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Understanding the social aspects of earthquake early warning: A literature review

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Earthquake early warning (EEW) systems aim to warn end-users of incoming ground shaking from earthquakes that have ruptured further afield, potentially reducing risks to lives and properties. EEW is a socio-technical system involving technical and social processes. This paper contributes to advancing EEW research by conducting a literature review investigating the social science knowledge gap in EEW systems. The review of 70 manuscripts found that EEW systems could benefit society, and the benefits may go beyond its direct function for immediate earthquake response. The findings also show that there are social processes involved in designing, developing, and implementing people-centered EEW systems. Therefore, social science research should not just be concerned with the end-user response but also investigate various stakeholders' involvement throughout the development process of EEW systems. Additionally, EEW is a rapidly evolving field of study, and social science research must take a proactive role as EEW technological capacities improve further and becomes more accessible to the public. To improve EEW effectiveness, further research is needed, including (1) advancing our understanding of why people take protective action or not, and ways to encourage appropriate action when alerted; (2) enhancing public understanding, investigating best practices for communicating, educating, and engaging with the public about EEW and overall earthquake resilience; and (3) keeping up with technological advances and societal changes and investigating how these changes impact communities' interactions with EEW from various standpoints including legal perspectives.

KEYWORDS

earthquake early warning, social science, warning systems, literature review, earthquake resilience

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Introduction

When an earthquake occurs, an earthquake early warning (EEW) system can warn end-users further afield of the incoming ground shaking. The several tens of seconds of warning (to potentially as much as 120 s) from such systems provide potential benefits such as reducing injuries and fatalities, protecting infrastructure, reducing disruptions to services, and improving overall earthquake preparedness and resilience.

The last decade has seen the rapid development of methodologies and technologies that have given us a deeper physical understanding of earthquakes and improved EEW processes to achieve better earthquake warnings (Allen and Melgar, 2019). As a result, many locations worldwide already have operational EEW systems that broadcast warnings to the public before strong ground shaking arrives. Examples of governmental or official EEW services include Japan (Kodera et al., 2020), Mexico (Santos-Reyes, 2019), Taiwan (Wu et al., 2017), South Korea (Sheen et al., 2017), and the West Coast of the United States of America (Chung et al., 2020). In other places, such as India, Turkey, and Romania, EEW systems do not yet issue alerts to the public but send warnings to 'advanced users', such as governmental units or industrial users (Wang et al., 2020). Italy's EEW system is active in the Campania Region but is not yet available to the broader public (Velazquez et al., 2020). Many other locations in the world are also exploring, developing, and testing EEW systems, for example, various regions in China, Europe and South America (Wang et al., 2020).

Furthermore, EEW development is no longer limited to geographical jurisdictions. The ubiquity of technology allows EEW to be implemented across borders. The earthquake network (EQN) initiative, one of the earliest smartphone-based EEW systems, has provided EEW services across 25 countries since 2013 (Finazzi, 2020; Fallou et al., 2022). Commercial counterparts can also provide EEW products and services. For example, a Google initiative introduced the Android Earthquake Alerts System in New Zealand and Greece in April 2021 (Voosen, 2021) without the involvement of warning authorities from those countries (McDonald, 2021).

The success of an EEW system relies on the end-users, such as the general population, accepting and reacting appropriately to the system and its warnings (Minson et al., 2018). Thus, as EEW systems become increasingly available and transboundary, there is also an ever-increasing need to understand the social aspects of effective EEW systems, their design, development, implementation and use. In this paper, investigation of social aspects means considering factors from various branches of the social sciences including, but not limited to, sociology, behavioral science, psychology, geography, law, economics, and communication. This paper seeks to contribute to the current discourse on EEW by reviewing the literature and the state of research on the social facets involved in EEW systems. This literature review starts with the broad question: "What research has been conducted on the social aspects of earthquake early warning systems?"

This paper is structured as follows. Section Background on earthquake early warning systems contextualizes the review by providing a background to the study, briefly discussing EEW concepts and EEW in the context of broader warning systems. Section Method outlines the methodology. Findings from the literature review are presented in Section Findings. The discussion (Section Discussion and conclusion) examines the findings regarding current and future social research trends for EEW and concludes with a summary of recommendations for future research.

Background on earthquake early warning systems

EEW systems provide real-time information about ongoing earthquakes. Based on two primary concepts, information about earthquakes can be supplied ahead of ground shaking. First, information can travel faster than seismic waves (Cremen and Galasso, 2020). Second, different types of seismic waves travel at various speeds. The P-waves (primary waves) travel fastest, but the damaging energy from an earthquake usually comes from S-waves (secondary waves) and surface waves, and for locations far from the epicenter, they arrive much later than P-waves (Cremen and Galasso, 2020). EEW systems use these concepts to warn users at a distance of incoming ground shaking. People can take protective action, and automated systems can execute pre-programmed responses before the damaging ground shaking arrives (Allen and Melgar, 2019). Timely warnings and appropriate responses can potentially reduce injuries and damage to property (Allen and Melgar, 2019) and help with people's psychological preparedness for ground shaking (Nakayachi et al., 2019).

Traditional EEW systems rely on fixed sensors with configurations that are based on regional systems, on-site systems, or a hybrid of the two (Cremen and Galasso, 2020). Regional (or network-based) systems have dense seismic networks where an array of sensors is deployed in areas with high seismicity potential. The system's warning window starts when the first wave is detected at a source point. The network sends warning to target areas further afield; it allows several tens of seconds of warning depending on the distance between the source and the target sites (Zollo and Lancieri, 2007). On the other hand, on-site systems have sensors instrumented at a single station. The lead time for the warning is estimated using parameters from a few seconds of recorded P-waves on the station's location to predict the ground motion for S-waves or surface waves (Bindi et al., 2015). An EEW system can also be a hybrid of the two; for example, California and Taiwan have hybrid systems (Wu et al., 2019). In recent years, another aspect of EEW research has been conducted on systems that are not based on fixed sensors but instead rely on mobile sensors (e.g., using people's smartphones). Crowdsourced EEW is an evolving domain where EEW systems utilize the participation of people and use mobile and low-cost technologies (e.g., accelerometers of mobile phones) and send warnings through apps or programs built into the mobile's operating systems. Examples of crowdsourced EEW systems are the Earthquake Network (Finazzi, 2020), MyShake (Allen et al., 2019), and the Android Earthquake Alerting System (Cardno, 2020).

UNISDR (2005) and UNDRR (2015) priorities in developing and implementing people-centered early warnings as integral to disaster risk reduction. EEW systems resemble other forecast and warning systems for other natural hazards. These warning systems need to have robust scientific and technical bases, and they must also have a strong focus on the people at risk and have an approach that incorporates all of the relevant risk factors, such as understanding social vulnerabilities and short-term and long-term social processes (Basher et al., 2006). Similarly, an effective EEW system relies not solely on the reliability and accuracy of technological capabilities and processes but also on its embeddedness with human and social systems (Dunn et al., 2016; Velazquez et al., 2020).

EEW systems, however, have unique challenges compared to other warning systems. Due to the physical processes of an earthquake, EEW can only commence once an earthquake rupture has started. Thus, EEW systems can only give short warning times of up to several tens of seconds, in contrast to other hazards, such as weather or tsunami warnings, for which warnings can come days, hours, or a few minutes before the events occur (Strauss and Allen, 2016). The short period also implies a high degree of automated processing and near-instantaneous warning, which does not afford time for further human validation (Gasparini et al., 2011; McBride et al., 2020). The nature of short warning time impacts how EEW systems are designed to effectively communicate the hazard (McBride et al., 2020) and how people and automated systems respond and make decisions (Velazquez et al., 2020).

EEW generally follows the "Goldilocks principle" (Cochran and Husker, 2019). Too far from the earthquake rupture, warnings can become more accurate and lead times longer, but the intensity of shaking is weak and not dangerous. Too close to the rupture, intensity is expected to be more dangerous, but little to no advanced warning may be sent out. Furthermore, predicting impending ground shaking is still an ongoing scientific feat, with multiple methods still being developed and refined (e.g., Hoshiba, 2021). Thus, EEW systems inevitably will have false and missed alerts from the perspective of their end-users. False alerts occur when alerts are issued but the user does not observe the expected ground motion; missed alerts occur when ground shaking is felt but no alert is received (Minson et al., 2018; McBride et al., 2020). Challenges for EEW systems include controlling false and missed alerts, managing expectations, and communicating about the uncertainties and limitations of EEW.

Research advances on the social aspects of EEW are still relatively young. One recent study is Velazquez et al. (2020) state-of-the-art review of the technical and socio-organizational components of EEW. The review covered selected established EEW systems–Italy, United States (U.S.) West Coast, Japan, and Mexico–where it was concluded that although there has been increased awareness of people-centered EEW systems, multi- and cross-disciplinary research on EEW remains relatively unexplored. However, Velazquez et al. (2020) review only covered existing EEW systems and did not include those under exploration, planning, and implementation. Further research is needed to understand the social processes and interactions when establishing EEW systems. This systematic review contributes to the literature as it investigates EEW more broadly. It covers not only established systems but includes research papers that are exploratory and projected toward future EEW systems. This review provides an overview of past research and explores future directions for social EEW research in the context of evolving environments.

Method

The literature review method followed the scoping review process defined by Arksey and O'Malley (2005). Scoping reviews, also known as mapping studies, frame the nature of existing literature on a particular topic (Kitchenham et al., 2011; Par et al., 2015); in this study's case, to frame the social science research of earthquake early warning literature. The scoping review starts at a broad level, frames a research trend, and develops inclusion/exclusion criteria to scope a particular topic (Kitchenham et al., 2011; Par et al., 2015).

This study started by defining a broad research question: "What research has been conducted on the social aspects of earthquake early warning systems?" Then relevant studies were identified by conducting a literature search using the Scopus database to ensure coverage of significant publications on EEW systems. The scope of the review only includes papers published until September 2021–the time the search was conducted. Table 1 summarizes the search and selection of relevant studies for this literature review. Only peer-reviewed manuscripts were considered. As the researchers have fluency in English and Chinese, manuscripts in both languages were included in the review. A keyword search was used to filter for relevant manuscripts. The search criteria included the term "earthquake early warning" combined with a set of keywords to cover social aspects such as *social*, *behavio** (behavior, behavior, and other variants), *perce** (perception, perceptions, and other variants), *accept** (acceptance, acceptable, and other variants), *user*, *people*, *community*, and *public*. The initial search resulted

TABLE 1 Literature search results.

Search	2nd Keyword	Number of results	Duplicates removed	Unique results	Excluded	Included
1	Social	29	0	29	19	10
2	Behavio*	40	5	35	25	10
3	Perce*	34	5	29	20	9
4	People	60	19	41	27	14
5	User	72	25	47	31	16
6	Accept*	13	6	7	5	2
7	Community	48	23	25	19	6
8	Public	69	41	28	25	3
	Total	365	124	241	171	Final: 70

*A search logic that returns all words that begins with the stem truncated by the asterisk.

in 365 documents. After the removal of 124 duplicates, a total of 241 manuscripts remained.

The 241 manuscript abstracts were reviewed and subjected to inclusion and exclusion criteria. Technically focused papers that did not discuss any social aspects of EEW systems were excluded. Examples of exclusions were: papers with abstracts focused solely on algorithms; magnitude characterization; prediction models or methods; network infrastructure; sensors; routing protocols; automated structural response; use case of EEW to infrastructure (dams, buildings); simulations; artificial intelligence; and machine learning. Manuscripts included had abstracts that discussed stakeholder collaboration, public perceptions, user tolerance, user acceptance, user requirements, community impacts, social benefits and challenges, the potential use of EEW for communities, public education, risk reduction, behavior response, and similar themes. Seventy manuscripts (68 in English and 2 in Chinese) were considered for the review after the inclusions-exclusion criteria.

A limitation to this exclusion-inclusion method is that only the abstracts' contents were considered for filtering out the articles. Some articles may have been dropped even if they had social science components in the body but may not have explicitly mentioned those aspects in their abstract. Consequently, technical papers (e.g., Cua and Heaton, 2007; Böse and Heaton, 2010) were picked up because their abstracts contained a reference to user perspectives (e.g., user-specificity, communication to users, or subscriber's perspective). Despite the technical focus on algorithms of such papers, the qualitative analysis investigated the sections that discussed social or user standpoints.

The 70 articles were subjected to qualitative analysis using thematic coding (as per Flick, 2018). Two of the authors conducted the analysis. The thematic coding process involves sequentially building the case summaries for each article, where the manuscript details are organized according to themes (Flick, 2018). To answer the main research question, the case summaries for each manuscript were built around these three base sub-questions:

- What social aspects of earthquake early warning systems are discussed in this article?
- Does the article discuss end-users and broader societal acceptance, use, and perspectives of EEW systems?
- Does the article discuss collaboration between different stakeholders and decision-makers on the design and development of EEW systems?

The thematic analysis used these questions but was also reflexive in gathering other insights into themes. The identified themes were then continuously re-checked and modified after analyzing each case, with this process repeated for each manuscript (Flick, 2018). The findings of the qualitative analysis provided insights into what has been investigated in social research of EEW systems.

Findings

Summary of the papers

The 70 manuscripts included in this review primarily discussed or had a significant portion of the paper that discussed the social components of earthquake early warning.

Most of the papers included in this literature review were published from 2007 onwards—20 in the last 2 years (2020 and 2021). Figure 1 illustrates the number of articles included per year. Only one paper from the literature search was published before 2000. Goltz and Flores (1997) paper was on public policy and behavioral response to Mexico's Sistema de Alerta Sismica – one of the earliest EEW systems that issued alerts to the public EEW, initiated in 1989 and completed in 1991.

The articles from 2007 to early 2011 concentrated more on EEW algorithms and relating them to user-specific decision-making (e.g., Cua and Heaton, 2007; Böse and Heaton, 2010), future application prospects (Iervolino et al., 2007; Kamigaichi et al., 2009), and estimation of people's willingness to pay for a hypothetical EEW (Asgary et al., 2007).

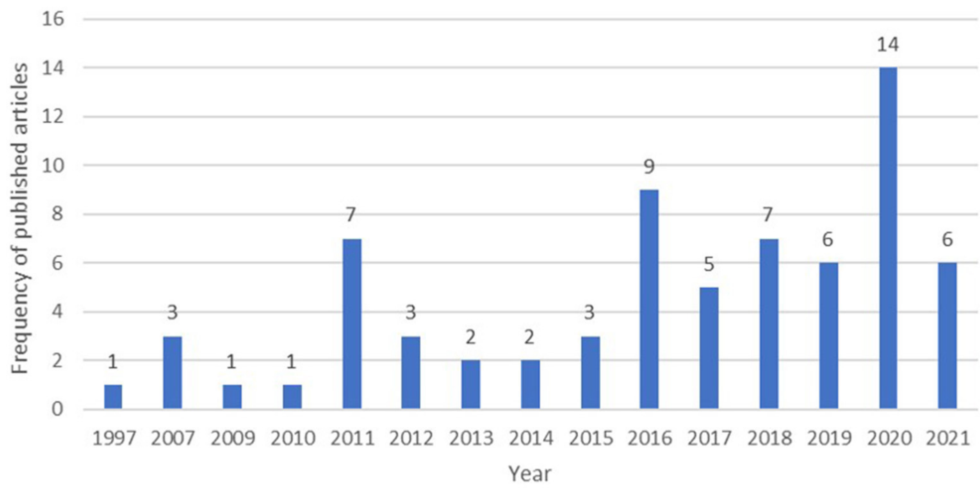

FIGURE 1
Number of published articles included in this review per year.

After the 2011 Tohoku-oki earthquake and tsunami event, several publications included in this review looked into Japan's EEW performance (Ritsema et al., 2012; Fujinawa and Noda, 2013; Ohara and Tanaka, 2013; Hoshiba, 2014). Also, after 2011, as evidenced by the surge in academic publications from different parts of the world on EEW, more countries and territories were exploring and implementing EEW. The articles included in this review discussed EEW performance or prospects from various geographical locations (See Figure 2), including the U.S. West Coast (14), Japan (11), China (3), Mexico (3), New Zealand (3), Ecuador, India, Iran, Italy, Kazakhstan, Pakistan, Taiwan, and Turkey. Nineteen articles did not specify any location, but the EEW concepts and observations could be applied generically. Five articles investigated the broader European region, while another five discussed or compared EEW systems from multiple locations (e.g., Japan and Italy, etc.).

The 70 articles focused on varying topics within EEW research, each with its own objectives. See Supplementary materials for the list of articles included in this study and the objectives of each paper. Because of the varying focus of each article, a comprehensive appraisal of the EEW systems' technical performance is not within the scope of the review. However, the paper covers research themes resulting from the analysis of the articles as guided by the research questions. The resulting overarching themes are (1) EEW benefits and challenges, (2) end-users' perceptions, (3) multi-stakeholder involvement, and (4) crowdsourced EEW and its implications. See Table 2 for the summary of these themes; note that each theme is not mutually exclusive from the other. Each theme will be discussed in detail in the succeeding sub-sections.

EEW benefits and challenges—social perspectives

Most articles in this review discussed the implications of having or developing EEW systems ($N = 50$), arguing for the benefits and highlighting the associated limitations and challenges of having EEW systems. The following 2 subsections discuss the findings on EEW benefits and challenges.

EEW benefits in the disaster lifecycle

Most of the articles discussed the potential benefits of EEW systems to society. The articles highlighted that the main potential benefit of EEW systems revolves around the ability of people and systems to respond to the alert, thus minimizing harm to life and property. Thirty-eight of the 70 articles mentioned the benefit of taking personal protective action. Twenty-eight of the 70 articles mentioned that systems can benefit from EEW if pre-programmed tasks can be performed to minimize impacts (e.g., slowing down of bullet trains, allowing elevators to stop at the nearest floor). People also see the benefit of EEW to mentally brace themselves for the incoming shaking (Nakayachi et al., 2019). Specialized users can also use EEW for situational awareness when responding to earthquake events. Emergency responders can utilize EEW systems to get quick information that will allow them to improve situation awareness through understanding the disruptions and cascading hazards (Allen and Melgar, 2019). Urban Search and Rescue (USAR) teams can use EEW systems to reduce surprise effects and stop dangerous operations (Auclair et al., 2021). EEW can also prompt people to evacuate buildings (Wu et al., 2017) or

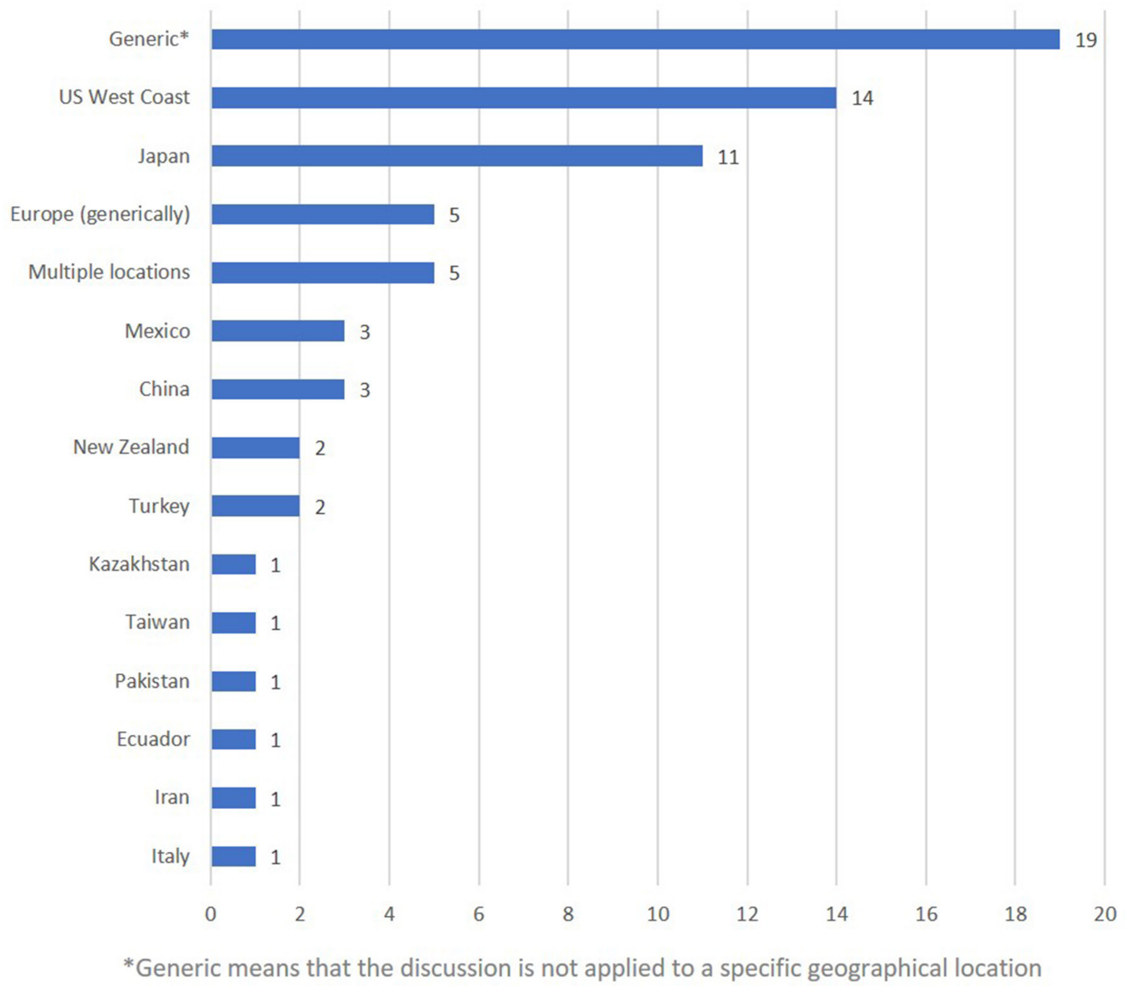

FIGURE 2
Locations of focus for the articles included in this literature review.

evacuate coastal areas in preparation for a tsunami (Necmioğlu, 2016).

Many of the articles included in this review also discuss EEW systems' potential benefits beyond the immediate response to the warning to other stages of the disaster lifecycle. Table 3 summarizes the potential benefits EEW can provide during various disaster phases. For recovery, EEW systems can be incorporated in protecting critical structures, transport, and lifelines from secondary (e.g., fires) and aftershock effects; protecting infrastructures would help society return to normal after an event (Gasparini et al., 2011). For mitigation, setting up EEW systems would help decision-makers know more about exposure and vulnerability, thus potentially helping play a role in policies managing risks (Iervolino et al., 2007). Mitigation can be applied in managing critical infrastructures using EEW systems. For example, the public might have more confidence in a nuclear facility if they know that it is equipped with an EEW system to minimize risks (Cauzzi et al., 2016). Finally, having an EEW system can also promote a culture of preparedness. Public education regarding the system can encourage people to think about earthquakes and their impacts and prepare for them (Dunn et al., 2016; Allen and Melgar, 2019).

Benefits of EEW can be seen from an economic point of view based on savings or loss reduction–computing potential losses when EEW is implemented and comparing the results with the estimated losses if EEW is not implemented (Oliveira et al., 2015). Some attempts have been made to measure and estimate the benefits. A case example of a semiconductor facility in Miyagi prefecture investing USD 600,000 in retrofitting and EEW automation demonstrates EEW cost savings. The facility had estimated losses of USD 15 million from two moderate earthquakes before implementing earthquake mitigation measures, compared to $200,000 losses after experiencing two similar-sized earthquakes

TABLE 2 Research themes of the study.

Research theme	Description	N*	Sample papers
EEW benefits and challenges	The papers discussed the benefits, challenges and limitations of existing, developing, or future EEW systems	50	Allen and Melgar, 2019; Becker et al., 2020a; Wald, 2020
End-users' perceptions	The papers looked into end-users' perspectives and expectations on EEW. Topics in this theme include perceptions on useful lead time, risk and decision making, and alerting issues.	36	Le Guenan et al., 2016; Nakayachi et al., 2019; Auclair et al., 2021
Multi-stakeholder involvement	The papers considered social processes with various stakeholders in the design, development, or implementation of EEW, not limiting social considerations only to the alerting aspect of EEW.	25	Parolai et al., 2018; Herovic et al., 2020; McBride et al., 2020
Crowdsourced EEW and its implications	The papers in this theme discussed using crowdsourcing for EEW systems, including the potential and challenges.	9	Minson et al., 2015; Kong et al., 2019; Finazzi, 2020

*Themes are not mutually exclusive.

TABLE 3 Summary of benefits discussed by the articles on having an EEW system through the disaster management phases.

Phase	Benefits	N*
Response	Personal protection	35
	Automated responses for systems to reduce impacts	27
	Situational awareness (for emergency responders, industrial users, decision-makers. etc.)	11
	Mental preparedness for earthquake shaking	6
	Prompt evacuation	2
Recovery	Help with the returning to normal after an event	2
Mitigation	Knowing exposure and vulnerability	5
	Build public confidence in systems	1
Preparedness	Create a culture of earthquake awareness and preparedness	8

*Number of articles that mentioned the benefit.

with retrofits and EEW automation (Strauss and Allen, 2016).

However, measuring savings on a broader scale is challenging as not all losses can be measured monetarily, and any projection of losses will be based on a landscape of possibilities (Oliveira et al., 2015; Strauss and Allen, 2016). Estimating benefits on a broader scale may work with some indicative assumptions. For example, Strauss and Allen (2016) anticipated that EEW could reduce injuries by more than 50% if everyone acted to drop-cover-and-hold after an alert. The saving is estimated at USD 200 million per year on costs the U.S. government would have to expend to address earthquake-related injuries (Strauss and Allen, 2016). Measuring such benefits should be taken with caution, as it is necessary first to have a clear idea of what can actually be done with a few seconds of warning (Oliveira et al., 2015).

Despite the potential for EEW, the benefits of public alerting make assumptions about people's reactions; there is still limited proof of its actual effectiveness in terms of people's responses (Nakayachi et al., 2019; Cremen and Galasso, 2020). Wald (2020) expressed two concerns about EEW on the U.S. West Coast: (1) effective warning times of EEW systems are often less than claimed, and (2) the suggested actions responding to the alerts are more challenging than anticipated and thus not as effective as expected. The short warning times of EEW limit the possibilities for effective response (Wald, 2020). A study shows that despite the successful issuance of EEW alerts in the cases of Gunma and Chiba – Japan, the alerts did not motivate people to take action as recommended by official agencies (Nakayachi et al., 2019). In the same cases, the tangible benefit of EEW from people's perspectives is for mental preparation rather than the suggested and anticipated physical response for personal protection (Nakayachi et al., 2019). Thus, the review shows that despite claims EEW is beneficial, there is still a need to understand the nature of the benefits in-depth. Most of the success metrics for EEW have been on the seismological aspects, but EEW's success should also be scrutinized from the end user's lens (Cremen and Galasso, 2020).

Challenges for public-facing EEW systems

EEW systems are complex as they include both technical and social attributes (Li and Jia, 2017). Implementing EEW comes with financial, political, and sociological challenges (Allen, 2011). The papers reviewed also recognize social challenges in achieving effective EEW systems. Some articles discuss various issues that impede the success of EEW systems. The most commonly identified social challenges were (1) the culture of awareness and preparedness education, (2) users' actions in

TABLE 4 Top three social challenges to overcome for effective EEW systems.

Challenge	N*
Culture of awareness and preparedness education	21
Users' actions in response to warnings	18
Implications of alerting errors	16

*Number of papers that mentioned the challenge.

response to warnings, and (3) implications of alerting errors. There are other challenges identified, but these three were identified most frequently by the articles in the review (See summary in Table 4).

Twenty-one articles mention the challenge of creating a culture of awareness about the system and preparedness education. It is widely recognized that installing and operating EEW technology requires substantial investment (Ahn et al., 2021). Still, sometimes the costs of public education campaigns are overlooked. Public education for EEW systems must be accounted for to teach people how to use EEW information (Allen, 2015). For example, in Washington State, USA, people have an appetite for EEW but have low earthquake preparedness (Bostrom et al., 2018). Educational and training programs are needed to develop people's ability to know the appropriate self-protection actions (Herovic et al., 2020; Sutton et al., 2020). The designers of Japan's public EEW system recognized that EEW would have very short warning times (up to several tens of seconds). Hence, people need to know the principle, purpose, and technical limits of EEW beforehand to ensure effectiveness without causing unnecessary confusion (Kamigaichi et al., 2009). Nakamura et al. (2011) emphasized the need to educate the public about EEW's limitations and integrate comprehensive earthquake preparedness education. It is essential to avoid overreliance on EEW for disaster prevention. The public must be encouraged to have reasonable self-management for earthquake protection beyond an earthquake warning itself (Nakamura et al., 2011). However, even with awareness and education, intended action may not result in actual behavior (Becker et al., 2020b) and may still result in inappropriate actions (Becker et al., 2020a).

Eighteen articles highlighted the challenge of understanding how users respond to alerts. These articles discussed whether alerts translated to appropriate user actions. Anticipated mitigating actions to alerts may not materialize as expected. For example, in Japan, Nakayachi et al. (2019) study (n = 359) showed that more respondents used the alerts to mentally prepare for shaking (25%) than to take physical action of moving nearby to a safe place (7%).

Some responses may be affected by the mode in which EEW is delivered. Alerts can be delivered *via* different means (e.g., sirens or wireless broadcasts), but often they are delivered in the form of short messages. The short message style might mean that people may feel they are only receiving partial information. Consequently, they may result to *milling*–looking for additional information or confirmation–before taking protective action (Goltz and Flores, 1997; Sutton et al., 2020). Responses may also be affected by personal attributes or experiences; for example, different people may also have different thresholds on the level of shaking that would trigger them to take action (Minson et al., 2017). Despite public training and education, it is uncertain how many people perform the official protective action advice of drop-cover-and-hold upon receiving an alert, as highlighted by literature from the West Coast, USA (Porter, 2018), and the Japanese study by Nakayachi et al. (2019). In another case study from Japan, a proportion of the people intended to take action during the Mw9.0 Tohoku-oki earthquake but could not because of the short warning time before the arrival of the shaking (Hoshiba, 2014). Some studies also highlight the importance of understanding how long a user needs (e.g., seconds, tens of seconds) to take useful action before shaking begins (Minson et al., 2019).

Sixteen articles discuss the challenge of alerting errors, as they can affect people's perceptions and have broader implications for EEW. One often raised risk is that false alerts may trigger mass panic, which is why systems must be configured to reduce false alerts (Asgary et al., 2007). Due to the technicalities of EEW systems, there is a trade-off between missed alerts and false alerts (Saunders et al., 2020). False alerts occur when alerts are issued, but no shaking follows, while missed alerts occur when shaking happens, but no alerts are issued. An optimized alerting strategy needs to consider community tolerance of these false and missed alerts (Saunders et al., 2020). False alerts can negatively impact trust in the EEW system. McBride et al. (2020) note that the issuer (i.e., alerting agencies) and recipients (i.e., end-users) may have different perceptions and thresholds for false alerts.

Scientists expect that the more educated people are about EEW, the higher the acceptability of information error, blind zones, and false and missed alerts (Guo et al., 2012). In Guo et al. (2012) study in China, a survey with 214 participants from all over China, only 23% of respondents accept information errors. In comparison, in a 2012 questionnaire by the Japan Meteorological Agency (n = 12,000), Japanese respondents had higher acceptability of errors; a significant proportion of the population (78%) is aware of EEW's shortcomings and understands the possibility of false alarms (Fujinawa and Noda, 2013). The difference between Chinese and Japanese respondents can be attributed to the Japanese being more exposed to and experienced with earthquakes and EEW information (Guo et al., 2012). From multiple EEW experiences, researchers have found that despite false and missed alerts, the public in Japan has some acceptability of alerting inaccuracy. A large proportion (85.6%) of respondents (n = 3,000) from Ohara and Tanaka (2013) study accept the possibility of missed warnings. Despite false and missed alerts, the majority in Japan – more than 90% in Tohoku ($n = 817$) and 80% nationwide ($n = 2{,}000$) in Hoshiba (2014) study feel that EEW is useful.

Furthermore, there are situations where multiple EEW issuers are at play (e.g., government authorities vs. private companies in Mexico). One party's false or missed alerts can reduce trust in EEW in general (Reddy, 2020). Liability questions arise on who should send the alerts and who is responsible for false or missed alerts (Gasparini et al., 2011). If false or missed alarms are poorly handled, it can cause chaos and financial loss; therefore, a sound legal framework must be considered for EEW effectiveness and accountability (Li and Jia, 2017). In this regard, only six of the 70 articles mention the legal aspects of EEW. This is an area ripe for further research.

End-user perceptions

A proportion of the articles ($N = 36$) include in their discussion an investigation of end-users' and broader societal acceptance, use, and perspectives of EEW. EEW systems have various end-users, including advanced users and the public.

Advanced users' perceptions

Advanced users (i.e., not the public), such as governmental agencies or industrial users, use EEW information for decisions that often have broader implications that may impact society and infrastructure. Advanced users have different contexts for decision-making. For example, a nuclear facilities manager might need to decide whether to shut down a reactor, emergency managers might use EEW information to deploy resources for emergency response, and urban search and rescue teams may decide whether to stop or continue rescue. Advanced users will have different views, depending on their contexts, on what are meaningful EEW lead times between warning and shaking (Oliveira et al., 2015) and on their tolerance for false or missed alarms (Le Guenan et al., 2016). Oliveira et al. (2015) survey showed that 83% of industry operators think 12 se provides sufficient time to take actions to minimize risk for the facility, while 17% did not feel confident that 12 s is sufficient. Le Guenan et al. (2016) study showed that decision makers' risk behavior affects their tolerance for false alarms. A decision-maker with a risk-neutral attitude can tolerate as many as five false alarms a year, but decision-makers with a more risk-prone attitude can handle more (Le Guenan et al., 2016).

In facilities management, the decision on how EEW is approached depends on the vulnerability of the facility and the costs of inaccuracies of estimated ground shaking (Böse and Heaton, 2010). For example, shutting down a nuclear reactor will be costly and have significant consequences (Cauzzi et al., 2016; Minson et al., 2019). Operators would like to know an EEW system's reliability beforehand and the system's propensity for false and missed alarms. The chance of missed and false alarms would need to be weighed with the costs and benefits before EEW can operationally be used for nuclear facilities (Cauzzi et al., 2016).

On the other hand, more tolerant users may prefer to get an earlier warning in other contexts even if they are more likely to receive false alerts. For USAR, teams working in high-risk environments (i.e., in unstable and vulnerable structures) find false alarms tolerable if the EEW system overall benefits the life-safety of the rescuers (Auclair et al., 2021). In a study of USAR personnel, 50.9% of respondents considered false alarms to have a low to very low impact in terms of loss of time and efficiency in USAR operations. However, repeated false alarms rather than isolated ones would affect a USAR team's confidence in a system (Auclair et al., 2021).

Two papers included in this review studied advanced users and quantitatively modeled their risk perceptions and decision-making. Le Guenan et al. (2016) emphasized that a participatory viewpoint is necessary for EEW since such systems can affect many groups, including infrastructure owners and elected officials. Le Guenan et al. (2016, p. 318) study tried to account for end-user preferences using a 'combination of multi-attribute utility theory and a Bayesian network for earthquake loss assessment'. Their method looks at the different views on acceptable risks, investigating setting a ground motion threshold for decisions to trigger an alert that would have benefits outweighing costs. Cremen and Galasso (2021) pointed out that while Le Guenan et al. (2016) method accounts for risk tolerance, it only works for binary actions (i.e., to trigger or not trigger an alarm). Cremen and Galasso (2021) then proposed an advanced methodology using a multicriteria decision-making (MCDM) approach coupled with a performance-based earthquake engineering framework incorporating Bayesian real-time seismic hazard analysis. Cremen and Galasso (2021) approach goes beyond binary decisions and enables multiple mitigation actions to be evaluated for various dimensions of uncertain risks. These two papers show that modeling risk-based decision-making will help EEW systems become end-user-driven tools to become more effective in promoting seismic resilience.

Public perceptions

Several studies in this review investigate public perceptions of EEW. Four recurring themes relate to public perceptions of EEW end-users. Generally,

(1) The public has favorable views of EEW.
(2) The public's views and level of support are critical to EEW's success.
(3) People's lived experiences with earthquakes affect their views on EEW.
(4) There are concerns regarding public alerting.

Positive public reception

Despite people's mixed responses to warnings (Huggins et al., 2021), people's perceptions of EEW are positive in areas with operational EEW systems available to the public. Studies in Japan (e.g., Fujinawa and Noda, 2013; Ohara and Tanaka, 2013; Nakayachi et al., 2019) show that the public generally views EEW as useful. Similarly, studies in Mexico (Santos-Reyes, 2019) and West Coast USA (Saunders et al., 2020) show that even with limitations in warning times and shaking thresholds, people deem EEW beneficial. In Taiwan, where EEW sensors are installed in schools, teachers view EEW as a valuable tool for promoting and teaching disaster prevention (Wu et al., 2017).

Public views and support for EEW success

National interest will vary dependent on the context of each country (Clinton et al., 2016). In Europe, at the time of writing, EEW was "not yet a product demanded by the general public or even the scientific community (Clinton et al., 2016, p. 2442)." The critical variable for the success of an EEW system is whether the public perceives the indispensability of EEW to keep them safe (Goltz and Flores, 1997). Gaining the public's insights is critical in the early stages of considering or developing EEW. A survey (n = 3,084) exploring the potential for EEW in New Zealand (Becker et al., 2020b) shows a different public perception of EEW compared to Europe. The survey in New Zealand, a seismically active nation, shows that most respondents supported an EEW system, signaling an opportunity to move EEW conversations forward (Becker et al., 2020b). Aside from considering public perspectives, the social context in which EEW is being developed should also be understood (Becker et al., 2020b).

Furthermore, the U.S. West Coast experience shows the successful spread of ShakeAlert was attributed to local stakeholders gathering support and funding to operationalize EEW at the early stages (Kohler et al., 2018). EEW also requires public funding, at least partially, for which public support is needed (Ahn et al., 2021). Where there may be user-pay models of funding, people's willingness to pay depends on their perceptions of earthquake risks and the level of protection they perceive EEW will provide (Dunn et al., 2016; Ahn et al., 2021).

Lived experience affects EEW views

Another recurring theme in public perceptions is that people's lived experiences affect their views on EEW. Ahn et al. (2021) study shows that people with lived experiences of earthquakes also perceive a higher risk of harm from earthquakes, thus influencing their views on EEW's usefulness and willingness to pay for EEW. Similar observations can be inferred from Hoshiba's (2014) paper, where it was observed that Tohoku residents, who were most impacted by the 2011 earthquake, were more likely to view EEW positively compared to the national average. Moreover, after earthquake events, there is heightened awareness and recognition of earthquakes among the public, especially in affected regions (Fujinawa and Noda, 2013; Ohara and Tanaka, 2013).

Concerns about public alerting

Despite the generally positive reception from the public about EEW, there are concerns related to the public's perceptions and knowledge of EEW alerts. The examples below show that the public may have misconceptions about EEW and associated information and sources that will impact their perception and trust in EEW, thus potentially delaying them from taking appropriate protective action when alerts are issued.

Not all shaking warrants an alert. The alert parameter for ShakeAlert in Los Angeles (LA) to issue a warning is set at Modified Mercalli Intensity Scale Level four (MMI-IV) or above. Yet, this may not be common knowledge for users. During the 5 July 2019 Mw7.1 Ridgecrest Earthquake, many LA residents felt the earthquake and were left unimpressed when no alert was delivered, even though the intensity in LA was MMI-IV and thus below the delivery threshold (Saunders et al., 2020). Because of public pressure from the perceived 'poor' performance of the ShakeAlert, the target parameter for the system was lowered for the LA area to MMI-III (Cochran and Husker, 2019; Saunders et al., 2020). However, shaking at MMI-III is considered weak where it may not be easily recognizable as an earthquake. Setting the system's threshold at this level will pose a different challenge; people may then receive an EEW alert but not feel or recognize the earthquake–which may lead to a perception of false alerts (Cochran and Husker, 2019; Saunders et al., 2020).

There may also be pre-conceived notions about earthquake alerts that may not necessarily be helpful. For example, in Mexico City, residents believe that an alert would always give them at least 60-s of warning before shaking arrives (Santos-Reyes, 2019). This belief is partly because of how the Seismic Alert System of Mexico (SASMEX) was designed from the Guerrero Gap to Mexico City, allowing for a close to 60 s prevention time if the rupture comes from the subduction zone along the Pacific coast. The risk of large earthquakes for Mexico City mainly originates from the Pacific coast, which has resulted in SASMEX issuing alerts with warning times of 60 to 90 s in most felt earthquake events. However, earthquakes in Mexico do not only originate from the Pacific coast, such as the 19 September 2017 Mw7.1 earthquake near Mexico City (Santos-Reyes, 2019). In such a case, confusion among the public can ensue when the system does not provide as much warning time as anticipated (Santos-Reyes, 2019). There should be basic public education on how EEW functions; education should be provided on EEW Systems and seismic hazards (Santos-Reyes, 2019).

The public also may struggle with delineating EEW information to warrant responsive action. Many people did not know the difference between EEW and standard earthquake information (Fujinawa and Noda, 2013). Furthermore, in areas where multiple parties can issue EEW alerts, the public finds

TABLE 5 EEW Stakeholders identified by the articles.

Stakeholders	Mentioned in *N* articles
Emergency managers	5
International/national seismic networks and research groups	5
Seismologists	5
Private sector	4
Social scientists	4
Communication practitioners	3
Government agencies	3
Policymakers/ political stakeholders	3
Researchers/scientists (generic)	3
Engineers	2
Technologists	2
Telecommunication sector	2

it difficult to differentiate the authorities from other players (Reddy, 2020).

Multi-stakeholder involvement

Although many of the papers included in this review focused on EEW end-users, some articles ($N = 25$) also covered different stakeholders' involvement in the design, development, and deployment of EEW systems. The stakeholders may also be advanced end-users but play a role in influencing the design and use of EEW systems. The findings show that multiple players are involved in EEW conversations. Table 5 summarizes the various stakeholders mentioned by the articles and shows the frequency of articles that refer to them.

EEW involves a multi-disciplinary effort. Research is not only conducted by seismologists and physical scientists, and cooperation is needed for the various stakeholders involved in the design, development, and implementation of EEW. For example, Parolai et al. (2018) emphasized the need for better cooperation between seismologists and engineers to deliver better EEW applications. Technology experts are also needed for the technological factors of the software and hardware interfaces of EEW systems (Goltz and Flores, 1997; Minson et al., 2015). Collaboration with social scientists is crucial in optimizing public warning systems (Allen and Melgar, 2019; Minson et al., 2020). McBride et al. (2020) showcased the value of an interdisciplinary working group that allowed the development of best practices in post-EEW alert messaging.

EEW collaboration also means working across borders with different seismic networks and research groups. In Europe, the project REAKT brought about a consortium of EEW researchers from seismic networks and research groups in the region (Oliveira et al., 2015). Because of the limited capabilities of smaller seismic networks, building effective EEW in Europe will require coordination and sharing of resources in the community (Gasparini et al., 2011). Similarly, for ShakeAlert to work across different states in the U.S., it needs to leverage the Advanced National Seismic System, a federation of cooperating seismic networks throughout the nation (Kohler et al., 2018). Developing an earthquake and tsunami monitoring network and an exploratory EEW system in Central America also saw invaluable data exchange and cooperation across borders between seismological institutions in Central America and Japan (Strauch et al., 2018).

EEW is not purely a research endeavor. Its effectiveness in society also requires close collaboration with various practitioner-based sectors. Earnest partnership between government agencies, policymakers, telecommunication operators, and researchers is indispensable for implementing warning systems (Malik and Cruickshank, 2014). The emergency management sector and communications specialists also play vital roles for EEW in ensuring public safety through appropriate messaging and educational strategies (Allen et al., 2019). EEW conversation must also include the private sector. In some locations, such as Mexico, commercial entities can issue EEW alerts alongside official agencies (Reddy, 2020). There also should be a good relationship between the officials and private providers to avoid confusion with end-users (Reddy, 2020). Furthermore, as advancements in technology allow smartphone devices for crowdsourced EEW, cooperation is crucial with device manufacturers to adapt to technological changes and commercial demands (Minson et al., 2015).

The findings show that aside from end-users, multiple stakeholders are involved in the various stages and processes of EEW systems. This implies that research on the social aspects of EEW should not be limited to downstream alerting and post-alerting communication to the public. It must also investigate the multi-stakeholder and interdisciplinary social dynamics in the design, development, and implementation of EEW systems.

Crowdsourced EEW and its implications

A recurring theme, especially in the more recently published articles, is the concept of crowdsourced EEW. Crowdsourced EEW is a developing area where EEW systems utilize the distributed participation of people and use mobile or low-cost technologies (e.g., smartphones or portable sensors). Nine articles included in this review have revealed advancements in EEW in using portable sensors and mobile devices (e.g., laptops or smartphones) for crowdsourcing EEW. Community-owned commercial or off-the-shelf devices have been recognized as powerful resources for sensor networks (Faulkner et al., 2011). In addition to these community-owned sensors, the ubiquity of mobile devices has expanded the scale of crowdsourced EEW in recent years, as networks can potentially use data from consumers' smartphones rather than solely relying on installed sensors (Minson et al., 2015).

The review has shown that the social challenges to crowdsourced systems include (1) public participation and user retention and (2) liability issues, and (3) commercial demands and ramifications.

Public participation in crowdsourcing

For some of these crowdsourced EEW systems, public participation is necessary. Users need to download an app and register their phones to become sensors in the network and receive warnings (Allen et al., 2019). Example of such system includes MyShake (Kong et al., 2019) and the Earthquake Network project (Finazzi, 2020). One of the challenges for opt-in systems is user retention (Finazzi, 2020). Such systems need to consider how they can keep users interested in installing and keeping the apps on their phones (Allen et al., 2019). EEW systems should find ways to incentivize users to contribute to crowdsourcing efforts (i.e., not uninstalling the app) (Panizzi, 2016). Smartphone app design should consider user interaction as customer satisfaction becomes crucial. For example, how the app consumes energy directly relates to satisfaction (Zambrano et al., 2017).

Liability concerns

EEW, whether crowdsourced or official, has not been fully utilized in many parts of the world because of liability issues; emergency managers are reluctant to automate EEW because of accountability in case of false or missed alarms (Gasparini et al., 2011). For crowdsourced EEW, it also becomes a blur on who is responsible for false or missed detections (Finazzi, 2020). Moreover, privacy and data protection must also be considered when handling user location information for crowdsourced systems (Finazzi, 2020).

The existence of official, crowdsourced, and privately-run EEW can confuse matters. Multiple parties, official and non-official, can issue alerts, but the public cannot usually distinguish between them (Reddy, 2020). Sometimes, alerts from different sources are also not delivered to their intended recipients, and one party's false or missed alerts can reduce public trust in EEW as a whole (Reddy, 2020). There may also be no barriers limiting competing parties from sending intentional false alerts to subdue competition (Reddy, 2020). Such liability considerations and issues impede EEW progress (Finazzi, 2020).

Commercial demands and implication

Finally, the use of smartphones for EEW comes with the pressure to keep up with commercial demands (Minson et al., 2015). Using smartphones provides opportunities for crowdsourced EEW systems, as they do not need significant capital outlays for equipment (Minson et al., 2015). However, this also means that crowdsourced EEW systems should align and keep up with the multiple existing mobile operating systems and their levels of permission access to data (Minson et al., 2015; Zambrano et al., 2017). Minson et al. (2015) also point out that the objectives of crowdsourced EEW systems might not align with the commercial intent of smartphone devices. Any implementation issues may have ramifications for the commercial products.

Discussion and conclusion

The results and subsequent discussion have several limitations that must be acknowledged. The interpretation of results is limited to the 70 papers written in English and Chinese texts found in the Scopus database. The research gaps identified herein are within the context of these 70 papers. Therefore, there may be papers or subject areas unexplored. Additionally, EEW is a rapidly evolving field of study, and there will inevitably be papers published since September 2021 that were not included in this review (e.g., Becker et al., 2022; Fallou et al., 2022; McBride et al., 2022; Vaiciulyte et al., 2022). Future research should consider expanding the literature coverage by including different databases and more recent publications. The focal point of this paper is to determine the extent of research thus far on the social aspects of earthquake early warning.

The 70 articles have touched on a breadth of social science research topics. However, multiple gaps still exist in investigating the social aspects of EEW. Three fundamental areas to further investigate: (1) understanding EEW effectiveness from the social standpoint, (2) uncovering integrated multi-stakeholder approaches throughout the disaster lifecycle and the EEW design cycle, and (3) understanding how EEW and society adapt to innovations and changes–including legal perspectives.

EEW effectiveness

The effectiveness of EEW systems has been measured from seismological and technological standpoints. They can be evaluated on the accuracy and timeliness of ground motion estimates (Meier, 2017) or using the latency of alert time and lead time (Kamigaichi et al., 2009; Minson et al., 2018). An economic valuation can also estimate effectiveness by measuring the estimated loss reduction in relation to investment (Oliveira et al., 2015). From the human behavior perspective, the view of effectiveness is in how end-users recognize, interpret, and respond to EEW (Wald, 2020).

End-users' reactions to warnings are crucial to EEW systems' effectiveness in society. However, twenty of the papers in this review presumed that EEW would provide benefits (e.g., individuals will use the lead time to drop-cover-and-hold). However, those that reported the actual outcomes of EEW, such as in the Japanese contexts, indicated that fewer than the expected number of people took the prescribed protective action. As Nakayachi et al. (2019) indicated, despite numerous indications of the potential utility of EEW, there is limited evidence of the actual (not potential) benefits of warnings to the public. Research thus far, to some extent, has relied on the potential benefits of EEW (Wald, 2020). Future EEW research must operate beyond these assumed benefits and should work with realistic representations of the EEW benefits to society. Further investigation is needed on the actual effectiveness of EEW from a social standpoint.

It must be acknowledged that gathering data for people's actual reactions can be challenging, as people's response to an earthquake is dependent on the specific conditions that it is difficult to compare across earthquake events. Furthermore, it is hard to compare groups of people (who got the warning to those who did not) in a particular situation. Therefore, the usual way, so far, to gather such data is through surveys that require respondents' introspection. Future studies should investigate improving the data gathering methods and finding innovative ways to capture end-user perspectives on EEW effectiveness (e.g., earthquake simulation or analysis of alternative data such as CCTV or social media).

More importantly, researchers should investigate why there are low numbers of people taking protective action with EEW. A recent study in Peru ($n = 2{,}625$) confirms the past studies' findings that most alert recipients do not take protective action (Fallou et al., 2022). To improve the effectiveness of EEW, more study is required to understand why action is taken (or not) and how to motivate more people to take appropriate protective action. A people-centered EEW means building social capacity in people's disaster risk knowledge and their ability to respond to warnings appropriately. People-centered EEW also challenges system designers and researchers to consider the heterogeneity of end-users. Different groups' accessibility to the system (for example, the elderly and differently-abled) should be considered. More research is needed to understand people's experience, knowledge, and capability to respond to the alerts.

Involvement throughout the disaster management lifecycle and EEW design cycle

This study has shown that most social research on EEW has focused on the response stage of the disaster management phase. However, the articles have also revealed that people also interact with EEW in the other phases of disaster management. Further research should explore EEW's role beyond the response stage of the disaster lifecycle. Particularly, EEW can be used to promote earthquake preparedness and create a culture of earthquake awareness and readiness. Improving risk communication pre-crisis and throughout the earthquake crisis lifecycle could potentially improve EEW's overall effectiveness (Herovic et al., 2020). For EEW, pre-crisis education could provide (a) information about the potential for earthquakes, EEW and its limitations, and possible impacts on the community, (b) how to prepare, and (c) campaigns about appropriate self-protection actions during earthquakes in general and when receiving alerts (Becker et al., 2020a; Herovic et al., 2020). Future research should investigate integrating EEW public education across the disaster management phases of recovery, mitigation, and preparedness to improve earthquake resilience. Another area for research investigation is the design, implementation, improvement, and evaluation of the EEW education programs toward the overall effectiveness of EEW and earthquake resilience of communities. More research could expand on the best practices for EEW public education, considering different types of users and their context of use for EEW.

Any disaster risk reduction effort needs to incorporate awareness, education, training, and collaboration mechanisms (Malik and Cruickshank, 2014). Research on EEW should not focus only on communicating to end-users but also needs to investigate the interactions between various entities involved in the EEW design process. EEW research often involves a design science process–where the design of a solution (i.e., EEW system) also produces generalizable knowledge that can be appropriate to a research community (Johannesson and Perjons, 2014). Creating an EEW system requires strong foundations in the technical knowledge base. Still, for EEW to be effective, it must also be appropriate to its application domain (i.e., relevant to its stakeholders). Implementing EEW suitable for society will require engagement with multiple stakeholders throughout the process, including the public, scientific experts, and sectoral and industrial partners. A collaborative framework is needed to engage EEW research and practice. Tan et al. (2021) formed a community of practice for earthquake early warning discussions in New Zealand; the collaborative framework shows the value of diversity of perspectives to enhance knowledge exchange toward developing an EEW system. Future research should investigate integrated stakeholder approaches for advancing EEW. Research is also needed to enhance communication and collaborations for EEW researchers and stakeholders across disciplines throughout the system design, development and implementation.

Social EEW research should adapt to the fast-changing trends

With innovation in technologies, many opportunities arise for EEW design and implementation. This review has shown that smartphones are now being used for crowdsourced EEW. The ubiquity of smartphones means that EEW is becoming transboundary. EEW design and development are no longer limited to geographical jurisdiction and can be implemented across borders. For example, the Google initiative introduced the Android Earthquake Alerts System in New Zealand and Greece in April 2021 (Voosen, 2021). This also raises the concern of EEW players' civic responsibility, and a step further is the concern of legal liability. As of writing, minimal research has focused on the legal aspects of EEW systems. Articles in this review may have included some legal topics in their discussion, but only two articles (Li and Jia, 2017; Valbonesi, 2021) in this study focused primarily on the legislative components of EEW. But with the changing contexts due to technological trends, evidenced-based research is needed to inform regulation, policy, and planning of effective EEW in countries and territories.

Multiple countries and territories now have official EEW systems. Still, most of those capable of having official operational EEW are high-income countries/territories (e.g., Japan, West Coast USA, Taiwan etc.). These EEW systems are costly to deploy, implement, and maintain (Given et al., 2014; Prasanna et al., 2022). Because of high costs, lower-income countries have not had the same opportunity to access EEW as an earthquake mitigation tool. However, low-cost alternative technological solutions, such as using micro-electromechanical systems (MEMS) (Cochran et al., 2011), smartphones and apps (Cardno, 2020; Bossu et al., 2022), and decentralized architectural networks (Prasanna et al., 2022) can make EEW more accessible to lower-income countries. Future social science research should investigate how these low-cost technological solutions will be utilized by various countries (e.g., high-income and low-income) as mitigation tools. Social challenges arising from low-cost solutions should also be monitored and investigated.

Low-cost alternatives such as smartphones and other low-cost devices for crowdsourced EEW imply that more players can issue EEW alerts. While more options can generate benefits, they can also create problems. As in the case in Mexico, a false alert issued by an independent app caused confusion, created concerns for the official authority and raised the question of what civic responsibility might mean for people behind EEW systems (Reddy, 2020). Technological changes bring about new ways to design and implement EEW systems, and it also changes end-users perspectives. EEW research would need to reassess and update knowledge and assumptions as it applies to new and changing contexts.

Conclusion

Across the world, EEW systems already exist, and more countries are considering designing and implementing EEW for earthquake resilience. The rapid development of technologies and methods has provided a deeper physical understanding of earthquakes and improved the EEW processes for better warnings. As EEW innovates further and becomes more accessible and transboundary, social science research must also take a proactive role in the research advances of EEW, including legal perspectives.

This paper addresses the social science knowledge gap on EEW by reviewing the literature. Each of the 70 articles included in this review had different objectives, but collectively they have provided insight into the social science research relating to EEW systems. The articles in this review look at EEW from different perspectives, such as advanced end-users, the public, and the various EEW stakeholders. The findings reiterate that public education is critical for effective warning systems. The articles show that despite the various potential benefits of EEW to society, there is still a further need to understand EEW's impacts and interactions with society.

Social research in EEW is not just about delivering alerts to end-users. Social science research is needed to improve EEW systems further; in understanding how people, stakeholders and end-users, interact with EEW throughout its development process and when implemented through the various phases of disaster management. Suggested topics for future research include (1) advancing our understanding of why people take action or not and ways to encourage appropriate action when alerted with EEW, (2) enhancing public education – best practices for communicating, educating, and engaging with the public about EEW and earthquake resilience, and (3) keeping up with technology advances and societal changes, investigating how these changes impact how EEW interacts with society from various standpoints including legal perspectives.

Author contributions

Conceptualization and funding acquisition: MT, RP, JB, KS, AB, CK, and EL. Methodology, writing—original draft preparation, and visualization: MT. Formal analysis: MT and AC. Investigation: MT, JB, KS, RP, and AC. Writing—review and editing: MT, JB, KS, RP, AB, CK, AC, and EL. Project administration: MT and RP. All authors have read the manuscript agree to be accountable for the content of the work.

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Conflict of interest

Author EL is employed by Sysdoc Ltd., Wellington, New Zealand.

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Supplementary material

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