NATURAL HAZARDS

Global growth of earthquake early warning

Public-private partnerships provide a method for vastly expanding sensor networks

By **Richard M. Allen**[1,2] and **Marc Stogaitis**[2]

Observations of physical Earth processes used to be the exclusive domain of governmental agencies. In the United States, NASA satellites observe surface changes, National Oceanic and Atmospheric Administration buoys monitor the ocean and the atmosphere, and US Geological Survey (USGS) seismometers detect earthquakes, allowing scientists to tackle questions that were unimaginable before these observational networks were built. Today, much larger observational networks exist in the private sector that could also be harnessed to study Earth processes and reduce the impact of natural hazards. The development of public-private partnerships is therefore increasingly key for Earth scientists to use the complete observational dataset needed to answer fundamental scientific questions and solve societal challenges.

The recent rapid growth of earthquake early warning (EEW) globally (see the first figure) is one example of such a public-private partnership and how a massive observational network in the private sector can be applied to accelerate the implementation of a life-saving technology.

EEW uses seismic sensors close to an earthquake epicenter to rapidly detect an earthquake and then deliver an alert to those in harm's way ahead of the shaking. Warnings are typically a few seconds, but can be up to a minute for larger earthquakes, and are used by individuals and institutions to reduce the shaking hazard (*1*). The idea behind EEW dates back to the 1906 San Francisco earthquake, with the first implementation in Japan in the 1960s. The first public alerting system did not arrive until 1991, when an array of seismometers along the subduction zone coast of Mexico was used to start providing alerts to Mexico City.

This slow development was due to the substantial scientific and technical challenges to operating an EEW system. An array of seismic sensors has to be operating in the earthquake source region continuously. Algorithms to characterize the earthquake source must process large volumes of data in real-time to determine when and where an alert should be issued. Then, the alert must be delivered to the affected area. This process must all happen within a few seconds if the alerts are to be useful. These challenges slowed the implementation of EEW globally.

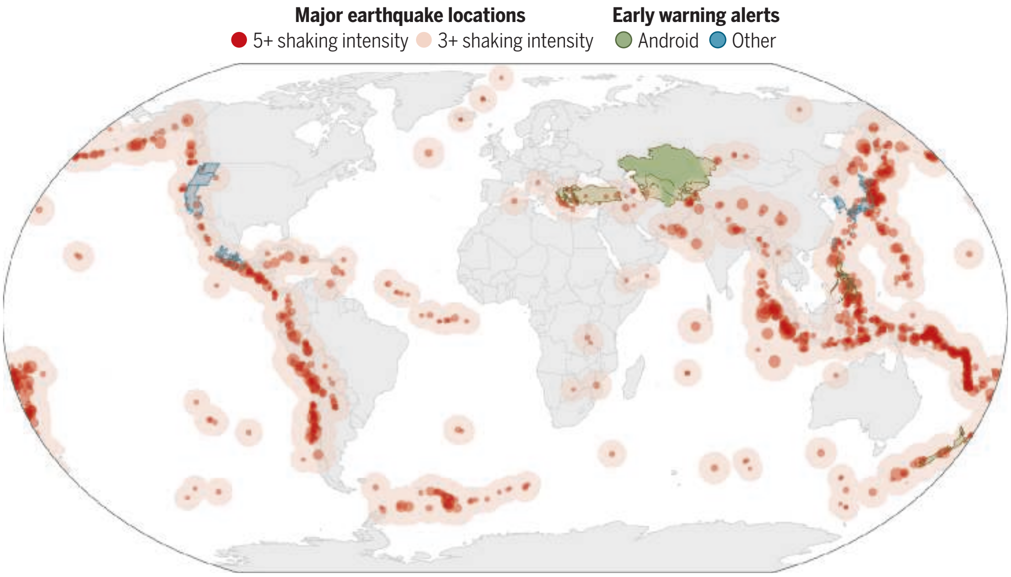
After the implementation in Mexico City, it took 16 years before the next public system was implemented in Japan in 2007. Another decade passed until the Taiwan and South Korea systems were implemented, bringing the total population with access to alerts to just over 210 million by 2018. Next came the 2019 public launch of ShakeAlert, providing EEW to the 40 million occupants of California. The state also adopted the MyShake smartphone app that both delivers alerts and records earthquake shaking (*2*). ShakeAlert extended into Oregon and Washington in early 2021, bringing the total global population with access to EEW to 260 million people (see the second figure).

All of these systems use traditional seismic networks that are mostly operated by governmental and academic institutions with fixed and dedicated sensors. The accelerating expansion of these systems continues, with testing underway for a public system across much of China and Israel. The alerting algorithms used are often the product of international seismological collaboration [for example, (*3*–*6*)].

In 2020, Google launched the Android Earthquake Alerts system. Initially, in a public-private partnership with the USGS, it delivered ShakeAlert messages to all Android phones in California. Then in 2021, it started delivering alerts to New Zealand and Greece. Later in the year, Turkey, the Philippines and central Asia were added. Building on the MyShake model (*7*, *8*), alerts in these countries are made possible by using the accelerometers in private Android phones to detect the earthquakes and to deliver alerts. The addition of the Android system has added another 150 million early-warning users in the first year of operation. More than 400

Global distribution of earthquake shaking and early warning systems

Earthquake early warning (EEW) systems are important for regions likely to have damaging earthquakes. Each circle shows the approximate shaking regions for magnitude 6.5 and larger earthquakes. The pink regions are where shaking is felt, and the red regions are where shaking causes damage. The current geographic distribution of EEW are highlighted in blue and green, with green areas entirely depending on Android Earthquake Alerts. Japan, Mexico, South Korea, and Taiwan have systems that use permanent seismic networks. The western US states have ShakeAlert, which initially sent alerts using wireless emergency alerts, MyShake, and other apps, but they now also have alerts delivered through Android Earthquake Alerts.



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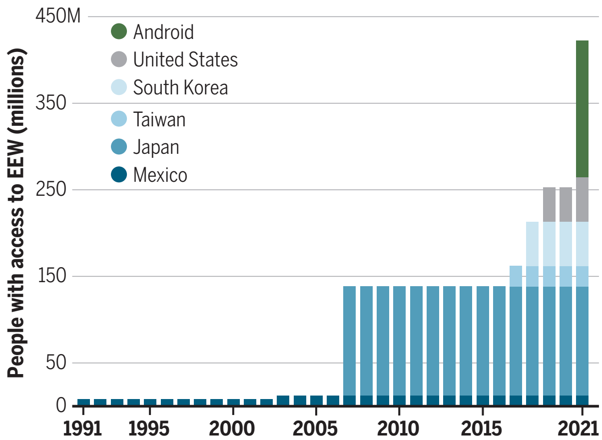
Global growth of EEW

Mexico implemented an EEW system in 1991. Japan followed with their own more than a decade later, with Taiwan, South Korea, and finally the United States adding warning capabilities. However, adding Earthquake Alerts to Android phones almost doubled the number of people with access to early warning in a very short time frame.



million people have access to EEW today. Google has also stated its goal to make the Android Earthquake Alerts system available globally (*9*), which is possible because there are now, for the most part, phones wherever there are people.

The rapid expansion of an early-warning service could potentially save lives. But ongoing human and technical challenges remain: The public must be engaged in effective use of the alerts. Typically, the first time a user becomes aware of the system is when they get their first alert. In that moment, users are overwhelmingly enthusiastic about this technology as they feel the shaking a few seconds later. The challenge is in translating that enthusiasm into appropriate protective actions (*10*). This not only includes individual actions for personal safety but also integration of the alert technology into the infrastructure of our lives. Trains already slow and stop, and self-driving cars could be programmed to do so as well. Our increasingly automated homes and offices could also react to reduce risk.

On the technical side, the challenge remains to ensure the best performance of the warnings, getting the fastest possible alerts to the most accurate estimate of the shaking region. The metamorphosis of research-oriented seismic networks into public-safety infrastructure has expanded the available datasets. On the US West Coast, the number of observatory-quality seismic stations will have almost tripled thanks to the implementation of ShakeAlert. Similar seismic networks are being installed in other earthquake-prone countries, such as China and Israel. The release of MyShake demonstrated the use of personal smartphone accelerometers to record earthquake shaking, increasing the number of sensors from thousands to more than a million (although not all sensors are recording all the time). With the integration of this capability into Android, more than a billion sensors are now in use. This proliferation of sensors is providing a more detailed picture of earthquake shaking and the factors that affect amplifications and variability in motions.

The progress we outlined, and the ability to meet the challenges ahead, are dependent on interdisciplinary, interinstitutional, and intersector partnerships. EEW came out of a research project that worked with public safety and emergency response agencies to deliver alerts. Seismologists partnered with social scientists to identify the intersection of what is physically possible with humanly useful. Emergency management agencies are currently funding dual-use scientific-grade sensor networks that provide the data for alerts and for research into earthquakes and other physical Earth processes that will inevitably lead to new strategies for hazard reduction.

Including the private sector into these partnerships—to leverage the massive sensor networks they operate for a variety of purposes—is leading to a paradigm shift. In the case of EEW, it is the adaptation of personal smartphone sensors and the scalability that comes from integration with Android that is enabling alerts globally. Other disciplines may also benefit from similar sorts of partnerships. Smartphone sensors include pressure, magnetic field, and infrasound. Pressure data can be used to improve weather forecasts (*11*). The magnetometer could be used to detect severe geomagnetic storms (*12*), and infrasound could be used to detect natural and human-made hazards, including eruptions, landslides, and explosions.

Beyond smartphones, Raspberry Shake, Weather Underground, and Purple Air crowdsource privately owned sensor networks of accelerometers, infrasound, pressure, temperature, and air particulate content to provide ground motion, weather, and air quality data. The National Lightning Detection Network operates in the private sector but provides data for atmospheric research and wildfire response. Multiple private constellations of satellites now collect radar images of the Earth's surface, repeating observations every few days. The resulting InSAR images reveal millimeter-scale deformation of Earth's surface that could be used to study surface deformation such as landslides and subsurface fluid flow of water and magma. Transoceanic communications cables can be used to detect earthquakes (*13*), as can dark fiber beneath our cities (*14*).

Various questions arise about the longevity of these networks and their products and about the motivations of the for-profit companies that operate them. Even in the case of entirely public networks, their longevity and continued funding require demonstrating value, whether that is in terms of risk mitigation or in the development of private-sector products such as weather information networks. In the private sector, some amount of value must be delivered back to the owners in exchange for the data collected. Respecting user privacy is paramount. Data can be anonymized in various ways, including through the use of differential privacy, aggregated sensor data, and with licensing agreements. But with the right partnership, these networks can provide by orders of magnitude more observations than were available a few years ago, and they can be leveraged for research and societal good. Such public-private partnerships not only provide the data to understand physical Earth processes, they also provide networks that could speed the development and delivery of solutions. ■

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