Efficacy and Usefulness of an Independent Public Earthquake Early Warning System: A Case Study—The Earthquake Network Initiative in Peru

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Abstract

Public earthquake early warning (PEEW) systems are intended to reduce individual risk by warning people ahead of shaking and allowing them to take protective action. Yet very few studies have assessed their actual efficacy from a risk-reduction perspective. Moreover, according to these studies, a majority of people do not undertake safety actions when receiving the warning.

The spectrum of PEEW systems has expanded, with a greater diversity of actors (from citizens to private companies), increased independence from national authorities, and greater internationality. Beyond differences in warning and messaging strategies, systems' characteristics may impact the way the public perceive, trust, understand, and respond to these warnings, which in turn will influence PEEW systems' efficacy and perceived usefulness, enhancing the need for additional research.

We take the example of earthquake network, an independent, voluntary, community-based and free system that offers a PEEW service. Through a quantitative survey (*n* = 2625), we studied users' perception and reaction to a warning sent related to an M 8.0 earthquake in Peru (where no national system existed). We observed that even though only a minority of users actually took protective action, the system was appreciated and perceived as useful by the majority because it enabled mental preparation before the shaking. We found evidence for a tolerance for perceived late, missed, and false alerts. However, because it is a voluntary and independent system, the social dimension of the warning was incomplete because only a fringe of the population benefited from the warning. Therefore, many users' first reaction was to warn their relatives. We discuss the need for partnerships between PEEW operators and national authorities to guarantee universal access to the service and maximize PEEW system efficacy.

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Supplemental Material

Introduction

Public earthquake early warning (PEEW) systems aim at rapidly detecting earthquakes and informing the public of incoming *S* waves' shaking that they are about to feel. The hope is to reduce seismic risk by giving the public a valuable window (from few to dozens of seconds) to get to safety. PEEW systems could reduce the number of injuries from earthquakes by more than 50% if everyone received warnings and took protective action (Strauss and Allen, 2016).

Over the past decade, PEEW systems have notably been set up at local or national levels in Japan, Taiwan, Mexico, South Korea, and the United States (Cremen and Galasso, 2020). PEEW systems have become a public expectation in many regions where earthquake risk is significant (Becker *et al.*, 2020; Dallo and Marti, 2021), yet their development is hampered by the implementation and operating costs of such systems (Strauss and Allen, 2016).

From a risk-management perspective, PEEW systems are considered effective if they contribute to risk reduction and prevent casualties. The technical performance and current limitations of PEEW systems have been extensively assessed

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(Allen and Melgar, 2019; Minson *et al.*, 2019; Cremen and Galasso, 2020). However, their efficacy in terms of individual risk reduction also depends on social and cultural components. People need to receive, understand, trust, and act on the warnings (Reddy, 2016; Wald and Eeri, 2020). Therefore, a burgeoning series of theoretical and prospective works has explored the importance of both alerting and messaging strategies. Previous literature focuses on alert thresholds, tolerance for missed and false alerts, and how systems should be explained beforehand to manage expectations (Cochran *et al.*, 2018; Allen and Melgar, 2019; Becker *et al.*, 2020). When it comes to messaging, the format, design, and content of the message matter (Allen and Melgar, 2019; Sutton *et al.*, 2020). Warnings should be user-centered, considering inter-alia cultural context, technology access, spoken languages, literacy, and preparedness level (Basher, 2006). In the end, beyond technical performances, the primary criterion to assess PEEW system efficacy remains whether people take protective action or not.

Still, there have only been a handful of studies on how people actually react to PEEW systems. Empirical studies were conducted after earthquakes in Mexico and Japan (Hoshiba, 2014; Allen *et al.*, 2018; Nakayachi *et al.*, 2019), and in all cases, most of the respondents had not taken a protective action following the warning. However, in the Japanese case, citizens still perceived the service useful because they were able to mentally prepare for the shaking (Nakayachi *et al.*, 2019).

Three salient points emerge from the existing research. First, warning response behaviors are not always rational and depend on social and psychological factors (Mileti, 1999; Wood, 2018). Risk culture, preparedness level, training (Paton, 2008), and situational parameters such as warning time and feasibility (e.g., having a table nearby, being able to move) are at play (Allen *et al.*, 2018; McBride *et al.*, 2019). Second, PEEW systems are appreciated by users even though they are not always effective or optimum in terms of individual risk reduction. Therefore, not only efficacy but also perceived usefulness should be taken into account. Finally, more empirical sociological studies are needed because intended behaviors may vary from actual ones (Nakayachi *et al.*, 2019).

Empirical studies become even more important as a diversity of actors is entering the PEEW field. Private companies such as Grillo, SASMEX, and Skyalert are already operating in Mexico (Allen *et al.*, 2018), and Google has announced a new service for Android users (Stogaitis, 2020). Citizens are also becoming a key part in the emerging PEEW system in Aotearoa New Zealand (Tan *et al.*, 2021). They are already deeply involved with earthquake network (EQN), the first demonstrated, voluntary, and smartphone-based PEEW system (Bossu *et al.*, 2021). Smartphones are also used in fixed locations in the new ASTUTI PEEW network in Costa Rica (Brooks *et al.*, 2021). Many of these initiatives are not coordinated with national authorities and can function regardless of borders. Beyond differences in warning and messaging strategies, the multiplication of independent actors and different systems' characteristics may impact the way the public perceive, consider, trust, understand, and respond to these warnings, which in turn will influence PEEW systems' efficacy and perceived usefulness.

This article explores how PEEW systems' characteristics influence public perception and response to warnings. This is done through an empiric case study approach focusing on one specific and independent PEEW system: EQN. By analyzing the results of a questionnaire (n = 2625) sent to EQN users following a warning issued for an **M** 8.0 earthquake that hit Peru in 2019, we assess how the system's characteristics affected users' perceptions and responses to the warning. This piece of research complements a previous article (Bossu *et al.*, 2021) that focused on EQN's technical performance and showed that despite a good understanding of the warning, only 25% of respondents took protective action.

We start with briefly describing the EQN PEEW system's main characteristics and the general context. After describing the methodology and main results, we discuss how the system's characteristics impacted users' perceptions of and reactions to the warning. In addition, we debate actors' complementary roles and how partnership with national authorities could increase the system's efficacy. Finally, we suggest avenues for future research.

Elements of Context: EQN Warnings and the M 8.0 Earthquake in Peru

The EQN initiative offers a crowdsourced PEEW service based on a dynamic smartphone network and that is accessible through an app. The system uses charging smartphones' accelerometers to detect, in real time, the shaking induced by an earthquake (Finazzi and Fassò, 2015). When an earthquake is detected, the app issues a warning and sends it to all smartphones with the app in the area (Fig. 1). If not too close to the detection point, users may then receive a warning in advance of the seismic wave that causes the shaking and thus benefit from an earthquake early warning (EEW) (Finazzi, 2016; Bossu *et al.*, 2021). The EQN app is free to download, available in eight languages, and can be run all over the globe. EQN also enables users to manually report earthquakes that they feel and chat with others (Finazzi, 2020).

Contrarily to national PEEW systems, EQN is a voluntary, community-based, and independent PEEW system. This implies that (1) users have to download the app to receive the alerts; (2) the more users there are, the more efficient the system; (3) the system is not supported by national authorities; and (4) alerts can only be sent to people who have downloaded the app. To benefit from the service, people must then own a smartphone, speak one of the eight languages of the app, have internet access, have heard about the app, and have downloaded it.

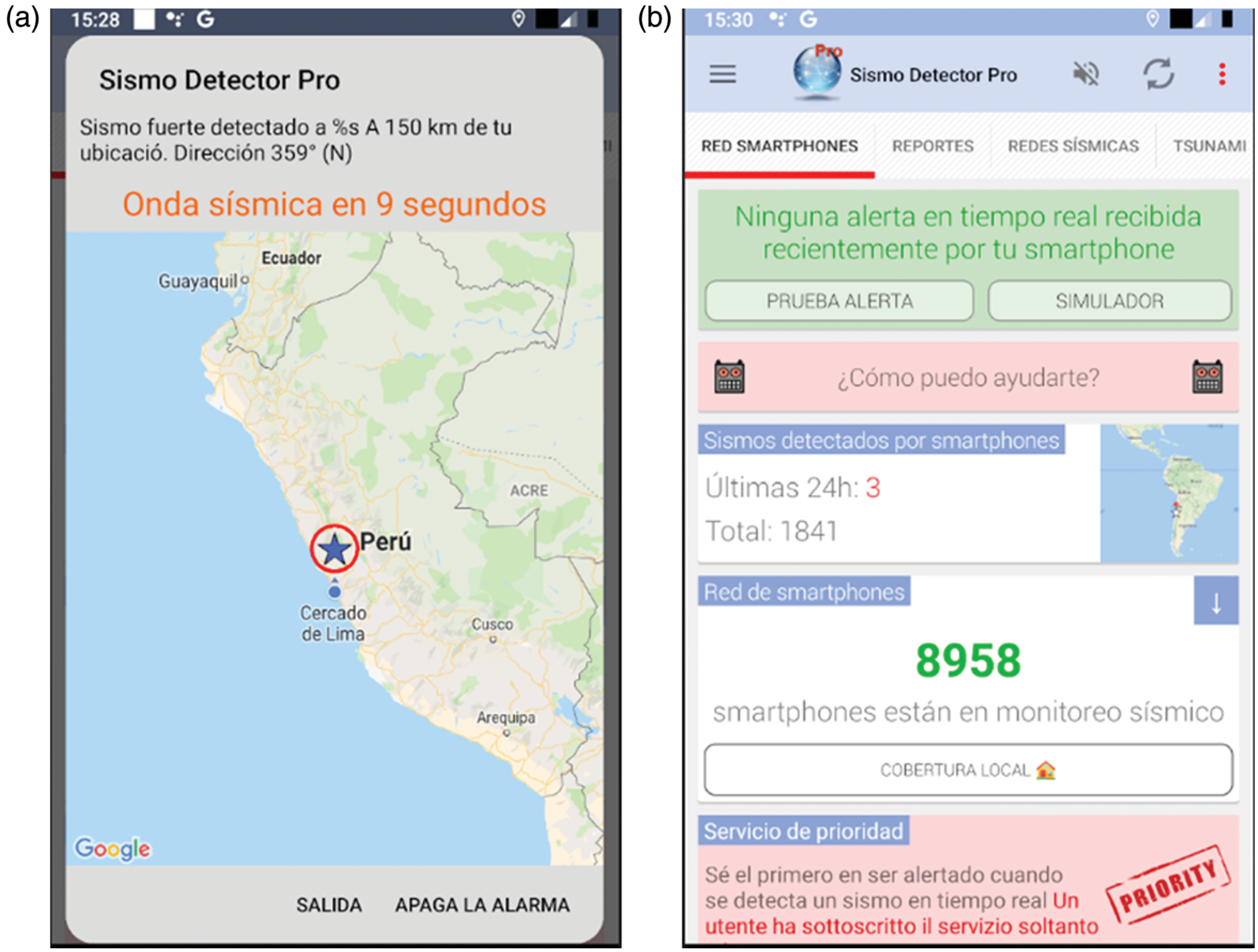

Figure 1. (a) Screenshot of the start page of the earthquake network (EQN) app and (b) an EQN earthquake early warning (EEW) notification. The app has not been designed by a professional web designer and is in constant evolution. Screenshots were made on 26 May 2019 and correspond to users' experience at the time of the studied earthquake.

The warning sent by EQN is designed to be very simple and contains only the most relevant information. It includes a countdown to the shaking, a visual representation (map), and the user's distance from the detection point (Fig. 1). In addition, the warning comes with a loud alarm sound. No information on the expected intensity, earthquake magnitude, or safety tips are part of the warning message. The app sends alerts for felt earthquakes that can be received by users who will not feel the earthquake, which is especially true for small-magnitude earthquakes (Bossu *et al.*, 2021). The warning is sent in the language chosen by the user. They can modify warning distance and generate test warnings to be better prepared.

We analyzed users' reaction to a warning sent by EQN on 26 May 2019 when an **M** 8.0 earthquake hit northern Peru at 02:41 a.m. local time, with a focal depth of 120 km. It was largely felt 1000 km from the epicenter and more sporadically up to 2000 km from the epicenter, a felt area that covers several nearby countries, including Colombia, Ecuador, and Bolivia. Two people died, and about 30 were injured. The warning was sent to more than 54,000 EQN users over the felt area. At the time, EQN was already very popular (33,000 users) in Peru, where no official PEEW system existed. After the **M** 8 earthquake, EQN's PEEW system benefited from media and social media coverage in Peru.

Methodology

This article is based on a quantitative survey; the questionnaire was designed after a literature review and two exploratory interviews. The literature included theoretical and practical research focusing on people's behavioral response to warnings (Mileti, 1999; Lindell and Perry, 2012; Wein *et al.*, 2016; Wood *et al.*, 2018; Nakayachi *et al.*, 2019). Interviews were conducted with two EQN users in Peru who were both very active in the chat forum, one of them being also a popular seismology amateur. They enabled us to collect qualitative information about the local earthquake culture, EQN perception, and PEEW system experience in Peru.

The questionnaire aimed at (1) assessing users' expectations for the PEEW system; (2) estimating the perceived experience of successful, late, missed, and false warnings; (3) assessing warning understanding; (4) collecting reactions to the warning; (5) rating tolerance for missed and false warnings; and (6) collecting feedback and improvements. It was designed with respect to the European General Data Protection Regulation regarding data privacy issues (European Commission, 2016) and launched online through Google Forms in Spanish.

The questionnaire targeted EQN users who were in the felt area region at the time of the earthquake. An invitation to fill in the questionnaire was sent to all EQN users using the app in Spanish through a pop-up message that users could see when opening the app. Explicit consent was collected for each respondent. Data were collected between 23 July 2019 and 19 August 2019, two months after the earthquake. During the data collection period, no early warning was issued in the area. The dataset was analyzed with basic descriptive statistics and contingency tables made with Excel, available in Tables A1–A6 in Appendix.

Dataset and limitations

A total of 2625 EQN users who were 18 years of age or older and in the felt area at the time of the earthquake responded to the questionnaire; 77% of them were in Peru, 19% in Ecuador, 3% in Columbia, and the remaining others were in Venezuela or Brazil. Two-thirds of them declared to be between 500 and 1000 km from the epicenter at the time of the earthquake. Respondents were not asked about their precise location or how intensively they felt the earthquake. However, at 1500 km from the epicenter, U.S. Geological Survey and European-Mediterranean Seismological Centre estimated the intensity to have been between III and IV on the modified Mercalli scale (which measures the effects of an earthquake at a given location).

Overall, 82% of the respondents had already felt an earthquake in the past, and 25% had already received a PEEW. Among all respondents, 962 downloaded the app after the **M** 8.0 earthquake and were only questioned on their knowledge and perception of EQN's early warning features in general.

By targeting EQN users and collecting data from the whole felt area, which was international, the sample is not meant to be representative of the Peruvian population. Indeed, being an EQN user requires the possession of a smartphone, and in 2018, only 32.1% of the Peruvians owned one (Newzoo, 2018). Men and people aged between 25 and 44 yr old are slightly overrepresented in our sample compared with the Peruvian population. Our sample is also more educated because 65% of respondents went to university, whereas the average number of years of schooling in Peru is 10 years (UNDP, 2019).

Other limitations include that users' perceptions and remembrance of the events may have been altered by the 2 months' delay between the earthquake and the survey. Moreover, due to the dissemination method, the questionnaire could only be sent to users who still had the app at the time. Those who had deleted the app because of dissatisfaction could not be reached. Yet we observed that the EQN user number in the region increased after the earthquake from 33,000 before to 1,50,000 two days after the earthquake, stabilizing ~70,000 in November 2019 and ~2,00,000 in July 2021 after more recent events.

TABLE 1
Reasons for Earthquake Network Use

Q4. Why do you use the app?	
To receive warnings about earthquakes that can affect me	73.7%
To get information about earthquakes around me	45.9%
To be part of a network of volunteers and citizens sensors	30.0%
To increase the quality of seismic data in my country	29.1%
To share information on earthquakes I feel	25.6%
To contribute to an innovative project	17.6%
Because a relative suggested I download it	6.3%
Other	0.8%

Base: All respondents (n = 2625).
Note: Several answers possible.

Results

A strong expectation for PEEW

The main reason (73.7%) for installing the app was the possibility to receive PEEWs, which demonstrates the strong public expectation for this service (Table 1). This was supported by one of the interviewees, who reported that some Peruvians even traded their iPhones for Android operating smartphones to get the app (which was only available on Android at the time).

Among the respondents who downloaded the app after the earthquake, 68% did it expressly to get these warnings (Table A1).

App users have a good understanding of the community dimension of the app and the fact that they could contribute to improving earthquake-related information for their fellow citizens by using the app (Table 1). In addition, this was mentioned under "other" responses, which showed some app users to have a certain level of pride to be part of the network.

		Received the warning			Total
		Yes		No	
		Before the quake	After the quake		
Felt the earthquake	Yes	Accurate early warning 34.3%	Late warning 34.6%	Missed warning 14.1%	83.0%
	No	Perceived false warning 10.6%		Accurate absence of warning 6.4%	17.0%
Total		79.5%		20.5%	100%

Base: EQN users who had the app before the earthquake (n=1662)

Figure 2. EQN users' experience of EEW for the **M** 8.0 earthquake

EQN early warning users experience

We found that 40.7% of the respondents were notified accordingly with what they experienced. To better understand the different situations, we need to consider a series of scenarios related to the relative success of the warning system (McBride *et al.*, 2020). We established five categories depending on whether users received the warning and whether they felt the earthquake (Fig. 2). These categories are based on the user's perceived experiences and do not necessarily compare with technical performance evaluated from a seismological perspective (Bossu *et al.*, 2021).

Overall, 34.3% of the users declared that they were warned before feeling the shaking, which corresponds to an accurate warning situation. In addition, 6.4% experienced an accurate absence of warning because they did not feel the earthquake and did not receive the warning.

Among others, we identify three cases. Late warnings concern 34.6% of respondents who were warned after they had felt the shaking. About 14.1% did not receive the warning even though they felt the earthquake, which corresponds to a missed warning situation. Finally, 10.6% were warned but did not feel the earthquake, which, from their point of view, can be considered a perceived false warning. This is to be distinguished from a technical false warning, which occurs when a warning is issued but no earthquake happened.

We use these categories to analyze the results and assess users' perceptions and reactions to the warning.

Users' perception and reaction to accurate warnings

Perceived warning time. When asked about warning time, 52.8% of the respondents who received an accurate warning estimated that they received it between 1 and 5 s before the earthquake, 26.4% between 6 and 15 s, 9% between 16 and 30 s, and 5.9% around a minute before, or more. Time perception in such situations may be modified, and this does not necessarily represent the reality of how long in advance they were warned. Yet it still gives an idea of the time users had to understand the notice and get ready for the earthquake, given that most of them were probably sleeping (the earthquake having occurred at night).

Users' understanding and emotions. Among the respondents who experienced an accurate warning, 78.9% understood the message correctly (Table 2). Understanding of the notification increased with previous earthquake experience (81.6% vs. 61.8%) and with previous EEW experience (85% vs. 74.1%) (Table A2). The warning led to a state of vigilance rather than panic in those who received it. Most of the respondents felt "alerted" (77.7%), whereas the proportion who felt anxious is rather low (11.2%) (Table 3). The term "alerted" translates from the Spanish "alertado" and refers here to a state of increased vigilance, respondents being "on the qui vive."

TABLE 2
Understanding of the Earthquake Early Warning Notification

Q14. What did you think when you received the information?	
An earthquake is about to hit!	78.9%
An earthquake has occurred.	12.1%
What is this sound?	6.1%
My alarm clock is ringing.	6.0%
Someone is calling me or sending me a message.	3.2%
Other	2.8%

Note: Several answers possible.
Base: Users who received the notification before the earthquake (n = 570).

TABLE 3
Emotional Reaction to the Earthquake Early Warning Notification

Q15. How did the notification made you feel?	
Alerted	77.7%
Surprised	15.3%
Calm	13.3%
Anxious, stressed out	11.2%
Confused	5.6%
Excited	2.5%
Other	1.0%

Note: Several answers possible.
Base: Users who received the notification before the earthquake (n = 570).

Those who understood the notification proportionally felt more "alerted" than others (82% vs. 61%), whereas those who did not were proportionally more "confused" (11.3% vs. 5%). Having experienced an earthquake in the past also played a significant role: unexperienced users were proportionally more confused and anxious, whereas those who had already felt an earthquake in the past were proportionally more alerted (Table A3).

Users' reaction to the warning. Only a quarter of the respondents adopted a safety behavior after receiving the warning (Table 4). The most frequent reaction was a social one: the majority stated that they warned their relatives either physically present with them (54.6%) or through technological means (22.1%). Others simply waited for the first shaking (35.4%) (Table 4).

Those who understood the notification were relatively more likely to warn their relatives physically present (58.9% vs. 38.3%) and to take protective action (26.2% vs. 20.8%). Those with previous earthquake experience were also more likely to take protective action (26.3% vs. 17.1%), and those who had never felt an earthquake warned their relatives through social media or SMS more than others (36.8% vs. 19.8%). However, previous early warning experience is not associated with a higher likelihood to take protective action. Yet users who had received an early warning in the past are proportionnally more numerous to wait for the shaking than others (40.9% vs. 31.0%) (Table A4).

TABLE 4
Earthquake Network Users Reactions to the Earthquake Early Warning Notification

Q16. What did you do when you received the notification?	
I warned my relatives physically present with me.	54.6%
I waited for the first vibrations of the earthquake.	35.4%
I went to a safe place in my house (under a table…) dropped, covered and hold on.	25.1%
I warned my relatives through social media, SMS…	22.1%
I ran outside.	9.6%
Nothing	2.8%
Other	2.8%

Note: Several answers possible.
Base: Users who received the notification before the earthquake (n = 570).

Despite the small share of respondents who actually undertook a safety action, 74.8% of the respondents who received the notification before feeling the earthquake agreed or strongly agreed that it was useful and 72.8% that it was understandable.

Respondents' perceptions and reactions to late, false, and missed warning situations

In general, despite their experience of perceived late, false, or missed warnings and the downsides that come with them, users are not categorically negative about the app and expressed a certain tolerance and benevolence toward the system.

EQN users who experienced late warnings declared mixed feelings. For some of them, the notification added to the anxiety because they thought another earthquake was going to hit (34.1%). An equivalent share declared, on the contrary, that they felt relieved and that the information helped them decrease their anxiety levels. Even though 12.7% of these users trusted the app less, nearly a quarter of them still felt confident that the system would work in the future (Table 5).

Perceived false warning experience did not seem to decrease users' confidence in the system. Half of them still declared a high level of confidence in the fact that the system would function for future earthquakes (Table 6). Among the "other" responses, many EQN users explained that they were probably

TABLE 5
Perception of Earthquake Network Users to a Late Warning

Q21. You received an alert for an earthquake you had already felt. How did you feel about that?	
Relieved, it gave me information about what had happened.	34.1%
Anxious, I thought another earthquake was about to happen.	32.4%
I'm sure it'll work next time.	23.1%
I didn't expect to be warned, so that's fine.	15.1%
This reduced my confidence in the application.	12.7%
Skeptical, I don't understand how this warning works.	8.6%
Angry	2.9%
Other	3.1%

Note: Several answers possible.
Base: Users who received the notification after they had felt the earthquake (n = 575).

TABLE 6
Reaction of Earthquake Network Users Who Experienced False Warning

Q20. You received an alert for an earthquake you did not feel. How did you feel about that?	
I'm sure it will work next time.	50.0%
Anxious, I waited for the earthquake for a fairly long time.	19.0%
This reduced my confidence in the application.	8.2%
Skeptical, I don't understand how this warning works.	6.0%
Angry	1.1%
Other	20.1%

Note: Several answers possible.
Base: Users who received the notification but never felt the earthquake (n = 177).

too far away from the epicenter for the system to function well or that they had changed their app parameters. This demonstrated a good level of understanding of how the system works. However, these false warning situations still raised anxiety for 19% of users in this situation as they waited for the shaking.

For missed warnings, we also observed mixed feelings (Table 7). Respondents who declared that they would trust the system in the future were as numerous as those who declared a decrease in trust in the app (22.9% each). Many chose the "other" option to state that they were asleep and had turned off their phones, so they could have not be warned. Others explained again that they were probably too far away from the epicenter to receive the warning.

TABLE 7
Reaction of Earthquake Network Users Who Experienced Missed Warning

Q23. You didn't receive the earthquake warning information in advance, how do you feel about that?	
This reduced my confidence in the application.	36.3%
I'm sure it'll work next time.	31.6%
I don't understand how this warning works.	17.9%
I think I was in an area that could not be warned in advance about the earthquake.	17.1%
Angry	6.4%
I didn't expect to be warned, so that's fine.	6.0%
Other	7.3%

Note: Several answers possible.
Base: Users who did not receive the notification but felt the earthquake (n = 234).

EQN improvements

Respondents were asked to rate the importance of several types of improvements for the app (Table 8). Because of the question format, all propositions received a high rate of importance. However, distinctions can still be observed. The most popular demand expresses the need for more seismological information, especially magnitude (60.9%). The second most important feature requested was the possibility to quickly share the information with relatives who do not have the app. This is in agreement with the hypothesis of the social dimension of warnings previously mentioned that cause users to think of warning their relatives before they think about taking a protective action for themselves.

Interest in damage information (after the warning) also reached a high level of interest for more than half of the respondents. Safety tips and drills as well as information on expected damage and about the system functioning seemed to interest respondents slightly less (~40% for each modality).

In addition, 81.8% declared that they would rather receive warnings for all earthquakes they could potentially feel than for damaging earthquakes only (Table A5).

Perceived legitimacy and propensity to pay for the service

When asked about who they perceive as legitimate to provide a PEEW system, EQN users were 53% in favor of governments. About 26% turned to the scientific community, 18% to the civil protection, and only 2% to private companies. About 1% selected the "other" modality.

Nearly half of the respondents declared that they would not be willing to monthly pay for a PEEW system, whereas 37% would agree to pay but no more than 3 SOL (~1$)

TABLE 8
Earthquake Network Improvements Assessment

"What kind of information or feature would you like to receive in the notification that warns you that an earthquake may hit your location?"

	Very important	Important	Neutral	Not very important	Not important at all
Include information about the magnitude	60.9%	20.2%	3.1%	4.2%	11.6%
Be able to share quickly the information with my relatives who don't have the app	55.9%	22.2%	5.3%	5.0%	11.6%
Receive information about the earthquake and the damages AFTER the earthquake	52.1%	25.1%	6.5%	4.8%	11.5%
Include information on the expected damages	43.2%	29.6%	9.1%	6.6%	11.5%
Include safety tips on what to do in case of earthquake	41.7%	30.9%	9.6%	6.4%	11.4%
Include information on the way the system works	40.9%	30.9%	11.1%	6.1%	11.0%
Include drills and test messages to be better prepared when a real earthquake occurs	39.1%	29.3%	13.8%	6.5%	11.3%

Base: All respondents (n = 2624) on a combination of responses for questions 9 and 28.

and 15% would agree to pay more (Table A6). These results must be weighed against the fact that we were addressing users who could benefit from this service free of charge thanks to the application.

Discussion

In the case of the **M** 8.0 earthquake in Peru, EQN succeeded in sending an understandable alert ahead of the shaking to a significant part of its users in the region. Thanks to the EQN app, a sizeable number of users benefited from an early warning, for free, in which no other PEEW system is yet implemented. With its simple alerting and messaging strategy, the EQN warning was well understood by those who received it. The app largely met users' expectations and reached high-satisfaction levels. Yet it was not fully satisfactory for those who experienced missed, false, and late warning. Technical improvements are therefore required to reduce inaccurate and missed warnings and meet the needs of a larger audience.

The survey results enable us to confirm a series of findings from the literature, which seem common to many PEEW systems. Similarly to what was found in Japan and Mexico (Allen *et al.*, 2018; Nakayachi *et al.*, 2019), the majority of warned respondents did not take protective actions. This could be considered a major drawback for PEEW efficacy. Indeed, the Strauss and Allen (2016) estimation that PEEW could reduce injuries by 50% was only based on the hypothesis that people would take pre-emptive behavior. Yet a series of elements suggest that behaviors could change in favor of more protective actions. Users tend to be more reactive when they have previous earthquake experience. The chance to take protective actions also increases with notification understanding, which advocates for more testing of warning designs (Sutton *et al.*, 2020). Even though it is a user demand, whether safety tips should be included in the warning—and in what format—is still an open debate. It is unclear if it will confuse the message or give an incentive to act, and recommendations may vary from country to country (Strauss and Allen, 2016; Fallou *et al.*, 2019).

Despite the fact that they mostly do not act on the warnings, users perceive the system as useful. Mental preparation for the shaking is still pointed out by participants as a benefit of PEEW, as was the case in Japan (Nakayachi *et al.*, 2019). This finding confirms that beyond PEEW efficacy, one should also consider perceived PEEW usefulness for users.

Our results also confirm findings from Allen *et al.* (2018) in which a general acceptance for the technical limitations of EEW systems and a higher tolerance of unnecessary alerts rather than missed alerts are found among users (Allen and Melgar, 2019). Technical limitations and the fact that the systems are mainly designed on the assumption that people will not feel the *P* wave make these false alarms unavoidable (Minson *et al.*, 2019). However, it is crucial to understand reactions to false, missed, and late alerts because they may decrease users' trust toward the PEEW system in the long term. Our results tend to confirm that false alerts are better understood if the risk of overalerting the public is explained beforehand (Minson *et al.*, 2019). Postwarning communication is also essential to explain who was warned, who was not and why, as was the case for Ridgecrest earthquake for instance (Chung *et al.*, 2020; McBride *et al.*, 2020).

Beyond confirming previous findings, our study also enlightens some salient points, intrinsically linked to EQN's characteristics:

- The community aspect was revealed to be the strength of the system and was endorsed by the users who well understood this functionality. A certain pride for contributing to the provision of such a service to others emanated from several responses. This tends to advocate for an increased implication of citizens in PEEW systems through citizen science, for instance (Haklay *et al.*, 2018; Hicks *et al.*, 2019; Becker *et al.*, 2020). In addition, the community aspect could explain the high tolerance for failures expressed by those who received missed and false alerts because they understand how the system works and its potential fragilities. In addition, it could account for the high level of confidence that the system "will work next time" among users, including those who have experienced late, false, and missed warnings. Yet it is uncertain how this benevolence will evolve in time and whether repeated warning experience may decrease trust in the app.

- Being a voluntary system, EQN is not universal. Only citizens with functioning smartphones and an internet access can benefit from the service. Moreover, contrary to other warning systems, users need to be active (download the app) to be part of it. This may act to increase the comprehension level of how the system works and of the warnings themselves, which could result in users taking more seriously the alerts. But the flipside is that the system can alert only members of the community who already have the app, which is proving to be an obstacle to protective behavior because users tend to worry for their relatives who did not get the chance to be warned before considering taking protective action. Because of this social dimension of the warning, we can assume here that the system would be more effective and efficient if it were universal. Inclusivity and integration of minority groups and vulnerable people are still major challenges for PEEW systems (IFRC, 2018).
- The impact of EQN's independence from national and local authorities leads to somewhat paradoxical opinions for two reasons. On the one hand, EQN is a system that fills a need not satisfied by the state, which leads to a certain benevolence and confidence of users toward the system of which they are part. On the other hand, citizens still consider governments as the most legitimate actors to develop these systems. This is confirmed by Allen and Melgar (2019), who reported on a 2016 study that 88% of the sampled population was in favor of a statewide PEEW system and that 75% were willing to pay for such systems. Moreover, the involvement of national authorities may impact trust (Dallo and Marti, 2021).

Putting warning systems and their specific characteristics into perspective, the necessity of state action emerges. To increase PEEW efficacy, partnerships between authorities and independent actors, such as EQN, seem necessary where government alone cannot offer the service. Collaboration between authorities and independent actors could bring access to the service to the greatest number while contributing to educating the public on protective actions and bringing substantial knowledge on local cultures. Drills, for instance, could be organized at the local or national level in partnership with the system. This could make the role of experience in taking safety action more effective because we found that those who had already received an early warning were not proportionately more likely to take safety action. However, building such partnership for more effective warning systems also requires thinking of philosophic social and economic dimensions of community safety and actors' intervention. Who can and should get access to the warnings, and who should pay?

Conclusion

Despite their limitations, PEEW systems remain a tremendous opportunity to reduce individual risk. When countries are not in a position to supply such a system to their citizens (often because of the development and operational costs), alternative systems such as EQN are an effective way to provide this service to a part of the population.

In the Peruvian case, the EQN application has effectively issued early warning to some of its users, who, even if they did not all take safety measures or receive the warning in time, seem to be generally satisfied and approve of the usefulness of the system.

However, beyond its usefulness, the system could gain in efficacy with a partnership with the government to overcome the limitations inherent in the system's characteristics. It could thus guarantee the universality of the service while improving risk education and response behavior. Moreover, protecting citizens is one of the government's sovereign powers. The government's role as coordinator could even become essential in the years to come to limit the potential confusion linked to a multiplication of systems. The question may arise, for example, in New Zealand, where Google is setting up a service for its users while at the same time a new system involving citizens is being developed (Becker *et al.*, 2020; Tan *et al.*, 2021).

Beyond the question of multiple warning providers, there is currently a lack of historical perspective in empirical research to study warning fatigue and the effect of these warnings (and their failures) over the long term. For this purpose and to complete the present research, the questionnaire will be improved and the survey replicated. This will enable three kinds of comparisons: (1) between cultures, launching it in different countries and regions to assess the impact of risk culture, preparedness level, and EQN use on perceptions and reactions to the warning; (2) between seismic scenarios, launching it in similar regions but for earthquakes causing different level of damages or different felt intensity levels; and (3) between PEEW systems if a PEEW is activated for the same earthquake by EQN and another system.

Data and Resources

Data used come from the online quantitative survey described in the Methodology section. The anonymized database is available as a supplemental material to this article. L. Fallou, R. Bossu, R. Steed, F. Finazzi, I. Bondár. A Questionnaire Survey of the Earthquake Network App's Users in Peru Following an M 8 Earthquake in 2019. V. 0.9. GFZ Data Services (2021; DOI: 10.5880/fidgeo.2021.001).

Declaration of Competing Interests

The authors acknowledge that there are no conflicts of interest recorded.

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Appendix

The appendix includes Tables A1–A6.

TABLE A1
Awareness of the Earthquake Early Warning Feature among New Users

Q7. Did you know there was such a feature in the app?	
Yes and that's partly why I downloaded it.	67.8%
Yes, but that's not why I downloaded it.	7.0%
No, I didn't know.	25.3%

Base: New users who did not have the app when the M 8.0 earthquake occurred (*n* = 962).

TABLE A2
Comparison between Previous Earthquake and Early Warning (EEW) Experience and Notification Understanding

Q14. What did you think when you received the earthquake warning?

	Had previous earthquake experience		Had previous EEW experience	
	Yes	No	Yes	No
An earthquake is about to hit!	81.6%	61.8%	85.0%	74.1%
An earthquake has occurred.	11.5%	15.8%	10.6%	13.3%
What is this sound?	5.9%	7.9%	3.1%	8.5%
My alarm clock is ringing.	4.9%	13.2%	5.9%	6.0%
Someone is calling me or sending me a message.	2.8%	2.6%	2.4%	3.2%
Other	2.4%	7.9%	4.7%	1.9%

Base: Users who experienced an accurate warning (*n* = 570).
Note: Several answers possible.

TABLE A3
Comparison between Previous Experience and Emotions Felt When Receiving the Warning

Q15. How did the notification made you feel?

	Previous earthquake experience		Previous early warning experience	
	Yes	No	Yes	No
Confused	4.5%	13.2%	4.7%	6.3%
Anxious, stressed out	10.7%	14.5%	12.6%	10.1%
Alerted	79.6%	65,8%	76,4%	78,8%
Surprised	12.8%	31.6%	9.8%	19.6%
Excited	2.2%	3.9%	1.6%	3.2%
Calm	13.2%	14.5%	15.0%	12.0%
Other	1.2%	2.6%	1.6%	1.6%

Base: Users who experienced an accurate warning (n = 570).
Note: Several answers possible.

TABLE A4
Correlation between Users' Reaction to the Warning and Their (1) Understanding of the Warning, (2) Previous Earthquake Experience, and (3) Previous Early Warning Experience

Q16. What did you do when you received the warning?

	Understood the warning		Had previous earthquake experience		Had previous early warning experience	
	Yes	No	Yes	No	Yes	No
I warned my relatives physically present with me.	58.9%	38.3%	55.1%	51.3%	55.1%	54.1%
I waited for the first vibrations of the earthquake.	36.7%	30.8%	36.6%	27.6%	40.9%	31.0%
I went to a safe place in my house (under a table…) dropped, covered and held on.	26.2%	20.8%	26.3%	17.1%	23.6%	26.3%
I warned my relatives through social media, SMS…	23.6%	16.7%	19.8%	36.8%	20.1%	23.7%
I ran outside.	9.6%	10.0%	8.5%	17.1%	9.1%	10.1%
Nothing	1.8%	6.7%	2.4%	5.3%	2.8%	2.8%
Other	1.8%	6.7%	2.0%	7.9%	3.9%	1.9%

Base: Users who experienced an accurate warning (n = 570).
Note: Several answers possible.

TABLE A5
Preference for Warning Threshold

Q27. Would you rather?

Receive warnings only in case of earthquakes with potential damage	18.2%
Receive warnings of all earthquakes you may feel	81.8%

Base: All users (n = 2626)

TABLE A6
Propensity to Pay for Public Earthquake Early Warning

Q30. How much would you be willing to pay monthly to get an earthquake early warning system?	
I would not be willing to pay	48%
3 SOL or less (1$)	37%
Between 4 and 15 SOL (2–5$)	13%
Between 16 and 32 SOL (6–10$)	2%
More than 32 SOL (11$)	1%
Total	100%
Base: All users (n = 2625)	

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