response actions as well as substantial lessons learned from the use of EEW in Japan, point to more limited opportunities to warn and protect than perhaps many expect. This is in part because potential warning times vary by region and are influenced by tectonic environment, hypocentral depth, and the fault’s proximity to the alert user. For the U.S. West Coast, particularly for crustal earthquakes, warning times are shorter—and possible mitigation actions are likely to be less effective—than often maintained. Nevertheless, EEW is an additional arrow in the quiver of earthquake information tools available in the service of earthquake risk reduction. What is called for, then, is transparency and balance in the EEW discussion: along with its potential, the acknowledgement of EEW’s inherent and practical limitations is needed. Recognizing these limitations could, in fact, make EEW implementation more successful as part of a holistic earthquake mitigation strategy, where its role among other earthquake information tools is quite natural.

INTRODUCTION

“The [...] reason that technology so often disappoints and betrays us is that it promises to make easy things that, by their intrinsic nature, have to be hard” (Stephens, 2018). The goal of earthquake early warning (EEW) is to provide timely alerts that are sufficiently rapid to allow

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warnings\textsuperscript{1} that may reduce harm or impacts of earthquakes (e.g., Allen and Melgar, 2019). In that sense, EEW is both a scientific and a societal challenge. It would be wonderful to see EEW save many lives and reduce societal losses in future earthquakes. But are such expectations realistic? Is it that straightforward to reduce the impact of earthquakes with EEW, above and beyond other efforts to do so?

The challenge is not only to rapidly determine whether to send out an alert, but how, to whom, and with what warning for users to heed? These highly visible, critically important, publicly distributed decisions are serious technical challenges in their own right. But widely communicating actionable warnings turns out to be even more difficult. It is also well known from other natural hazards that providing rapid, actionable warnings, although beneficial, is challenging\textsuperscript{2}, and EEW alerts come with much shorter lead times than warnings for other perils. What’s more, exactly what actions should be taken are imprecisely known (e.g., Johnson et al. (2017). Realistically, even if the EEW system correctly estimates shaking in a timely fashion for warning purposes, they may not be sufficient to significantly alter an earthquake’s impact in many cases. To date, there are few examples of how reducing losses with EEW can be accomplished.

There are two key points discussed herein that raise concerns about EEW in the U.S. West: (1) effective warning times—especially when accounting for delivery and response—are less impressive than purported, effectively increasing the area of the blind zone where no warning is possible, and (2) possible mitigating actions are more challenging than anticipated and are thus less likely to be effective than often claimed. Indeed, shorter-than-expected warning times fundamentally limit the range of opportunities for risk reduction. Consequently, overall expectations for EEW alert timing and consequent societal benefits may not be met. Therein lies the need for full transparency, and for better clarity about the realistic benefits and the limitations of EEW.

\textsuperscript{1} In the hazard arena, an “alert” is usually defined as a hazard detection notice disseminated by computer (e.g., an alarm), and a “warning” as a statement based on a hazard detection recommending users to take action, e.g., drop, cover, and hold on (DCHO).

\textsuperscript{2} Even with tens of minutes, tornado warnings don’t necessarily produce the desired result (for example see, Why High-Tech Weather Forecasts Don’t Save More Lives, Time Magazine, http://time.com/5551298/weather-forecasts-deaths/).
The purpose of this note, then, is to provide an additional perspective\textsuperscript{3} that amplifies the need for complete transparency and balance in the overall EEW conversation, commensurate with such an important, publicly delivered emergency earthquake information system. It is important to properly consider which specific aspects of risk reduction could be achieved with EEW, and to do so by not only being realistic about potential warning times, but also by recognizing the importance of other earthquake information products and more mundane (albeit more expensive) mitigation strategies. After reviewing the current scientific literature and engaging with EEW practitioners, other scientists, and potential users, I offer observations and conclusions toward this end.

BACKGROUND

The process underlying EEW entails assessing P-waves at the closest seismic station(s) to the epicenter and rapidly estimating shaking due to later-arriving, larger S-waves\textsuperscript{4}. If the projected S-wave shaking is likely to be strong at any location, a warning can be sent ahead of the S-wave arrivals, at least under some conditions, and certainly at more distant locations where weaker shaking is expected. Recent advances on many of the technoscientific components of EEW have indeed been impressive; up-to-date overviews of EEW’s potential and limitations have been provided by Allen and Melgar (2019) and Ogweno et al. (2019).

Early on, Nakamura and Tucker (1988) articulated opportunities along with several concerns about transporting EEW from Japan to California; their apprehensions included differences in tectonics, challenges in mitigating applications beyond primarily slowing trains, and even concerns about litigation. They also noted the challenges of serving a range of different users in California and the inherent need for a more complex system as a result, and further contended that the cost-benefit of implementing an earthquake early warning system would need to be documented given the competing needs for tax dollars and the lower level of concern over earthquake hazards in California versus Japan. Perhaps the earliest concerns from the seismic network manager’s perspective were from Malone (2008, p. 608); he also

\textsuperscript{3} Wald is a U.S. Geological Survey seismologist who does not work on nor advocate for the ShakeAlert project.

\textsuperscript{4} In fact, EEW comes in two general forms: seismic-network–based strategies (like ShakeAlert), which is the main focus of this study, and onsite approaches that employ single-station, P-wave detection to trigger local alerts. For a detailed overview and comparison see, for example, Hsu et al. (2018) and references therein.
emphasized that “the science and technology parts of such systems seem to be way ahead of their effective application.”

From a strictly seismological standpoint, Meier (2017) implored that EEW performance be evaluated in terms of the accuracy and timeliness of ground motion estimates from the EEW system (versus magnitude and location error). Based on recorded ground motions, Meier et al. (2017) also demonstrated that small and large earthquakes are indistinguishable in their beginnings, implying that EEW can only determine earthquake size after an event either ends or takes time to get larger; that is, larger events will take longer to evaluate for EEW purposes.

More challenging, Minson et al. (2018) made the case that—based on the assumption that the size of an earthquake is not encoded in its start—EEW systems provide only minimal warning times for very strong shaking. To paraphrase Minson et al.’s conclusions: from basic principles, areas with damaging shaking levels are very likely to receive little to no warning; moderately shaken areas will likely receive a short—<10 sec—warning; and light shaking areas will most likely receive a significant warning—10 sec or more.

Moreover, Minson et al. (2019) concluded that—due to the inherent large variabilities of ground motions—accurate EEW shaking-threshold alerts are unlikely to be the outcome, even when earthquake source information is accurately determined. Fortunately, false-alert-tolerant users—those willing to accommodate alerts at much lower thresholds than really necessary—would be less likely to miss an alert for damaging shaking levels.

Yet despite the known challenges, the EEW literature5 and coverage by the media are replete with statements implying that you’ll receive “up to a minute of warning.” In fact, of the thousands of papers, abstracts, and meeting special session presentations on EEW over the past decade6, very few describe EEW’s practical limitations along with its potential. Even social science studies focused on potential benefits of EEW often begin with the assumption of a warning of 10 or 50 sec (e.g., TriNet, 2001) or 10 to 60 sec (e.g., Wood, 2018) as an organizing principle.

5 Early and current promotional material (e.g., https://www.cisn.org/eew/eew.html) suggest that “warning times range from a few seconds to a few minutes depending on your location.” Rarely is it phrased more realistically—e.g., “zero to a few seconds, or rarely, a few tens of seconds.”

6 Remarkably, a Google Scholar search of “earthquake early warning” yields 152 thousand results; last accessed May 8, 2019.
How might EEW practitioners better communicate the area and effect of the blind (no-warni- 
ging) zone with respect to strongly shaken and affected areas? In essence, for most areas of 
strong shaking, warning times are very short or nonexistent, especially if one accounts for warning dissemination, receipt, and response times. Illuminating figures can be found for both recent and historical earthquakes. By looking to Japan’s experience with EEW for insight, 
several confounding challenges confront EEW in the western U.S. (the “ShakeAlert” system). 
With an understanding of the limited warning times, and the challenges ShakeAlert faces, this study examines the potential and limitations to taking mitigating actions with EEW in the western U.S.

Lastly, I discuss how such constrained opportunities to mitigate losses require a more nuanced approach to the way we analyze benefits and costs, and how we communicate and present EEW to our communities. In the process, I also recognize some of the potential benefits of EEW and provide some options for moving forward: by candidly acknowledging EEW’s limitations up-front, we can focus on EEW’s real benefits in the context of a continuum of other appropriate mitigation strategies.

UNDERSTANDING AND COMMUNICATING WARNING TIMES

A fundamental element to understanding the potential and limitations of EEW lies in communicating the meaning and extent of potential warning times. ShakeAlert warning latency is typically discussed in terms of alert time—the time the system takes to notice and recognize the seismic signal and estimate the shaking elsewhere. So, the alert time is the elapsed time between when an earthquake begins and when the alert is issued (Minson et al., 2018). In common-use literature the warning time (sometimes called lead time\(^7\)) is the number of seconds from issuance of that alert to the theoretical S-wave arrival at any given location (Kamigaichi et al., 2009). Simply put, warning time is the number of seconds after the alert is issued before the S-wave arrives at a particular location; it is the time available for potentially actionable information at a user’s location. Warning time is spatially variable, and can also be negative in the blind zone (or no-alert zone), where the S-wave arrives first. Unfortunately, the closer one is to the causative fault, the more compact and pulse-like the S-wave tends to be; thus, in close—where the strongest and most damaging shaking occurs—the S-wave arrival time is

\(^7\) For example, Wu et al. (2019) use the term lead time to indicate alert time prior to the arrival of the peak acceleration and peak velocity. This can be misleading, because the peak shaking can trail earlier strong shaking.
what matters most and is representative of the time before which action is needed. Moreover, a fact rarely noted in the literature is that the P-wave will often be very strongly felt ahead of the S-wave warning time in areas of potentially damaging S-wave shaking levels—a point to which I return later.

For accurate portrayal of projected (for scenarios) or actual warning times for earthquakes, the calculus must deliberately consider both the delay inherent for magnitude determination\(^8\) sufficient for shaking projections—which is considerably longer for larger earthquakes (see Minson et al., 2018)—and communication latencies, which further reduce the warning. Additionally, for human responses, one must also consider the time it takes to recognize, interpret, and respond to the warning message\(^9\). In this regard, some of the key latency times could be better explained and presented in everyday EEW discussions. Recommended actions, such as duck, cover, and hold on (DCH) and other anticipated reactions take precious seconds. If one only considers electronically automated uses, the warning time (assuming zero communication latency) is a reasonable interval to consider, depending on the time to activate and engage such automatic systems. Whereas some automatic systems can be protected nearly instantaneously (e.g., disengaging hard drives), many mechanical systems take several to many seconds to activate (e.g., moving elevators to the next floor and opening doors, opening garage doors, slowing trains).

Most EEW projections presume activation and response times to be instantaneous or ignore them altogether. Although empirical evidence for many of these latency or reaction times have not been well established, some are knowable, or can estimated. For example:

- **Alert times** (both Japan Meteorological Agency [JMA] and ShakeAlert): We can optimistically assume 5 sec, though the ShakeAlert system has not yet achieved that consistently for small-to-moderate earthquakes (Chung et al., 2019). Empirical evidence from JMA and from Minson et al. (2018) suggests it would be more proper to assume significantly longer delays as a function of increasing magnitude to alert the proper area.

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\(^8\) This is a limitation of the current ShakeAlert network-based approach of using magnitude and location to forecast ground motion. Forward prediction of ground motion (e.g., the PLUM method of Kodera et al., 2018) doesn’t necessarily require a magnitude or epicenter, but it typically adds latency in terms of warning times.

\(^9\) More properly, the warning time would be defined as the time difference between when the user receives an alert for the specified threshold of ground motion and when that threshold of ground motion arrives at that user’s location (e.g., Minson et al., 2018).
Note that alert times depend on earthquake location, network configuration, and station density, and could be longer\(^{10}\).

- **Communication latency**: In Japan, best-case alerting through public channels takes about 2-3 sec (K. Doi, oral communication; Pachett, 2017). ShakeAlert will not likely be faster than that; in the short term, it may be slower (e.g., Given et al., 2018). In the U.S., warnings are expected to be delayed due to technical limitations of our communication systems. Wireless emergency alert (WEA) testing in Oakland, CA—one of the main proposed ShakeAlert public notification methods—indicated greater than 5 sec of communication latency for 85% of users. The communication (delivery) latency for the ShakeAlertLA phone app, released in 2019 has not been publicly specified.

- **Reaction times.** BART reports that it takes about 10 sec to decelerate trains from 70 mph down to 40 mph (Gregory, 2018). Actually stopping a train takes longer, although any time available to reduce train speeds clearly may lessen the consequences of a derailment. In human terms, Porter and Jones (2018) substantiate that DCHO reaction times can be approximated with a lognormal distribution with an 8.8 sec median and 0.4 sec standard deviation; that is, only a small percentage of responses were able to DCHO in less than 5 sec.

In order to better communicate EEW latency challenges, just adding the shaking intensity to the alert-time maps used for explaining EEW (as JMA does for their post-earthquake summaries) is an effective first step. Yet, it is even more appropriate to indicate representative warning and reaction times (commensurate with specific locations and anticipated actions), not just the alert times. For recent and historical events, where the damage, injuries, and fatalities are known, we can use this information to evaluate how EEW would have performed. This can be taken a step further and used to communicate where and how EEW did or didn’t work, and for future earthquake scenarios, what we might realistically expect. For Japanese events, where EEW has been in place since 2006, the affected region and the *actual* EEW performance can be directly compared. In the western U.S., similar maps can be made for any recent, historical, or even scenario earthquake with informed assessments of EEW system latency, communication delays, and response times.

In the section that follows, Japan’s experiences for three fundamentally different tectonic settings are considered along with how their EEW system performed in each of these settings.

\(^{10}\) Recent large earthquakes near Ridgecrest, CA, in July 2019 provide additional evidence that 5 sec is a reasonable estimate for system latency and that indeed the larger events require substantially more time than that to achieve EEW-based magnitudes that begin to reach the final magnitude estimates. Both Ridgecrest events took substantially longer, as discussed later.
The relevance of these results to similar tectonic environments in California, Oregon and Washington is then discussed.

LESSONS FROM JAPAN

The Japan Meteorological Agency (JMA) has the most established EEW system in the world\(^{11}\). It has been regularly tried, tested, and adjusted for events small and large, and it has been alerting publicly since 2006 (Doi et al., 2011). Lessons can be learned from the numerous deadly earthquakes, year-in and year-out and EEW advancements at JMA—for example, their alternative to estimating shaking without magnitude and location—are continuously and rapidly deployed operationally (e.g., the PLUM method; Kodera et al., 2018).

Japan has invested very heavily in earthquake monitoring, mitigation, and preparedness. Both the Japanese support for their seismic networks and national imperative for EEW shows: JMA has achieved very dense station coverage and operates a highly sophisticated EEW system with government-mandated low latency (~2-3 sec) for public alerts that are widely communicated to the public via the airwaves and free and commercial apps (Doi et al., 2011; K. Doi, oral communication, 2018). In fact, all cell phones purchased in Japan come preconfigured with EEW alerts set to “on” by default (e.g., Patchett, 2017).

Despite all this, the success of EEW in Japan has been mixed, with results dependent on tectonic source zones. Japan is subject to three fundamentally different types of earthquakes: (1) distant, offshore megathrust earthquakes from Japan’s bordering subduction zones; (2) deep, intraplate events reflecting tensional earthquakes within the bending subducting plates; and (3) shallow crustal earthquakes from faults much closer to people and infrastructure. Of these, the subduction zone earthquakes provide for the greatest amount of warning time and have therefore been the most successful, while the crustal earthquakes provide the least amount of warning time, typically with the affected area being fully encompassed within the no-alert (e.g., “blind”) zone.

A noteworthy success occurred in 2011 in response to the great M9.0 Hanshin (Tohoku-oki) quake; though the magnitude was significantly underestimated, the JMA EEW system provided sufficient, actionable warning times (up to 15 sec) to many residents in the damaged areas (Hoshiba and Ozaki, 2014; Fujinawa and Noda, 2013). It’s not fully clear that losses were

\(^{11}\) Mexico, Taiwan, and some other nations have made substantial progress on EEW as well, yet Japan stands out in terms of technology, infrastructure, and communications.
mitigated significantly, but the advanced warning was provided and appreciated, and Shinkansen trains were systematically slowed (only one derailed). Because the magnitude was significantly underestimated, the EEW system in 2011 did not provide warnings to more distant areas such as Tokyo. However, this shortcoming is being addressed with the inclusion of better offshore monitoring and rapid finite fault capabilities as the system evolves.

Two deep intraplate (inlab) earthquakes with loss of life have occurred since publicly available EEW has been in place in Japan. The 2008 M6.8 eastern Honshu (deep, yet inland) earthquake afforded little warning in the strongest shaken areas (JMA, 2008). However, warning times of 10-15 sec were provided for the 2011 M7.1 Tokachi-oki (deep, yet offshore) earthquake, demonstrating the potential timeliness EEW could give for inlab Japanese subduction events.

Warnings for inland earthquakes in Japan, especially those tied to shallow crustal faults, have been less successful. Small to moderate crustal earthquakes (e.g., M5.5 – 6.0), for which damage is restricted to the irreducible blind zone even for optimal EEW systems, can be consequential. The 2018 M5.5 Osaka, Japan earthquake, for example, killed five people and injured over 400 in the epicentral area. JMA routinely provides maps of available warning time (Fig. A1.1; concentric circles; the alert time minus S-wave arrival time). I have supplemented JMA’s map, which shows the blind zone, by adding a 2-sec communication latency (dashed-dotted circle) and an additional 5-sec human-response latency (dashed circle). Defined this way, all of the impacts of the Osaka earthquake were well within the EEW blind zone.¹² Losses in such events—with damage limited to the immediate epicentral area—are not likely to be mitigated with EEW.

¹² See the Electronic Supplements, Appendices, for more details about the timing and other calculation, and for examples of such EEW and ShakeMaps for the 1995 M6.9 Kobe, the 2011 M9.0 Tohoku-Oki, the 2018 M7.0 Kumamoto, and the 2018 M6.7 Hokkaido, Japan earthquakes. Note that the JMA intensity scales for the JMA EEW figures are quite different than the dominant macroseismic scale used worldwide and depicted for the U.S. ShakeAlert system (Modified Mercalli Intensity, MMI). The following table provides a direct comparison based on Musson and Cecic (2012).

| JMA | 0 | 1 | 2 | 3 | 4 | 5 Lower | 5 Upper | 6 Lower | 6 Upper | 7 |
|-----|---|---|---|---|---|---------|---------|---------|---------|---|
| MMI | I | II | II | IV | V | VI | VII | VIII | IX | IX |
Since 2006, there have been 14 additional fatal inland (e.g., crustal) events in Japan during which JMA’s EEW system was fully functional and had been incrementally improved. Those losses were not mitigated by EEW, nor is there any published evidence to suggest that other losses were prevented. Figs. A1.1-3 of the *Electronic Supplement* show how the best EEW system in the world cannot provide adequate warning where it is needed the most—the blind zone. For these crustal earthquakes, the blind zone encompasses much or all of the impacted area. For this reason, Japan Railway has heavily invested in complementary strategies to help avoid high-speed derailments.\(^{13}\)

Recognizing the inherent differences in the effectiveness of the JMA system in these contrasting tectonic environments, Japanese researchers as well as the public distinguish *inland* from *offshore* (-oki) earthquakes, and they are painfully aware that fewer benefits are proffered by EEW for inland events. Inland earthquakes are underfoot, allowing only minimal warning times, while offshore events provide the opportunity for longer warning times. Despite the mixed results in Japan, the Japanese population wants and likes EEW (e.g., Doi et al., 2011; Patchett, 2017), a point returned to later in the discussion.

Although the focus of this discussion is on Japan, it is worth noting the similar situation and experience in Mexico. In Mexico City, offshore events can afford relatively long warning times in the city due to the unique situation: shaking is greatly amplified in the lakebed basin sediments of the city, yet it is distant from large offshore quakes. For this reason, Mexico developed a warning system following the deadly 1985 Mexico City earthquake. This system was tested twice during 2017 with two different intraplate events. First, a M8.2 earthquake occurred on 7 September 2017, off the southern coast of Mexico. This quake did, in fact, trigger a warning for Mexico City, although this particular quake did not result in any damage. In contrast, nearly 500 lives were lost in Mexico City on 19 September of 2017 from a 50-km-\(^{14}\)

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\(^{13}\) Importantly, after the 1995 Kobe earthquake, when numerous bridge and ground failures occurred along Shinkansen lines (though trains were not operating at night), Japan Railway (JR) took substantial actions to mitigate derailments. In addition to endorsing EEW, JR has multifaceted strategies, including bridge reengineering, anti-derailing devices, and ground improvements; and systematic communications and protocols during actual events (e.g., Nakamura and Tucker, 1985; Shimamura and Kayeki, 2013).

\(^{14}\) For a summary and translation of JMA’s 2015-2016 EEW survey of technical users, see Patchett (2017).
deep M7.1 intraplate event located well inland. This second earthquake was the deadliest event since EEW was implemented there. The SASMEX EEW audio alert was preceded by very noticeable strong shaking, so it did not alter this deadly outcome (Allen et al., 2018). The fact that neither earthquake matched the “design” megathrust earthquake is not a condemnation of the system; but, the challenge for providing effective warnings for non-megathrust earthquakes is clear.

The disparity in the potential benefits for EEW between offshore and inland quakes must be taken into consideration; whereas this is potentially good news for Oregon and Washington residents, it does not bode as well for Californians.

THE CASCADIA SUBDUCTION ZONE

The Cascadia subduction zone (CSZ) is a 1,000 km long dipping fault that stretches from northern Vancouver Island, Canada, to Cape Mendocino, California. The CSZ has produced magnitude 9.0 or greater earthquakes in the past and undoubtedly will in the future. The last known megathrust earthquake in the northwest was in January 1700, just more than 300 years ago. A large megathrust earthquake on the Cascadia subduction zone poses a significant threat to the southern Pacific Coast of Canada and the Pacific Northwest (PNW) coast of the United States.

Of particular concern with great subduction zone earthquakes is the potential for amplification of strong ground motion due to sedimentary basins. Nasser et al. (2017) note that the long-duration subduction earthquakes and the effects of basins combine to increase the risk of collapse, particularly for tall buildings and other structures affected by long-period shaking. So even though the source of the earthquake is more distant (a factor that would—all else being equal—result in decreased shaking), the basin setting of Vancouver, Seattle, and Portland results in increased hazard for these regions.

Fortunately, an offshore CSZ earthquake would likely be analogous to the 2011 Tohoku-oki M9.0 earthquake in Japan in that it offers the opportunity to realize a substantial warning to these metropolitan areas. The Tohoku earthquake example shows the potential for tens of seconds of warning over large regions in the PNW that could benefit from EEW. Patchett (2017) documented EEW benefits from that event in Japan, and the lessons they hold for a PNW EEW system. But currently in the US, warning times would likely be less due to the lack of offshore sensors. Precious seconds are lost waiting for the seismic signals to reach the
sensors along the coast. Japan has already addressed this limitation with offshore seismic and
geodetic sensors, while research is underway in the U.S. to explore ways to instrument the
seafloor. To fully maximize warning time, significant investments will be required to operate
and maintain an offshore component to the US EEW monitoring system.

**INTRA PLATE EARTHQUAKES IN THE PACIFIC NORTHWEST**

Along the Cascadia coast, intraplate earthquakes are also observed. In Washington State,
we expect about a dozen moderate-sized inslab (intraplate) earthquakes for every major
subduction interface event based on recent periods. Historically, these earthquakes are of
moderate size (~M7), although much larger intraplate earthquakes (~M8) have been observed
recently in such places as Sumatra, South America, Mexico, and Alaska. Past events in
Washington have shown that these events can be deadly and quite damaging (e.g., 1949, 1965,
2001), yet the warning times for these are (though longer than shallow crustal events)
considerably less than for great offshore events. In the case of the 2001 M6.8 Nisqually, WA
earthquake (Fig. A1.11), EEW times would have been very limited, particularly if you consider
the added time for human response. In the epicentral areas (Olympia, WA) where the damage
was greatest, warning time would have been effectively zero, while in more distant areas such
as Tacoma and Seattle, 3-10 sec of warning time would have been possible.

Most recently, the 2018 M7.1 Anchorage, AK earthquake provided a similar event for the
city of Anchorage (Fig. A1.12). There, too, areas damaged would have received very little
warning time (0-5 sec). Note, also, that the gain in warning time over crustal events is a result
of the larger depth of intraplate events, meaning also that the ground shaking is inherently
lighter than for crustal events.

**CRUSTAL EARTHQUAKES – WITH A FOCUS ON CALIFORNIA**

Like Japan, the West Coast of the U.S. is characterized by numerous crustal faults capable
of generating large, damaging earthquakes (e.g., M6-8). The focus of this section is on the
challenges of providing an early warning to California from these crustal earthquakes,
recognizing that Oregon and Washington are also subject to these same types of events. What
is unique about California, however, is that it does not have Japan’s (or the PNW’s) mix of
offshore and inland earthquakes: nearly all deadly California (south of the Mendocino Triple
Junction) earthquakes have been inland. Earthquake risk in California is dominated by a
combination of more frequent moderate-sized inland earthquakes that affect populated areas,
and less frequent larger inland events that shake greater regions. Losses from moderate-sized
(M<7) earthquakes have significantly dominated losses in the past century. In California, such
events include the 1971 M6.7 San Fernando, 1989 M6.9 Loma Prieta, 1994 M6.7 Northridge,
1987 M5.9 Whittier Narrows earthquakes [see figures in Appendix 1].

As in Japan, significant warning times are not expected in the most strongly shaken areas
for moderately sized crustal earthquakes. For example, Fig. 1 shows areas most strongly shaken
by the 1994 M6.7 Northridge, CA quake that killed dozens and injured thousands (Shoaf,
1998). Concentric circles show the approximate\(^ {15} \) warning times that could be achieved with
the current configuration of the ShakeAlert system, with an optimistic 2-sec assumption about
communication latency (since that challenge has not yet been solved). Notably, the P-wave
shaking—which was strongly felt in areas just beyond the blind zone—would have arrived
sooner than any warning (Fig. 1). The knowledge that stronger shaking can follow any
perceived shaking can be employed as a naturally occurring self-defense strategy\(^ {16} \) in
conjunction with or independently of EEW.

\(^{15}\) “Approximate” since warnings are targeted at specific locations or polygons such as sub-
prefectures (Japan) or potentially cell zones (U.S.) or other similar geographic zones (see Cochran et
al., 2017) for more details.

\(^{16}\) See Appendix 3 for more details about P-wave intensities and Appendix 1 for maps of other
notable California earthquakes.
Figure 1. 1994 M6.7 Northridge, CA earthquake ShakeMap. The epicenter is depicted with a star; the fault is shown as a rectangle angled northward from the epicenter. Concentric circles denote the alert time (dotted, 7.0 sec after origin time), the warning time (dashed-dot, 2-sec communication latency added) and response time (dashed, a 5-sec reaction time added). Blue dot-dashed circle is the location of the P-wave at the warning time. White text abbreviations refer to the Blind Zone (BZ), 2-sec communication latency added blind zone (CZ), the response zone (RZ) where users have between 0 and 5 sec to respond. The legend indicates color mapping from intensity to ground motion based on Worden et al. (2012). Most of the fatalities occurred very near the epicenter at the Northridge Meadows Apartment complex.
So, when alert, warning, and response time regions are shown along with ShakeMap shaking intensities, it is more clear which areas—and which shaking levels—could receive warnings. For the Northridge quake case, areas where shaking and thus damage were severe—and thus where the fatalities and most injuries occurred—would receive no warnings or very late ones. EEW recipients closer to the epicenter than the 5-sec “response” radius would have proportionately less time to act. It is fundamental to communicate these limitations—that substantive warning times occur primarily at relatively low shaking levels—particularly when promoting EEW through the media.

Yet, media reporting on EEW for California often further plays into the optimism for recent events for which EEW was in test operations: “A prototype system has proved successful in many recent minor and moderate California quakes, notably the 2014 magnitude 6 temblor that hit Napa, giving San Francisco eight seconds of warning. Earlier that year, scientists in Pasadena got six seconds of warning when a magnitude 5.1 earthquake hit La Habra.” (Lin, 2018). Notably, for the aforementioned Napa event, San Francisco shook at the MMI III-IV level (weak-to-light shaking; Fig. A1.9); for the M5.1 2014 La Habra event, Pasadena received the same low-level shaking (MMI III-IV). Of course, whereas it is quite possible to provide a short warning to distant (low-intensity shaking) areas, for both events, the only damage occurred in areas within the no-alert (blind) zones. This inconvenient reality is fundamental yet is not routinely portrayed in the media’s coverage of EEW.

The most significant California earthquake sequence to test the newly operational ShakeAlert system occurred near Ridgecrest, CA, in July 2019. The first alert for the July 4, M6.4 event was 7 sec after the origin time and had an initial EEW M5.7 estimate; the final EEW M6.2 was only reached after 20 sec (A. Chung, ShakeAlert Performance Report). The initial alert for the July 5 M7.1 event was 8 sec after the origin at M5.5 with a final EEW M6.3 also at about 20 sec. Station density is relatively low in the epicentral region, so the initial alerts were slower than average, but the magnitude underestimates were of more concern. Nonetheless, most of the reporting for these events focused not on the EEW magnitude underestimates which resulted in lower-than-actual estimates of shaking intensity in Los Angeles, but on the lack of alerting due to the perception that alerts should have been received. As a result, the alerting threshold for ShakeAlertLA (the cell phone app available to residents in the city of Los Angeles) has been since lowered from light shaking (intensity IV) to weak shaking (intensity III), this despite actual shaking throughout the city being well below
damaging levels, being felt by some but not nearly all in the city. So, whereas those in Ridgecrest—the epicentral residential area most heavily damaged—were within the blind zone for both events (and had no potential for a warning), media attention was focused not on the EEW system as a whole, but on populated areas where a warning of light shaking might have been available. Yet, such reporting is evidence that many would choose to receive early warnings even if they are unlikely to experience strong (damaging) levels of shaking.

**CHALLENGES FOR CALIFORNIA’S LARGER EARTHQUakes**

One advantage that California has compared to Japan is that large earthquakes along very lengthy ruptures, such as those along the San Andreas Fault (SAF), have the potential to allow for longer warning times (away from the unavoidable blind zone). However, EEW alerting for larger earthquakes is further complicated by the emerging nature of warnings: for larger events, the EEW system is continuously issuing warnings before the event is done. As the rupture extent expands, the magnitude updates follow, but not in time to get ahead of the expanding blind zone. So, unless you are far away and willing to get warned about what is initially estimated to be small shaking (e.g., Minson et al., 2018), you are subject to the same limitations as for small, nearby crustal events—the warning time is minimal.

And herein lies another challenge: the notion of a larger fault providing longer warning times has been overstated for the northern (e.g., Allen, 2006) and southern SAF (e.g., Burkett et al., 2014), suggesting over a minute of warning for San Francisco and Los Angeles, respectively. Such warning times cannot be substantiated theoretically or empirically. Earlier hopes that earthquakes are deterministic (e.g., Allen et al., 2006) have not panned out (e.g., Meier, 2017): the early stages of an earthquake are not fully diagnostic of its ultimate size, so it takes time for an event to grow to the size in which a regional warning is warranted. Thus, the reality is less favorable; the warning time gained by being farther away is mostly negated by the added time required to evaluate the size of the earthquake.

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17 As with JMA, the area alerted by the ShakeAlert system is meant to continuously expand with time as the magnitude estimate grows. For very large earthquakes, this can be tens of seconds. As succinctly summarized by Minson et al. (2018), the higher the shaking intensity predicted, the shorter the alert time due to larger fault rupture finiteness associated with widely generated strong ground motions: “Although long warning times (>1 min) are possible for low ground motion thresholds (for example, 2%g) in certain locations, warning times for strong ground motion (for example, 20%g) are still short (<10 s). It is not possible to provide long warning times for damaging ground motion because strong ground motion only occurs near the rupture of a sufficiently large earthquake, where there is
EEW’S ROLE IN RISK REDUCTION

EEW’s potentially realizable benefits for reducing risks come in several forms: reduction in casualties, reduced losses, and a sense of wellbeing from the rapid flow of information about an evolving hazard at a time of distress. Let’s examine these components further.

HUMAN (LIFE SAFETY)

Allen and Melgar (2018, p. 363) emphasized that “perhaps the most important category of users is the public, broadly defined as a group of individuals who want personal alerts and will take personal protective actions. The impact of public alerts and responses is perhaps the clearest case of the cost-benefit of EEW.” If personal alerts and actions constitute the most important user category, one must consider how long alerts take to reach such users, and how long it takes for them to respond appropriately.

Some direct potential life-safety benefits from ShakeAlert are obvious and quite achievable. DCHO and other protective actions are undoubtedly worthwhile. Yet, these actions can and should be done with or without a warning. A warning can expedite and clarify the immediate need for such actions if it arrives in time. But very little effort has been made to acknowledge (or quantify) the fact that adequately rehearsed behavior in response to shaking would not be significantly facilitated by EEW. After all, nature’s built-in EEW system—the P-wave—provides the opportunity to act independently of an EEW system. For nearly any S-wave shaking level that warrants a warning, the P-wave should be readily felt.\(^{18,19}\).

Porter and Jones (2018) estimated the potential for reducing injuries from DCHO for a hypothetical M7.1 earthquake on the Hayward Fault, the “HayWired” earthquake scenario. They assumed a 5-sec warning time; in other words, they assumed that the warning time for the M7.1 event would be as rapid as warnings for smaller quakes. They further assumed zero

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\(^{18}\) I like to say, “If an S-wave is going to cause damage, you’re going to feel the P-wave.” See Appendix 3 for more specifics concerning P-wave intensities.

\(^{19}\) Some encouraging examples of DCHO were captured on various CCTV cameras during the 2018 M7.0 Anchorage, AK earthquake. The deep hypocenter (intraplate earthquake) allowed for separation of the P-wave and S-wave—a natural warning. There is no way to tell how many people took this proper course of action when the quake occurred, but it is reassuring to see the official advice being at least partly adhered to. Based on the video footage and timing constraints, most of these actions can be attributed to feeling the P-wave and responding accordingly since no EEW system was in place.
communication latency and an extreme upper bound 89% injury reduction\textsuperscript{20} (in addition to an excessive $28,000 cost per injury\textsuperscript{21}) to compute $300M in potential savings from DCHO for that scenario. Based on earlier work on the Northridge earthquake (Porter et al. 2006), Strauss and Allen (2016) suggested over $1-2B in savings from DCHO alone for that event. Of course, the Northridge earthquake occurred at 4:30 a.m. local time, so DCHO was thus not a logical option for nearly the entire (sleeping) population.

In fact, for the Northridge earthquake, around 2.0\% of questionnaire respondents in the areas with MMI of VI or less were injured, similar to that percentage found in both the Whittier Narrows and Loma Prieta earthquakes; in higher-intensity areas, 20–25\% of respondents reported being injured (Shoaf et al., 1998). Shoaf et al. concluded that injuries generally occur in earthquakes that result in **MMIs of VII or higher**. Thus, nearly all of the injuries and fatalities occurred in areas that would not receive a warning, let alone have sufficient time to react. This is, for the most part, the same case for the HayWired scenario if proper warning time assumptions are made.

Strauss and Allen (2016, p. 365) suggested that EEW could “reduce the number of injuries in earthquakes by more than 50\%”; therefore, it would easily “pay for itself”. However, nearly all of the injuries (and all fatalities) occurred in areas that would not receive a warning (e.g., Meier, 2017; Minson et al., 2018), let alone have sufficient time to react. Nor is there any epidemiological evidence that DCHO would have been as successful in reducing injuries as assumed by Strauss and Allen and Porter and Jones (2018).

Systematic injury data indicate that roughly half of all injuries in earthquakes were due to primary (during-shaking) and secondary (post-shaking) actions rather than from shaking or its effects. Primary actions led to about half of the 2011 M6.3 Christchurch, New Zealand earthquake injuries, and an additional quarter of injuries were attributed to secondary actions (Johnston et al., 2014). Following the 2018 M7.1 Anchorage earthquake questionnaire, as many respondents reported that they were injured during the quake (223) as after the quake (252); for instance, when cleaning up (Porter and Tiffany, 2019). Thus, injuries should be

\textsuperscript{20} Consider the question: for avoiding injuries, i.e., via DCHO, what fraction of the public has a smart phone with a signal and the EEW app in audible range (not silenced), and who can react immediately?

\textsuperscript{21} Porter and Jones (2018) equate the Federal Government’s *acceptable cost to avoid a statistical injury*—in the realm of regulating the automobile industry—to the cost of an *actual* injury.
considered avoidable not solely in the context of EEW, but also through public education about personal protective actions and equipment (primarily foot protection), which could be part of a comprehensive EEW communications, education, and outreach (CEO) strategy facilitated by a large EEW outreach effort.

Hence, though Porter and Jones (2018) reported that DCHO could reduce injuries and fatalities in idealized cases, those injuries that occur in the heavily damaged areas are the most likely to receive little to no warning, and only in small part due to current limitations of alerting technologies. For all these reasons, the Porter and Jones (2018) result was an overly optimistic estimate of reduced injuries due to EEW; a more proper estimate would consider EEW as it advances response time or improves mitigating actions above and beyond the default behavior (of course, in either case conditioned on further education and outreach efforts to enhance the public’s reactions).

Though not intuitively obvious, reducing fatalities is all the more difficult to achieve in California than elsewhere because severe shaking causes many fewer fatalities per capita than in other hard-hit regions; this a function of the high quality of building codes and compliance as well as the recency of the building inventory. Consider that the fatality rate due to severe-to-violent shaking in California is approximately 50 times lower than it is in Japan\textsuperscript{22} and nearly 350 times lower than in Italy (Jaiswal and Wald, 2010). Likewise, most serious injuries and fatalities due to earthquake shaking occur under circumstances (like catastrophic structural collapses) that cannot be greatly mitigated through human reactions to very short warnings; instead, they must be reduced through more tried-and-true, long-term mitigation strategies addressing the built environment: building codes and their enforcement, structural and non-structural retrofit programs, and earthquake engineering.

Sheltering in place (including DCHO) and evacuation are end-member actions that are warranted under certain conditions; the latter is only recommended in areas of low, highly

\textsuperscript{22} See Table A5.1. Think of the comparable 1994 M6.7 Northridge, CA earthquake (33 fatalities) and the 1995 M6.9 Kobe, Japan earthquake (5,600 fatalities). Both events had similar populations exposed to very strong shaking. Below is a table of fatality rates per million people exposed to each MMI level for California, Japan, and Italy (Jaiswal and Wald, 2010).

| MMI | V | VI | VII | VIII | IX |
|-----|---|----|-----|------|----|
| California | 0 | 0 | 1 | 8 | 35 |
| Japan | 0 | 0 | 0 | 46 | 3,070 |
| Italy | 0 | 13 | 285 | 2,637 | 13,514 |
vulnerable structures where egress is likely to be more advantageous (e.g., GHI, 2018). A rather significant dilemma remains in advising populations on what EEW actions to take in regions where DCHO may not be, or is likely not, the advisable strategy (GHI, 2018). Johnson et al. (2017, p. xiv) suggest that “a range of appropriate warning responses (e.g., more than DCHO) is needed given the variety of situationally specific human activities that people may be engaged in when an earthquake occurs.” Johnson et al. (2017) go on to say that investigations are needed “to cover an array of socio-demographic, organizational, temporal, and functional situations, including for example, hazardous industrial and occupational scenarios, what individuals of different backgrounds and abilities might do in various private or public settings, and human-object interactions and the different warning response times ranging from only a few to many seconds.” While Johnson et al.’s recommendations are appropriate, the truth remains that the range of response opportunities that can reduce harm is limited given the short times and the high-quality nature of the building stock in California (in particular) and the western U.S., in general; the good fortune of inhabiting safe buildings affords one fewer opportunities to benefit from EEW.

Many social science studies also follow the media’s lead and assume “EEW can give a few sec to minutes” (Dunn et al., 2016) or “10-60 sec” warning (Wood et al., 2018) as the initial conditions for their analyses, rather than the much more likely 0-10 sec for damaging or injurious shaking levels (e.g., Minson et al., 2018). In order to draw beneficial conclusions, social science, communication, and preparedness efforts need to be based on realistic expectations of ShakeAlert’s anticipated capabilities and performance, not on optimal scenarios.

**INFRASTRUCTURE, INDUSTRIAL AND FINANCIAL IMPACTS**

In a review article published in 2016, Strauss and Allen showcased a variety of potential uses for EEW in Mexico, Japan, Turkey, Taiwan, China, Romania, and the U.S., noting that EEW could be used in hospitals, schools, elevators, manufacturing, transportation systems, and to support emergency responders. However, few documented mitigation examples were presented; most were either anecdotal or pointed to potential uses and savings.

Johnson et al. (2017, p. xii) also delineate many possible avenues for organizational use of EEW, yet they point out, “however, to date, these uses are mostly hypothetical.” This is to be expected for a nascent U.S. EEW system, where warning times are only now being documented and where communication paths and the content of warning messages are all still being
determined. Nevertheless, the ShakeAlert system boasts a large number of pilot users from a range of different industries and commercial sectors, suggesting interest is high in leveraging the EEW messages for machine-to-machine (electronic) applications that can occur automatically in a range of industrial, commercial, and public settings.

Yet, automatic actions taken in response to an EEW alert have not been the norm in Japan. Patchett (2017) translated a number of important documents in Japanese, and summarized JMA’s survey of business operators—who for over a decade have had access to Japan’s advanced-user EEW feeds. Patchett (p. 38) noted that “initially, an automatic halting of machine operation for production lines were expected to be high; however, the number of controlling operation of machines, production lines or halting of elevators are small, and automation of such processes are also low.” Noteworthy, documented, real-world applications in the utility sector exist, including an integrated EEW/rapid-response system in Istanbul for the Natural Gas Network (IGDAS). Upon EEW triggering, district regulators can interrupt the gas flow if any exceedance is detected (Zulfikar et al., 2016). Such documented examples are encouraging but rare.

One of those early adopters of ShakeAlert is the Bay Area Rapid Transit. BART’s goal in employing ShakeAlert is simple: by slowing down or ideally stopping trains before strong shaking arrives, BART hopes to reduce train derailments, thereby avoiding injuries and potential casualties. This application is a no-brainer: the cost is low (false alarms causing trains to slow are relatively harmless) and the potential benefit is high. Yet here, too, let’s consider the practical experience. It takes BART about 10 sec to decelerate from 70 mph to 40 mph (Gregory, 2018), so stopping a train given the expectation of <10 sec of warning time in areas that are strongly shaken is unlikely. Nevertheless, train derailment is a complex function of shaking intensity, train speed, and track curvature (or damage), and reducing train speeds prior to the arrival of shaking has the potential to reduce losses, thereby changing the risk profile for a network of moving trains distributed across a large metropolitan region.

Beyond infrastructure, the fact of the matter is that accounting for earthquake losses (and thus calculating future risk) in California is partly done not just in human terms, but by considering economic losses. The 1994 Northridge earthquake is estimated to have cost $40B (e.g., Eguchi et al., 1998). Most of the Northridge earthquake losses resulted from damage to residences and businesses that can only be mitigated by alternative (long-term, and granted, much more expensive) means. As summarized by Goltz and Flores (1997, p. 732): “It is
extremely unlikely, however, that [EEW] can be justified solely as a means of avoiding financial losses in a commercial and industrial setting or of providing industry with large financial savings derived from mitigative actions undertaken within a few sec.”

PERSONAL (AND EMOTIONAL) COMFORT

Although less quantifiable from a cost-benefit perspective, there is clear documentation of the socio-psychological benefits of EEW. JMA surveys show that the Japanese populations want and like EEW (e.g., Doi et al., 2011; Patchett, 2017) despite its mixed success. Similar survey results were reported following the 2017 Mexico earthquakes, where warnings were either late or irrelevant (Allen et al., 2018). In California, the demand in Los Angeles for lower alerting thresholds following the 2019 Ridgecrest earthquake sequence confirms the desire to use EEW for informational benefit and emotional support.

In a recent study, Nakayachi et al. (2019, p. 2) noted that “despite significant evidence of the utility of EEW for technical applications, there is limited information on the actual (not potential) effectiveness of EEW for personal protection” and that “how effective it actually is in practice is not yet clear.” Nakayachi et al. (2019) concluded that primary reactions were passive in nature, and that the overwhelming majority of survey respondents stated that EEW enabled them to mentally prepare for shaking rather than to take action. Their study supports the notion that EEW can provide important emotional preparedness prior to shaking. While this might best be categorized as “nice-to-know” rather than quantifiable loss reduction, the benefits are real.23

Additionally, a common refrain from the EEW community is that EEW can contribute to a “culture of prevention” (Goltz and Flores, 1997; Allen, 2017), thereby inculcating a population to be better aware of—and thus desire and support—better monitoring, EEW, and other earthquake mitigation efforts. Surveys of potential users suggested that EEW would help in “raising the level of personal and organizational awareness and preparedness for earthquakes, and reducing anxiety given the sudden onset of earthquakes” (Johnson et al., 2017, p. xii). Similarly, earthquake practice drills (“ShakeOuts”) provide important awareness and training on an annual basis. There certainly would be great value to a robust EEW system in delivering

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23 I also note that there have been a few examples of emotional angst (and subsequent physical harm) due to both EEW alerts and EEW false alarms, and numerous warnings during aftershock sequences (e.g., Kodera et al., 2018), a wider concern that has not received as much attention.
timely, accurate information about all shaking levels via customizable alert thresholds. The awareness of what shaking is expected in the chaotic seconds of strong shaking would likewise be highly welcomed by users, as we have seen in Japan.

In all of the above risk mitigation goals, the most fundamental approach is widely known to be good design, construction, and retrofitting of the Nation’s infrastructure (e.g., UN, 2015). Such earthquake engineering and construction must include structural as well as non-structural elements that could potentially cause fatalities and injuries. These are not either-or propositions: EEW is much less expensive than most systematic structural or even non-structural retrofit strategies.

COMMUNICATION, EDUCATION, AND OUTREACH

When is an early warning system suitable or ready for public consumption? The United Nations International Strategy for Disaster Reduction (UNISDR, 2006) has developed a set of best practices that relate to early warning; these have little to do with scientific knowledge and technical tools. Instead, they are focused on risk communication. Experts in this field have long documented the importance and complexity of appropriate communication for emergency alerts (Mileti and Sorensen, 1990; Sorensen, 2000; Tierney, 2004). Best practices in risk communication are by no means simple to achieve, and mistakes can lead to messages failing to reach vulnerable populations—or being ignored when they do. These insights have informed contemporary U.S. Geological Survey (USGS) risk communications recommendations, which include heavy stakeholder involvement at all stages of risk (Ludwig et al., 2018).

A central tenet to EEW education and outreach, therefore, is to ensure realistic expectations in terms of what EEW warning times will actually be. To this end, messaging needs to be tailored to the tectonic setting, meaning CEO education and outreach efforts in the Pacific Northwest, where subduction zone and intraplate earthquakes dominate and offer tens of seconds to perhaps a few seconds of warning, respectively, will inherently differ from that in California, where crustal earthquakes will likely result in no warning to areas exposed to damaging ground shaking. And the likelihood of not receiving a warning prior to shaking must also be presented as a high probability in all regions, depending on the location of the earthquake and other limitations in the technology of delivering warnings. If that likelihood of not receiving messages until after the strong shaking starts (and potentially even after it stops...
given long latencies with WEA-based public alerting) is more fully acknowledged, messaging could more properly reflect range of users’ experiences and thus better inform their actions.

The “last mile” of the ShakeAlert strategy—near-instantaneous delivery of the warnings to the public—was not fully vetted or verified in the first decade of its development, nor was the content of the messages to be delivered. Initial promotion of ShakeAlert considered an alert capable of providing both an estimate of the users’ expected shaking intensity and a countdown to the arrival of strong shaking (e.g., Given et al., 2014; Fig. A6.1). However, neither of these can be realized for the general public with the current available notification technologies (Given et al., 2018). Whereas solving the communication latency challenges is not in the purview of ShakeAlert operators, the system is incomplete without timely warnings, and education and outreach efforts are hindered by the lack of existence of simple, actionable, and timely messages.

While it remains to be seen how much risk reduction can be achieved from automated responses such as arresting moving systems, securing dangerous chemicals, shutting valves and securing machinery and equipment, it has always been clear that EEW alone will not fundamentally eliminate earthquake losses. To the contrary, it is likely that the amount of risk reduction achieved by EEW will pale in comparison to (much more expensive) highly successful risk reduction accomplishments achieved through retrofits, earthquake provisions in building codes, and improved structural design. For this reason, EEW messaging should not compete with long-term earthquake mitigation efforts; it should augment them. In fact, a less-touted benefit of EEW has already been achieved: helping the USGS improve its basic seismic monitoring operation, which in turn provides the data that researchers and engineers need to better understand hazards and risk, prioritize retrofits, and continue to design more earthquake-resistant buildings.

As with all new technologies, the potential for unforeseen benefits is profound. But adoptions of new technologies—the diffusion of innovations—also follow rather predictable trends (e.g., Rogers, 2003). Early adopters are key to communicating an innovation’s benefits, and they evaluate an innovation on its relative advantages. Transparency concerning limitations and delivering on expectations is thus essential in EEW’s ultimate adoption as a technology. Will the early adopters stick with the program? It’s too early to tell, but with ShakeAlert, the stakes are not just scientific reputations or proper governance, but potentially lives.
From a communications viewpoint, the following talking points could be considered as part of any comprehensive strategy to articulate EEW possibilities and limitations:

- **Depict** communications and response latency to expected alert times to yield a practical warning time—and publish specific scenarios as examples (e.g., the 1994 M6.7 Northridge earthquake). Current seismic network and communication limitations result in about a 25-km (15-mi) radius zone centered on the epicenter for which alerts are not possible. The size of this no-alert zone does not include the additional time required for people to comprehend and respond to an alert message; so, practically speaking, the “no-response” zone is substantially larger than a 15-mi radius. It should be shown for specific use/action scenarios.

- **Distinguish** between subduction zone environments, intraplate quakes, and crustal quakes in setting warning time expectations. This requires geographically specific communication strategies and materials.

- **Educate** users that if they feel shaking, they should take appropriate action (or appropriate inaction). They may or may not get confirmation from EEW in time to act.

- **Communicate** that EEW is not the only—nor even the best—strategy for reducing earthquake losses. Preparedness, training to take proper actions, and more standard mitigation efforts (building and non-structural retrofits, better infrastructure) are all needed.

- **Acknowledge** that early users need to be fault-tolerant since a) the EEW system will evolve and improve with time, b) it is going to issue false alerts and miss some events, and c) offshore earthquakes may challenge accurate and timely detection until there are sufficient offshore sensors.

- **Promote** EEW as part of the full suite of USGS earthquake information products. The societal effects of earthquakes just begin at the moment of severe shaking; the economic losses, social disruptions, and many of the injuries and deaths occur in the hours, days, and more following the mainshock. While EEW can be the initial “heads up”, it is rapidly supplemented by actionable maps of shaking intensity (ShakeMap), loss projections (PAGER), citizen science opportunities (Did You Feel It?), aftershock projections, and other advisories the USGS and its partners provide.
• **Keep** EEW front and center, but also promote it in the broader context of the available earthquake hazard and risk information products that meet a broad range of planning, mitigation, and response purposes.

**CONCLUSIONS**

The numerous significant technical refinements and scientific advancements aimed at EEW challenges in recent years have been impressive. Yet, providing effective EEW within seconds of an earthquake is more challenging than anticipated or readily acknowledged. Moreover, serious practical and technical EEW limitations reduce the range of possible actions that would significantly mitigate earthquake losses. Neither the practical limitations of EEW nor the narrow range of mitigation options have been widely articulated.

As the technology and infrastructure improve, and as costs are reduced, EEW is logically going to become a standard operating procedure, if the current communications challenges can be addressed. There are a number of straightforward benefits that EEW can provide, as well as future opportunities (including rail and other transportation sectors). It is likely that automated actions not yet envisioned will also become routine and contribute to reducing losses. Likewise, comprehensive communication, education, and outreach efforts developed under the ShakeAlert program may speed up and enhance personal and institutional responses to earthquakes. There is also room for optimism even for large inland earthquakes as more ideal (denser) seismic networks, refined EEW algorithms, and the next-generation communication technologies take hold. Evolving algorithms such as the rapid finite-fault analyses developed by Böse et al. (2017) suggest that it may be possible to alert some fraction of the strongly shaken populace for even large inland earthquakes, and research by Melgar and Hayes (2019) offers hope that a weak magnitude determinism will be informative for faster magnitude characterization. We can also count on significant improvements to warning timeliness for Pacific Northwest offshore subduction events as offshore networks are supported and deployed (e.g., Patchett, 2017).

Yet it is due to these enticing prospects that EEW science is essentially part of the public sphere. This study aims for more-nuanced EEW discussions that will facilitate efforts to adequately articulate EEW limitations whilst we explore its potential benefits; this needs to be done from an impartial, non-advocacy perspective. It is not unusual that proponents of new technologies are known to put words in the mouths of potential users. As recognized long ago
by Plato, “the parent or inventor of an art is not always the best judge of the utility or inutility of his own inventions to the users of them” (ca. 370BC). EEW system developers and scientists can play an important role in promoting their work for the betterment of society, but their advocacy role should be balanced and limited. When the experts in a technology are not their own critics, the scientific community surrounding them must be. The scientific process, and the public, warrant nothing less.

The USGS through the National Earthquake Hazards Reduction Program has prioritized seismic hazard assessment and research as a means to promote long-term risk reduction. Its National Seismic Hazard Model serves as the basis for earthquake-resistant code provisions that are adopted into building codes and other code standards directed at bridges, railways, and other infrastructure. Complementing these longer-term products are shorter-term USGS tools aimed at providing situational awareness following earthquakes and supporting pre-earthquake planning and mitigation activities. Examples include the ShakeMap, ShakeCast, and PAGER products, and newer products that forecast aftershock activity and predict ground failure and earthquake-triggered landslides following a mainshock.

In this context, the EEW ShakeAlert product is but one in a series of USGS products aimed at addressing the continuum of informational needs from decades prior to an earthquake to minutes and days following an earthquake. No single USGS product meets all the needs of the customer base—effectiveness comes from the continuum of products that seek to share information and inform users across the earthquake cycle. Engaging customers and addressing their needs from the perspective of the full USGS product line is thus recommended to not only maximize risk reduction but also minimize the potential for reliance on ShakeAlert alone for life safety and economic resiliency.

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**APPENDICES**

Appendix 1 – Shaking and Warning Times for Earthquakes in Japan and the Western U.S.

Appendix 2 – EEW Time Calculations

Appendix 3 – S- and P-wave Travel Times and Amplitudes

**APPENDIX 1**

**SHAKING AND WARNING TIMES FOR EARTHQUAKES IN JAPAN AND THE WESTERN U.S.**

Appendix 1 includes maps showing example Japanese and U.S. earthquake alert times (when earthquake early warning (EEW) was in place) or based on calculations (pre-EEW system) for significant recent earthquakes in both countries. For recent Japanese events, EEW times reported by Japan Meterological Agency (JMA) were used. For U.S. events, only the 2014 Napa earthquake had actual (test) EEW results; the rest are represented with ShakeMap and estimates of potential ShakeAlert EEW alert, warning, and response times.
Figure A1.1. EEW times for the M5.5 June 17, 2018 Osaka, Japan, earthquake. Solid contours depict warning times reported by JMA (2018). The high-intensity area within the dots-added, zero-second contour (approximate 21 km radius) is considered the “blind zone.” Adding the minimum 2-sec latency for typical Japanese media and cell recipients increases the zone to approximately 29 km (dash-dot circle). Between the dash-dot and dashed black circle, residents could have up to 5 sec to respond. Inset legend describes the JMA instrumental intensity reported in each prefecture. Available online: http://www.data.jma.go.jp/svd/eww/data/nc/pub_hist/2018/06/20180618075838/reachtime/reachtime.html.
Figure A1.2. EEW times for the September 6, 2018 M6.7 Hokkaido, Japan earthquake. The high-intensity area within the dot-added, zero-second contour is considered alert time. Adding the minimum 2-sec latency for typical Japanese media and cell recipients increases the blind zone to the warning time (dash-dot red circle). Between the dash-dot and dashed black circle, residents could have up to 5 sec to respond. Inset legend describes the JMA instrumental intensity reported in each prefecture. Forty-one people were killed, primarily in the worst-hit town of Atsuma, primarily by shaking-induced landslides. Available online: http://www.data.jma.go.jp/svd/eew/data/nc/pub_hist/2018/09/20180906030805/reachtime/reachtime.html.
Figure A1.3. EEW times for the April 16, 2018 M7.0 Kumamoto, Japan, earthquake. The high-intensity area within the dot-added, zero-second contour is considered alert time. Adding the minimum 2-sec latency for typical Japanese media and cell recipients increases the blind zone to the warning time (dash-dot circle). Between the dash-dot and dashed black circle, residents could have up to 5 sec to respond. Inset legends the JMA instrumental intensity reported in each prefecture. Available online: http://www.data.jma.go.jp/svd/eew/data/ne/pub_hist/2016/04/20160416012510/reachtime/reachtime.html.
Figure A1.4. Initial EEW times for the July 24, 2008 M6.8 inslab earthquake near the coast of Honshu, Japan. Hypocentral depth is 108 km. Contours on the left figure depict potential warning times if the initial location and magnitude resulted in estimated shaking above the alert threshold. Contours on the right provide early warning times given the actual alert determined. For details, see: http://www.data.jma.go.jp/svd/eew/data/nc/pub_hist/2008/07/20080724002635/reachtime/reachtime.html.
Figure A1.5. Initial EEW times for the earthquake April 7, 2011 M6.7 inslab earthquake off the coast of Honshu, Japan. Hypocentral depth is 66 km. Contours on the left figure depict potential warning times if the initial location and magnitude resulted in estimated shaking above the alert threshold. Contours on the right provide early warning times given the actual alert determined. For details, see: http://www.data.jma.go.jp/svd/eww/data/nc/pub_hist/2011/04/20110407233256/reachtime/reachtime.html.
Figure A1.6 Initial EEW times for the March 11, 2011 M9.0 Tohoku-oki (Great Hanshin), Japan earthquake. The high-intensity area within the dot-added, zero-sec contour is the alert time. Left: reported JMA intensities; right: estimated intensities at initial warning. Adding the minimum 2-sec latency increases the blind zone to the *warning* time (dash-dot circle). Residents along the east coast had up to 15-sec warning, but with much lower shaking estimates (right) than what occurred (left). No alarm was sent to Tokyo, where intensities reached 5 lower (left). Inset legend describes the JMA instrumental intensity reported in each prefecture. The initial alert (M7.2) was at 8.6 sec, at 22.2 sec was M7.6, and at 65.1 sec was M7.9. For details, see: [http://www.data.jma.go.jp/svd/ewd/data/nc/rireki/201103.pdf#page=4](http://www.data.jma.go.jp/svd/ewd/data/nc/rireki/201103.pdf#page=4).
Figure A1.7. 1995 M6.9 Kobe, Japan earthquake ShakeMap. JMA EEW was not in place at the time of this earthquake. The epicenter is a star; the fault is shown as two narrow rectangles. Small colored circles are reported intensities, and triangles denote seismic stations color-coded to intensity. Concentric circles denote the alert time (dotted, 7.0 sec after origin time), the warning time (dot-dashed, 2-sec latency added) and response time (a 5-sec reaction time added). The legend indicates color mapping from intensity to ground motion based on Worden et al. (2016). Blue dot-dashed circle is the P-wave location at the warning time.
Figure A1.8. 1994 M6.7 Northridge, CA earthquake ShakeMap. The epicenter is depicted with a star; the fault is shown as a rectangle angled northward from the epicenter. Concentric circles denote the alert time (dotted, 7.0 sec after origin time), the warning time (dashed-dot, 2-sec communication latency added) and response time (dashed, a 5-sec reaction time added). Blue dot-dashed circle is the location of the P-wave at the warning time. White text abbreviations refer to the blind zone (BZ), 2-sec communication latency added blind zone (CZ), the response zone (RZ) where users have between 0 and 5 sec to respond. The legend indicates color mapping from intensity to ground motion based on Worden et al. (2016). Most of the fatalities occurred very near the epicenter at the Northridge Meadows Apartment complex.
**Figure A1.9.** 2014 M6.0 South Napa, CA earthquake ShakeMap. The epicenter is depicted with a star; the fault is shown as a fine line northward from the epicenter. Small colored circles are reported intensities, and triangles denote seismic stations color-coded to intensity. Added concentric circles denote the alert time (dotted, 5.1 sec after origin time), the warning time (dot-dashed, 2-sec latency added) and response time (12.1 sec; a 5-sec reaction time added). The blue dot-dashed circle is the location of the P-wave location at the warning time.
Figure A1.10. 1989 M6.9 Loma Prieta, CA earthquake ShakeMap. The epicenter is depicted with a star; the fault is shown as a rectangle. Small colored circles are reported intensities, and triangles denote seismic stations color-coded to intensity. Added concentric circles denote the alert time (dotted, 7.0 sec after origin time), the warning time (dot-dashed, 2-sec latency added) and response time (a 5-sec reaction time added). The blue dot-dashed circle is the location of the P-wave location at the warning time.
Figure A1.1. 2001 M6.7 Nisqually, WA earthquake ShakeMap. The epicenter is depicted with a star; the fault is shown as a rectangle. Small colored circles are reported intensities, and triangles denote seismic stations color-coded to intensity. For this depth, there may be no blind zone (S-wave arrives after alerting). Concentric circles denote the warning time (solid, 2-sec latency added) and response time (dot-dashed, 5-sec reaction time added). The blue dot-dashed circle is the location of the P-wave at the warning time. Much of the property damage occurred in epicentral region, primarily to unreinforced masonry and concrete buildings, but significant damage occurred in Seattle neighborhoods where warning time could be as much as 10-12 sec.
Figure A1.12. 2018 M7.0 Anchorage, AK earthquake ShakeMap. The epicenter is depicted with a star; the fault is shown as a rectangle. Small colored circles are reported intensities, and triangles denote seismic stations color-coded to intensity. For this depth, there may be no blind zone (S-wave arrives after alerting). Concentric circles denote the warning time (solid, 2-sec latency added) and response time (dot-dashed, 5-sec reaction time added). The blue dot-dashed circle is the location of the P-wave at the warning time.
APPENDIX 2

EEW TIME CALCULATIONS.

For Japanese events, we use the earthquake early warning (EEW) alerting times reported by the Japan Meteorological Agency (JMA) (http://www.data.jma.go.jp/svd/eww/data/nc/pub_hist/). The alerting time is the time to compute the warning minus the S-wave arrival time; if the S-wave is earlier than the alert time, there is no warning there (the “blind zone”). The warning time is also depicted by adding 2 sec of communication latency (K. Doi, JMA, oral communication, 2018), as well as the response time by adding an extra 5 sec (Porter and Jones, 2018), and we depict the location of these additional lag times as dashed or dashed-dotted circles (Appendix 1). The 5-second response time is meant to approximate duck, cover, and hold on (DCH) times as suggested by Porter and Jones; other actions or mechanical operations could be faster or slower, of course.

For the Kobe, Japan (Fig. A1.7) and California events, which were all crustal earthquakes, the alerting time $t_A = R/V_s - t_r$—where $R$ is the hypocentral distance; $V_s$ is the average crustal shear-wave velocity (approximately 3.4 km/s; corresponding $V_p$ is 5.8 km/s); and $t_r$ is the time to compute the warning. The ShakeAlert compute latency time is limited by waiting for a sufficient number (3 or 4) of P-waves to arrive at the closest stations, and for the EEW system to compute the warning. We estimate $t_L$ by the P-wave time plus about 3 sec. This is comparable to JMA’s alert times and is consistent with the best performance to date in California for a moderate-sized earthquake—the ShakeAlert system alert time for the moderate-sized 2014 M6.0 Napa, CA earthquake was about 5.1 sec. Chung et al. (2018) report median alert times for in-network events with the latest ShakeAlert ElarmS-3 software to be 6.0 s (with a 2.0 sec standard deviation). In reality, ShakeAlert’s compute time may be a bit better; or more likely, slightly worse depending on the hypocentral depth, the epicentral station density, the nature of the P-wave arrivals, and the magnitude of the earthquake (e.g., Minson et al., 2018; larger events require more compute latency).

For the 1994 M6.7 Northridge, CA, earthquake, which had a relatively deep 18 km hypocentral depth $z$, we estimate the compute latency $t_L$ to be about 7 sec. The horizontal distance $h$ (the circle’s radius in this case) is computed as $h = \sqrt{z^2 - R^2}$, or 15.6 km. (Fig. A1.8). We depict the warning time by adding a 2-sec communication latency, so $h$ becomes 24.7 km. The radius of the response zone is 44.1 km after adding an additional 5 sec for
response (e.g., DCHO, slowing a vehicle). We also depict the P-wave front at the time of the warning time: this signifies that the P-wave, which is typically widely felt for strong S-wave shaking (see Appendix 3), would have already been experienced seconds earlier in areas that were just receiving a warning.

Events with hypocenters shallower than that of the Northridge earthquake afford less warning time; deeper events allow for greater warning times. For example, for the deeper \((z = 52\text{km})\) 2001 M6.7 Nisqually, WA earthquake, we adopt a lower crustal/upper mantle \(V_p = 6.9\) and \(V_s = 4.0\). Then, the alert time is later, but the S-wave is correspondingly later. We depict the radii for alert, warning, and response times for a 4-sec compute latency \(t_L\), plus 2 sec for communication latency, and a 5-sec response time (Fig. A1.11).

Likewise, there are two additional complexities that we ignore in our simple depiction of warning time. First, strong P-waves can arrive before the S-wave time so as to render the pre-S-wave alert insufficient. Second, since ShakeAlert and other EEW systems update their earthquake source and shaking estimates, the blind zone and warning times can evolve and form more complex patterns than concentric circles (see Cochran et al., 2017). In Japan, since alerts are issued at the subprefecture level, the actual warning times are more complicated than portrayed by JMA in their online post-earthquake summary reports depicted in Appendix 1.
APPENDIX 3

S- AND P-WAVE RELATIVE TRAVEL TIMES ANDAMPLITUDES

S-minus-P-Wave Travel times for estimating distance

At the Caltech Seismological Lab, we students learned early on that the earthquake distance (in km) for most felt earthquakes could be estimated immediately by the S-P-wave time difference times x 8. This holds fairly well for epicentral distances from a few score to several hundred kilometers (where P- and S-wave ray paths can be assumed to take roughly horizontal paths); it does not consider variations due to the range of earthquake depths, which in California tend to not vary all that much (6-18 km). With these approximations, the difference in the arrival times of the S and P waves is \( \Delta t = \frac{d}{V_{S-wave}} - \frac{d}{V_{P-wave}} \), where \( d \) is distance from the epicenter and \( V \) is speed of the S- and P-waves. Then, for S-waves in the crust of 3.4 km/s and P-waves of 5.8 km/s, the distance is the inverse of \( 1/3.4 - 1/6.0 \), or about 8 times the S-P interval.

This could easily be taught to California schoolchildren, for example, in an analogous way to finding the distance of lightning (after seeing lightning, count until the thunder, then divide by 5 to get the distance in miles). Even the use of miles is permitted (if we must) by multiplying S-P-wave time difference by 5 rather than by 8. Why learn this at an early age? Well, if one knows ahead of time that P-waves precede S-waves—and further, that the S-waves will be much stronger—one can take appropriate preparatory actions when one feels any significant shaking. Counting could be, perhaps, more calming an endeavor than responding to a shrieking alarm. And the warning comes for free, courtesy of Mother Nature.

More pertinent to the EEW discussion, it is safe to assume that if you do not feel the P-wave (or emerging S-waves), you are at a distance where the S-wave will not be damaging. How do you know? You’d be hard pressed to. But simply assuming than any weak shaking will be followed by stronger shaking is precaution enough. Initial strong shaking could be followed by stronger shaking yet, so always take precaution. Yes, responding to shaking in a natural way could be well addressed via primary and secondary school science and health curricula, and public education—individually of EEW.

A recent case in point: for the 2017 M7.1 Puebla, Mexico earthquake, which was relatively close to Mexico City (120 km away), the SASMEX EEW alert was issued about 5 sec after the
P-wave arrival. However, the P-wave was *very strongly* felt before the alarm was issued (Allen et al., 2018).

**P-wave versus S-wave intensities**

At these same close-in distances, in fact, the S-to-P amplitude ratio is on average less than an order of magnitude. So, even considering the differences in P- and S-wave frequency content, in which lower intensities are better aligned with higher frequencies (Sokolov and Wald, 2002), we would still expect the felt intensity of the P-wave to be only about 2 intensity units lower than that of the S-wave. That is, at least within a few tens of kilometers of crustal earthquakes, the S-to-P amplitude ratio is on average about a factor of 3, or 1-2 intensity units (Worden et al., 2012). At warnable distances, the ratio is about 4-10, or about 2-3 intensity units.

Thus, within typical EEW blind zones when shaking is damaging (MMI ≥ VI), P-waves will be very strongly felt (e.g., intensity ≥ IV). In fact, when users consider specific ground motion levels for alerting thresholds, such shaking thresholds are often already exceeded by the P-wave 35, 24, 13, and 6% of strong motion records that exceed 2, 5, 10, and 20%g, respectively, *before* the S-wave arrival. (Minson et al., 2018).

Some example seismograms for several of the events portrayed in Appendix 1 are illustrative of this point.
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