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SUMMARY

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The ShakeAlert Earthquake Early Warning System and the Federal Role

Portions of all 50 states, as well as U.S. territories and the District of Columbia, are vulnerable to earthquake hazards and associated risks to varying degrees. Among the costliest U.S. earthquake disasters was the 1994 magnitude 6.7 Northridge earthquake in California, which caused 60 fatalities and more than 7,000 injuries; left about 20,000 homeless; damaged more than 40,000 buildings; and caused an estimated $13-$20 billion in economic losses. *Earthquake early warning* (EEW) is one way to reduce earthquake risks (i.e., fatalities and injuries, as well as damage to structures and operations). EEW refers to sending a warning to areas that may experience the highest intensity shaking; the EEW is sent after an earthquake is detected, but before damaging ground-shaking reaches the areas. An EEW received in tens of seconds to minutes before shaking allows institutions and individuals to take protective actions (e.g., an institution can automatically stop a train to prevent derailment or an individual can avoid getting into an elevator to avoid harm).

EEW is among the most challenging of emergency communications. Earthquakes cannot be predicted and occur suddenly, and mass notification to high-risk areas must occur within seconds of earthquake detection to be effective. Congress directed the U.S. Geological Survey (USGS) to establish EEW capabilities in 2018 (42 U.S.C. §7704(a)(2)(D)), as part of the reauthorization of the National Earthquake Hazards Reduction Program (NEHRP). Under the Stafford Act (42 U.S.C. §5132), the USGS has authority through the President to provide alerts about earthquakes using federal and other communication services to states and civilian populations in endangered areas.

Development of Earthquake Early Warning in the United States

An EEW system consists of the following components:

- An understanding of earthquakes and faults to know where to locate an earthquake-sensing network
- An earthquake-sensing network that can detect the start of an earthquake in real time
- Robust and rapid telemetry (i.e., continuous transmission of instrument readings to data centers)
- Data analysis and alert decisionmaking
- A targeted and clear alert message
- Rapid mass notification through communication services to areas at risk

The USGS, with various federal, state, academic, and private partners, began public EEW on the West Coast via the ShakeAlert Earthquake Early Warning System (ShakeAlert) in California in 2019 and in Oregon and Washington in 2021. ShakeAlert started as a prototype EEW system in 2012. From FY2006 through FY2021, the USGS spent an estimated $132 million for EEW activities, including ShakeAlert; other nonfederal partners contributed $84 million for ShakeAlert between 2012 and 2021. In 2018, the USGS estimated annual operation and maintenance costs for ShakeAlert starting at about $40 million. The USGS aims to expand ShakeAlert into Alaska, Hawaii, and Nevada. In FY2022, Congress appropriated $28.6 million to the USGS for ShakeAlert and $1 million for ShakeAlert implementation planning in Alaska.

ShakeAlert sent 51 public alerts for earthquakes that caused light shaking and little damage between October 2019 and December 2021. EEWs sent via the Federal Emergency Management Agency (FEMA) communication pathways often did not arrive before intense shaking; these warnings frequently were delayed more than five seconds or were not delivered due to technical glitches. EEWs sent via cell phone applications over Wi-Fi or cellular networks were fast (i.e., with delivery delays of less than five seconds), giving cell phone owners enough time in most cases to take protective actions before ground shaking arrived.

Oversight and Policy Considerations

Congress may consider providing direction on policy priorities related to the authorities and mandates of the NEHRP Reauthorization Act of 2018 (P.L. 115-307) and the Stafford Act to expand, contract, or change EEW capabilities in the United States. Congress may seek additional information to assess ShakeAlert's performance and effectiveness. In addition, Congress may seek more information about the ability of FEMA communication pathways to provide rapid and targeted mass notification for earthquakes. Relatedly, Congress may explore policy options for improving FEMA communication pathways.

If Congress chooses to continue providing funding for EEW generally and ShakeAlert specifically, it may consider a range of options to do so, such as through annual appropriations or shared costs that are a mix of federal- and state-funded initiatives. Other funding options for consideration may include funding aspects of ShakeAlert through established or new National Science Foundation or FEMA federal grants, contracts, or cooperative agreements. In addition, Congress may consider policy options that would enable the National Oceanic and Atmospheric Administration or the National Aeronautics and Space Administration to contribute funds for EEW capabilities. Congress also may consider providing appropriations for NEHRP and allowing the program to establish priorities for ShakeAlert vis-à-vis other NEHRP priorities.

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Introduction

An earthquake starts by the sudden movement of rocky material under the Earth's surface along a plane of weakness (i.e., a fault). Seismic waves radiate outward from the starting point of the earthquake, much like radial waves moving outward from a drop of water.[1] Intense ground shaking from the seismic waves and motion from the fault slip that reaches the surface may damage people and property and may cause commercial, government, educational, social, cultural, and economic losses. An earthquake also may trigger other hazards, such as tsunamis or landslides.[2] Damaging earthquakes may impact local, regional, national, or international societies, and many governments establish and direct programs to understand earthquake hazards and reduce earthquake risks to protect their communities.[3] Congress provides direction, oversight, and funding for earthquake research to understand earthquake hazards, reduce earthquake risks, understand geologic structure below the surface, detect underground nuclear explosions, and for other purposes.

An important tool to monitor earthquake activity and mitigate the risk is an *earthquake early warning* (EEW) system.[4] An EEW requires detecting the start of an earthquake (i.e., near the earthquake's origin time) and warning high-risk areas that damaging ground shaking may arrive within seconds to minutes of receiving the warning.[5] An EEW system consists of a real-time earthquake-sensing network, data communications, data analysis, alert formulation, and an alert message distribution system. The earthquake-sensing network consists of an array of earthquake-sensing stations that continuously and autonomously monitor for earthquakes near faults. A station consists of seismic and/or geodetic instruments, power supplies, telemetry, and structures to protect the instruments and electronics.[6]

Seismic instruments, which include seismometers and accelerometers (sometimes called *strong ground motion accelerometers* or *strong ground motion instruments*), detect and measure the properties of earthquakes, especially the arrival of the first seismic waves and the earliest estimated location and magnitude (M) of the event.[7] A seismometer near an earthquake may not be capable of providing real-time data for large magnitude (M7.0+) earthquakes, causing a delay in detection, because the instrument cannot record large ground motion that originates close to the seismometer. As a result, some seismometers may not be used for EEW; other instruments, such

[1] For more details, see the U.S. Geological Survery (USGS), "What Are the Effects of Earthquakes?," at https://www.usgs.gov/natural-hazards/earthquake-hazards/science/what-are-effects-earthquakes?qt-science_center_objects=0#qt-science_center_objects.

[2] See the **Appendix** for more information about earthquake hazards.

[3] Richard M. Allen et al., "The Status of Earthquake Early Warning Around the World: An Introductory Overview," *Seismological Research Letters*, vol. 80, no. 5 (September/October 2009), at https://doi.org/ 10.1785/gssrl.80.5.682.

[4] Jessica A. Strauss and Richard M. Allen, "Benefits and Costs of Earthquake Early Warning," *Seismological Research Letters*, vol. 87, no. 3 (May/June 2016), pp. 765-772, at https://doi.org/10.1785/0220150149 (hereinafter Strauss, "Benefits," 2016).

[5] USGS, "Earthquake Early Warning – Overview," at https://www.usgs.gov/programs/earthquake-hazards/science/ earthquake-early-warning-overview.

[6] Telemetry is the automated recording and transmission of data from stations to processing centers.

[7] For earthquake early warning (EEW), location and magnitude (amount of energy and size of the earthquake) are estimated rapidly to determine if and where damaging ground shaking might occur. Ground shaking intensity is described using the Modified Mercalli Intensity Scale (MMI), where MMI I is the lowest intensity and MMI X is the highest intensity. See **Appendix** for more information about magnitude, shaking intensity, and hazards.

as geodetic instruments, help provide data for EEW in these circumstances.[8] Geodetic instruments on the ground measure ground displacement and peak ground acceleration caused by an earthquake using a Global Navigation Satellite Systems (GNSS) receiver.[9] The geodetic data recorded by geodetic instruments do not go off scale, regardless of the earthquake's magnitude or location. Geodetic data provide critical real-time information about ground motions to estimate large magnitude (M7.0+) events for EEW, especially for those events where the seismic data may be unavailable for the reasons described above.

Generally, an EEW should be communicated within 20 seconds of the earthquake's origin time, so institutions and individuals have enough time to take protective action before intense ground shaking arrives at their locations. EEW does not work for individuals and institutions very close to an earthquake because there is not enough time to detect the event and communicate a warning before intense ground shaking reaches nearby locations.[10]

An understanding of earthquakes and their hazards is essential to establish an effective EEW system.[11] Observing and measuring the characteristics of earthquakes helps to determine why they happen, where they occur, how frequently they may occur, and how much of a risk they may pose to society. Some earthquakes produce earthquake hazards, such as ground shaking and ground displacement; these hazards can cause damage and, in rare but significant cases, can cause catastrophic damage. Earthquakes cannot be predicted, so to prepare and respond to the sudden onset of a potentially catastrophic event, an EEW system needs to rapidly and accurately detect the starting time and initial location of a damaging earthquake and estimate where the most intense ground shaking may occur.

Congress established the National Earthquake Hazards Reduction Program (NEHRP) in 1977 (Earthquake Hazards Reduction Act; P.L. 95-124, 42 U.S.C. §7704) as a coordinated federal program focused on understanding earthquake hazards and reducing earthquake risks, including by warning the public about earthquakes. Four agencies—the U.S. Geological Survey (USGS), National Science Foundation (NSF), Federal Emergency Management Agency (FEMA), and National Institute of Standards and Technology (NIST)—constitute the program. Congress appropriated $160 million for NEHRP in fiscal year (FY) 2021.[12] NEHRP is mandated to reduce earthquake risks via three strategies:

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[8] *Geodesy* is the science of accurately measuring and understanding the Earth's geometric shape, orientation in space, and gravity field, and *geodetic* is anything related to geodesy.

[9] Geodetic instruments provide positions that are accurate to a few millimeters to centimeters in optimal conditions, and this accuracy is important for earthquake measurements. The Global Navigation Satellite Systems (GNSS) receivers are similar to "GPS receivers" found in mobile devices in the basic way that they work. The receivers gather satellite signals from the GNSS, which includes the U.S.-operated Global Positioning System (GPS) constellation of satellites, and determine their position in space and time. GPS receivers in mobile devices are miniaturized and not fixed (or stably mounted in one position) and are therefore less accurate in defining their position than geodetic instruments in earthquake-sensing networks.

[10] Jeffrey J. McGuire et al., *Expected Warning Times from the ShakeAlert® Earthquake Early Warning System for Earthquakes in the Pacific Northwest*, USGS, USGS Open File Report No 2021-1026, 2021 (hereinafter USGS, *Expected Warning Times*, 2021).

[11] Richard M. Allen and Diego Melgar, "Earthquake Early Warning: Advances, Scientific Challenges, and Societal Needs," *Annual Review of Earth and Planetary Sciences*, vol. 47 (2019), pp. 361-388, at https://doi.org/10.1146/annurev-earth-053018-060457 (hereinafter Allen and Melgar, "EEW Advances," 2019).

[12] See CRS Report R43141, *The National Earthquake Hazards Reduction Program (NEHRP): Issues in Brief*, by Linda R. Rowan, for more on NEHRP.

1. Understanding the hazards and assessing the risks
2. Mitigating the hazards by facilitating hazard-resistant structures
3. Warning about the hazards so actions may be taken to reduce risks[13]

In 2018, Congress directed the USGS, with international, federal, state, and local partners, to develop an EEW capability (P.L. 115-307, 42 U.S.C. §7704(a)(2)(D)). The first operational EEW system in the United States, ShakeAlert on the West Coast, provides warnings to individuals and institutions about intense ground shaking reaching their location in a matter of seconds to minutes from an earthquake detection. ShakeAlert consists of an earthquake-sensing network of seismic and geodetic stations that detect an earthquake and data processing centers with algorithms and decisionmaking software that prepare alert messages. The alert messages contain the estimated earthquake location, earthquake magnitude, and the areas that may receive intense ground shaking in an estimated time period. ShakeAlert has been developed and tested and is now operated, maintained, and improved based on past and current earthquake research and earthquake-sensing technology development. ShakeAlert began operations in California in 2019 and expanded operations into Oregon and Washington in 2021.[14] ShakeAlert had issued 51 public alerts by the end of 2021.[15] The USGS leads the ShakeAlert project and coordinates the work of other federal and nonfederal partners. ShakeAlert is funded by federal and nonfederal partners. The system does not eliminate all risks but is one component of NEHRP's objective to reduce earthquake risks. This report focuses on ShakeAlert and concludes with a discussion of potential issues for Congress regarding funding, policy, and priorities for EEW in the United States.

Federal Role in Identifying Earthquake Risks

The USGS and FEMA assess earthquake hazards and identify earthquake risks in the United States, as directed and funded by NEHRP. An effective EEW system to reduce risks may be established where the earthquake risks are the highest. The USGS Earthquake Hazards Program (EHP) conducts earthquake research; studies and catalogs earthquake activity; maps faults; assesses earthquake hazards; and prepares earthquake notifications that include estimates of earthquake hazards and damage, as well as information about an earthquake and its fault.[16] FEMA's Risk Management Program provides resources to identify and assess risks from natural hazards and consider ways to minimize these risks.[17]

[13] Hazard is not the same as risk; *hazard* is a source of danger, whereas *risk* is the possibility of loss or injury. *Earthquake hazards* are related to an earthquake causing intense ground shaking and other damaging effects. The degree of earthquake hazards is related to the probability of certain damaging effects caused by an earthquake occurring within a certain period. The degree of *earthquake risks* is the combination of the degree of earthquake hazards and the extent of the affected population (which includes the infrastructure supporting that population). Therefore, in general, large population centers may be at higher risk than small population centers for the same degree of earthquake hazards. See **Appendix** for more information about earthquake hazards.

[14] ShakeAlert, "ShakeAlert: An Earthquake Early Warning System for the West Coast of the United States," at https://www.shakealert.org/; USGS, "ShakeAlert," at https://earthquake.usgs.gov/data/shakealert/; and Douglas D. Given et al., *Revised Implementation Plan for the ShakeAlert System: An Earthquake Early Warning System for the West Coast of the United States*, USGS, Open-File Report 2018–1155, 2018 (hereinafter USGS, *ShakeAlert Plan*, 2018).

[15] ShakeAlert, "Post ShakeAlert Message Summaries," at https://www.shakealert.org/education-outreach/event-review-files/.

[16] See USGS, "Earthquake Hazards Program," at https://earthquake.usgs.gov/.

[17] See Federal Emergency Management Agency (FEMA), "Risk Management," at https://www.fema.gov/emergency-managers/risk-management.

The USGS National Earthquake Information Center maintains the Comprehensive Earthquake Catalog (ComCat), an archive of earthquakes in the United States and significant earthquakes globally.[18] ComCat earthquake summaries, which provide information to assess the hazards and risks from each event, are a public resource. These summaries are posted as soon as possible after an event and may be updated over time to provide the most accurate information about the earthquake and its impact. The ComCat data are used to test EEW systems using past earthquake scenarios, and ComCat posts summaries of ShakeAlert performance for alerts for earthquakes in California, Oregon, and Washington.[19]

The USGS Earthquake Notification System (ENS) provides earthquake information to individuals and institutions that sign up to receive notifications.[20] ENS points to the ComCat summary page for an event as soon as information is available. Earthquake notification information is useful to emergency responders and post-earthquake recovery, as it identifies regions that may be damaged.

ComCat technical data are a resource for researchers trying to understand earthquakes and earthquake hazards. Catalogs of past earthquakes identify active faults, how the faults are changing with time, and where earthquakes may be likely to occur in the future. Past earthquake assessment, current earthquake monitoring, and research helps the USGS identify and map active faults and their associated earthquake hazards.

Many earthquakes occur at the boundaries between large sections (plates) of the Earth's crust. These areas are referred to as *plate tectonic boundaries* (**Figure 1**). Most of the largest magnitude and most damaging earthquakes in the geologic record occur at collisional boundaries between major tectonic plates. Two major types of collisional boundaries, subduction zones and strike-slip zones, are of most concern to society because of the potential for damaging earthquakes.[21] Many subduction zones occur offshore, below the water surface. In some cases, when an earthquake occurs on a submarine subduction zone, the earthquake may trigger a tsunami (**Figure 1**).

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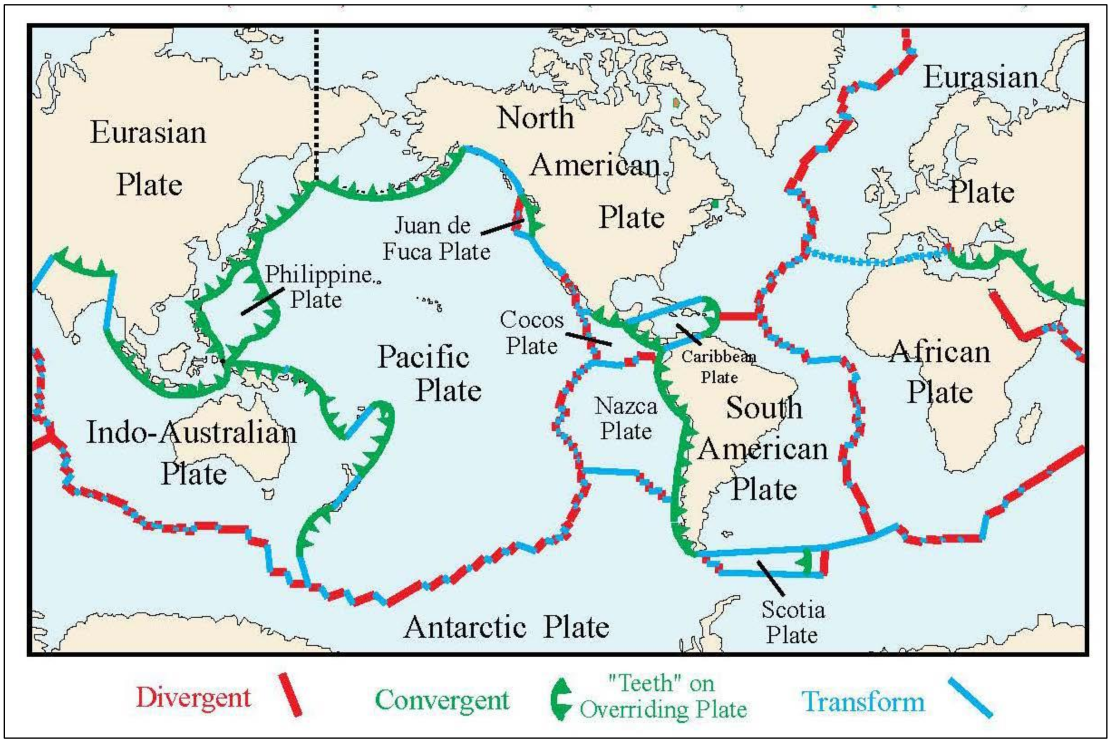
[18] See USGS, "National Earthquake Information Center (NEIC)," at https://www.usgs.gov/programs/earthquake-hazards/national-earthquake-information-center-neic.

[19] ShakeAlert performance metrics for earthquake detections are posted with the event summary on ComCat for earthquakes of magnitude 4.0 or larger. Performance metrics for all earthquake detections (i.e., magnitude greater than 3.5) that lead to the preparation and distribution of alert messages are posted on the ShakeAlert website: ShakeAlert, "Post ShakeAlert Message Summaries," at https://www.shakealert.org/education-outreach/event-review-files/.

[20] See USGS, "Earthquake Notification System," at https://earthquake.usgs.gov/ens/.

[21] *Subduction zones* are where tectonic plates converge, such that one plate is forced to bend and dive underneath another plate in a process called subduction by geoscientists (see USGS, "Introduction to Subduction Zones: Amazing Events in Subduction Zones," at https://www.usgs.gov/special-topics/subduction-zone-science/science/introduction-subduction-zones-amazing-events. Strike-slip zones are where tectonic plates laterally slide past each other and create a zone of faults where the two plates converge (see Britannica, "Strike-Slip Fault," at https://www.britannica.com/science/strike-slip-fault).

Figure 1. Plate Tectonics



Source: USGS, "Plate Tectonics Mapping," at https://pubs.usgs.gov/gip/99/pdf/gip99_ppt.pdf.

Notes: Divergent boundaries (red lines) denote rift zones or primarily normal fault type of motion (plates are pulling apart). Convergent boundaries (green saw tooth lines) denote subduction zones or primarily thrust fault types of motion (plates are pushing together). Transform boundaries (blue lines) denote primarily laterally sliding plate boundaries or primarily strike-slip fault type of motion (plates are sliding past each other). The lines generalize and approximate the surface trace of more complicated geologic structures that consist of many fault branches, and most plate boundaries reach the surface under water (i.e., submarine surface trace; shown by the colored lines in the blue ocean water on this figure). Major plate collisions expressed on the surface of major continents (shown by the lines on the tan continents on this figure) include the San Andreas Fault System (primarily strike-slip faulting) in California, the Great African Rift System (primarily normal faulting) and the continent-continent collision of the Indo-Australian Plate with the Eurasian Plate (primarily thrust and strike-slip faulting), creating the highest mountain range, the Himalayas.

The collisional boundaries that present the greatest earthquake hazards for the United States and its territories are three different subduction zones, offshore of Alaska, the Pacific Northwest, and Puerto Rico, and one strike-slip zone in California (**Figure 1**). The most active (i.e., have the most frequent earthquakes) and damaging subduction zones (i.e., have the potential to have large magnitude [M7.0+] events and may trigger tsunamis) that directly impact coastal populations and infrastructure in the United States are

- the Aleutian Arc Subduction Zone bordering southern Alaska,[22]
- the Cascadia Subduction Zone bordering the western coastlines of northern California, Oregon, and Washington,[23] and
- the Puerto Rico Trench Subduction Zone near Puerto Rico and the U.S. Virgin Islands.[24]

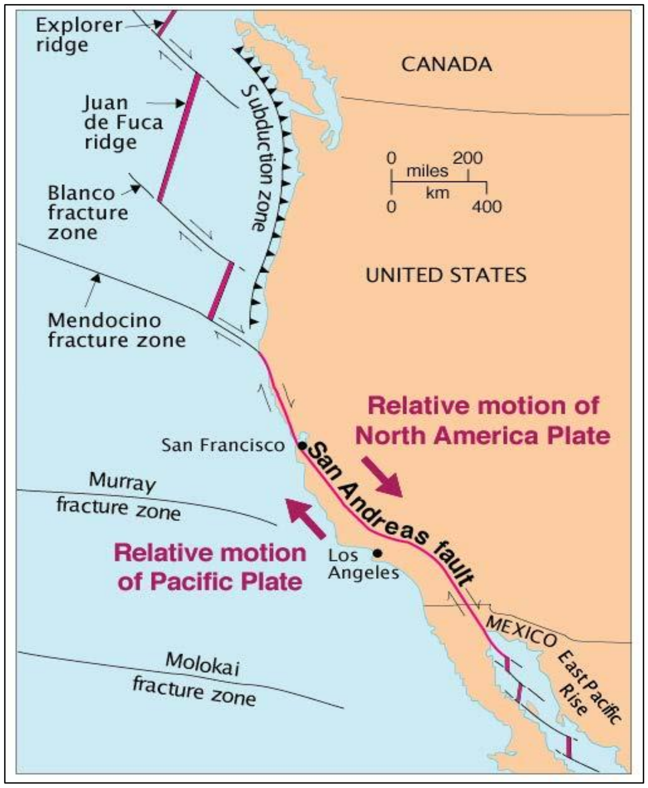
The San Andreas Fault System (SAF), which stretches about 800 miles from the Gulf of California through the state of California and then offshore just north of San Francisco (**Figure 2**), is a strike-slip fault system created by two tectonic plates that are sliding against each other. The Pacific Plate is sliding against the North America Plate, producing a wide area of multiple faults, including the San Andreas Fault. The collision of the plates produces many earthquakes, primarily in the shallow crust and because these earthquakes are shallow, they may produce intense ground shaking and/or ground displacement at the surface. Because the faults are extensive, an earthquake may slip over a large area and may produce large magnitude earthquakes (M7.0+). California is a high earthquake risk state because of the many shallow earthquakes on active and extensive faults near populated areas or areas with critical infrastructure (e.g., pipelines, roads, bridges, dams, and aqueducts).

[22] The Pacific Plate subducts beneath the North America Plate along the Aleutian Arc Subduction Zone offshore of southern Alaska and the Aleutian Islands. The Aleutian Arc Subduction Zone has generated multiple M8.0+ earthquake and tsunami sequences and these sequences may recur in the future. Six great earthquakes have occurred along the Aleutian Arc Subduction Zone since 1900: 1906 M8.4 Rat Islands, 1938 M8.6 Shumagin Islands, 1946 M8.6 Unimak Island, 1957 M8.6 Andreanof Islands, 1964 M9.2 Prince William Sound, and 1965 M8.7 Rat Islands, Harley M. Benz et al., *Seismicity of the Earth 1900-2010 Aleutian Arc and Vicinity*, USGS, Open-File Report 2010-1083-B, at https://pubs.er.usgs.gov/publication/ofr20101083B. The small population and sparse built environment limit the damage from these events and account for the lower earthquake risk in Alaska compared with some other states. Large Alaskan earthquakes may cause greater damage further away because of the tsunamis they trigger. Hawaii in particular has suffered significant losses from tsunamis triggered by Alaskan earthquakes. The 1946 M8.6 Aleutian Islands earthquake generated a tsunami, and the tsunami caused 5 fatalities in Alaska and 129 fatalities plus $26 million in 1946 dollars in damage in Hawaii.

[23] The Juan de Fuca Plate subducts beneath the North America Plate along the Cascadia Subduction Zone (CSZ) offshore of Northern California, the Pacific Northwest, and parts of British Columbia, Canada. M8.0+ earthquakes, many with tsunamis occur on the CSZ every 570-590 years, on average. There is evidence of at least 12 M8.0+ earthquakes on the Cascadia Subduction Zone over the past 6,700 years. Robert C. Witter, Harvey M. Kelsey, and Eileen Hemphill-Haley, "Great Cascadia Earthquakes and Tsunamis of the Past 6700 Years, Coquille River Estuary, Southern Coastal Oregon," *Geological Society of America Bulletin*, vol. 115, no. 10 (October 1, 2003), pp. 1289-1306. The last large magnitude earthquake (between M8.7 and M9.2) that triggered a large tsunami was in January 1700, more than 500 years ago, Brian F. Atwater, *The Orphan Tsunami of 1700* (Reston, VA: University of Washington Press/USGS, 2005). Earthquake probability forecasts estimate a 14% chance of a M8.0+ earthquake on the CSZ over the next 50 years, Alan Boyle, "Earthquake Experts Lay Out Latest Outlook for the 'Really Big One' That'll Hit Seattle," *GeekWire*, February 15, 2020.

[24] For more details about earthquake hazards and risks to Puerto Rico and the U.S. Virgin Islands, see National Oceanic and Atmospheric Administration (NOAA) Ocean Explorer, "The Puerto Rico Trench: Implications for Plate Tectonics and Earthquakes and Tsunamis," at https://oceanexplorer.noaa.gov/explorations/03trench/trench/trench.html.

Figure 2. Major Faults on the West Coast of North America



Source: U.S. Geological Survey, "San Andreas Fault," at https://www.usgs.gov/media/images/san-andreas-fault-3.

Notes: The West Coast of the United States is vulnerable to earthquakes because of the major collisions between tectonic plates. California is most vulnerable to earthquakes on the San Andreas Fault and many parallel and branching faults (these other faults are not shown on the figure). The San Andreas Fault is caused by the collision of the Pacific Plate with the North America Plate (see the relative directions of motions of these plates noted by the red arrows on the figure). The San Andreas Fault continues into Mexico, causing earthquake risks for Mexico. Northern California, Oregon, Washington, and British Columbia, Canada, are susceptible to earthquakes on the Cascadia Subduction Zone (labeled Subduction Zone on the figure). The Cascadia Subduction Zone is caused by the Juan de Fuca Plate (not labeled on the figure but located between the labeled subduction zone and the Juan De Fuca ridge) colliding and bending beneath the North America Plate.

The USGS maintains an interactive map of active faults in the United States and the USGS Subduction Slab Model maps subduction zones around the world.[25] The USGS generates and regularly updates its Seismic Hazard Maps for the United States and its territories using these maps and ComCat data.[26] The hazard maps forecast the probability of an earthquake occurring in a given area over a certain period of time (**Figure 3**). Alaska, California, Hawaii, Oregon, and Washington face the highest probability of a damaging earthquake (i.e., reaching a shaking intensity of VI, felt by all with slight damage to structures, on the Modified Mercalli Intensity Scale [MMI]) over the next 100 years.[27] These states face significant earthquake hazards and high

[25] See the USGS "Faults," at https://www.usgs.gov/programs/earthquake-hazards/faults. See the USGS "Slab2 - A Comprehensive Subduction Zone Geometry Model," at https://www.sciencebase.gov/catalog/item/.5aa1b00ee4b0b1c392e86467 and Gavin P. Hayes et al., "Slab2, a comprehensive subduction zone geometry model," *Science*, vol. 362, no. 6410 (October 5, 2018), pp. 58-61, https://doi.org/10.1126/science.aat4723.

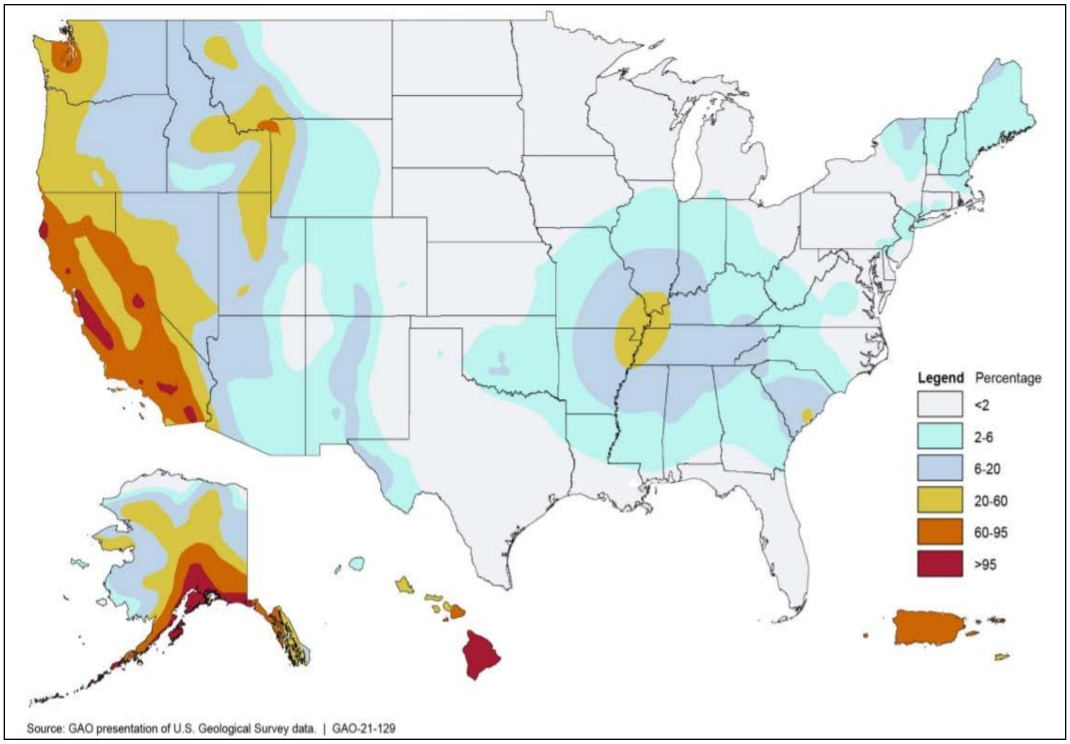
[26] See the USGS "Seismic Hazard Maps and Specific Data," at https://www.usgs.gov/natural-hazards/earthquake-hazards/seismic-hazard-maps-and-site-specific-data.

[27] USGS, "The Modified Mercalli Intensity Scale," at https://www.usgs.gov/programs/earthquake-hazards/modified-

earthquake risks because of past earthquakes, active faults, active volcanoes, and major tectonic plate boundaries in or near these states.[28]

Figure 3. USGS Seismic Hazard Map

(probability of a Modified Mercalli Intensity VI earthquake in 100 years, expressed as a percentage)



Source: U.S. Government Accountability Office (GAO), *Earthquakes: Progress Made to Implement Early Warning System, But Actions Needed to Improve Program Management*, GAO-21-129, March 2019.

Notes: Alaska, California, Oregon, and Washington have high earthquake probabilities (>60%) because they are near major plate tectonic collisional boundaries. Hawaii has high earthquake probabilities because of its active volcanoes. The Commonwealth of Puerto Rico has high earthquake probabilities because it is near a collisional plate boundary. Idaho, Montana, Utah, and Wyoming have medium to high earthquake probabilities (20%-95%) because of the Yellowstone volcano and the Intermountain Seismic Belt (including the Wasatch Fault) between the Basin and Range Province and the Rocky Mountains. The New Madrid seismic zone, at the intersection of Arkansas, Illinois, Kentucky, Missouri, and Tennessee, and parts of South Carolina surrounding Charleston have medium earthquake probabilities (20%-60%) because of past large-magnitude (M7.0+) earthquakes that occurred in the early to late 1800s. Little is known about the faults that caused these large earthquakes, because there is not enough information to decipher the structure below the surface. Other states with low earthquake probabilities (2%-20%) are vulnerable to earthquakes. Earthquakes cannot be predicted nor can the potential for an earthquake to occur in areas with some seismic history be ruled out. For more details about New Madrid and South Carolina, see USGS, "The New Madrid Seismic Zone," at https://www.usgs.gov/programs/earthquake-

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mercalli-intensity-scale. See the **Appendix** for more information about the Modified Mercalli Intensity Scale.

[28] Hawaii is not near a collisional plate boundary but has very high earthquake probabilities according to the USGS Seismic Hazard Map. Hawaii experiences earthquakes generated by the growth and activity of several volcanoes that make up the big island of Hawaii. In addition, Hawaii is the most tsunami-prone state. Tsunamis that impact the state can be triggered by earthquakes, landslides, or volcanic activity that occur in Hawaii or by earthquakes or volcanic activity originating from any of the major subduction zones that form a coastal ring around the Pacific Ocean Basin. Hawaii has experienced 135 confirmed tsunamis since 1812. Since 1923, nine tsunamis caused 294 fatalities and an estimated $703 million in damage. International Tsunami Information Center, "Hawaii Tsunamis," at http://itic.ioc-unesco.org/index.php?option=com_content&view=category&id=1436&Itemid=1436.

hazards/new-madrid-seismic-zone; and Martin C. Chapman et al., "Modern Seismicity and the Fault Responsible for the 1886 Charleston, South Carolina, Earthquake," *Bulletin of the Seismological Society of America*, vol. 106, no. 2 (February 16, 2016), at https://doi.org/10.1785/0120150221. See **Appendix** for more information about the Modified Mercalli Intensity Scale.

FEMA uses the USGS earthquake probability forecasts to estimate earthquake risks in the United States. FEMA estimates annualized building loss due to potential earthquake hazards using a hazard model called Hazus (**Figure 4**).[29] Building loss is a proxy for relative earthquake risk; California, Oregon, and Washington face the greatest risks for the largest annualized building losses based on the Hazus model. Other potential losses that are harder to estimate include damage to roads, bridges, utilities, dams and reservoirs, power plants, mines and quarries, and other structures, in addition to the disruption of commercial, education, government, and nongovernment operations. In 2017, FEMA estimated the annualized earthquake loss (AEL) to building stock was $6.1 billion and that California, Oregon, and Washington account for 73% of AEL due to the earthquake frequency, built environment density, and population size in these states.[30] FEMA has an online tool—the National Risk Index for Natural Hazards—that estimates the risks for different hazards, including earthquakes, in each county in every state.[31] The risk index includes expected annualized losses, social impacts, and community resilience.[32] According to this index, California, Oregon, and Washington have the highest risk index for earthquakes across a larger area and a larger population than other states.

[29] For more information about Hazus models and FEMA's Hazus Program, see FEMA, "Hazus," at https://www.fema.gov/flood-maps/products-tools/hazus.

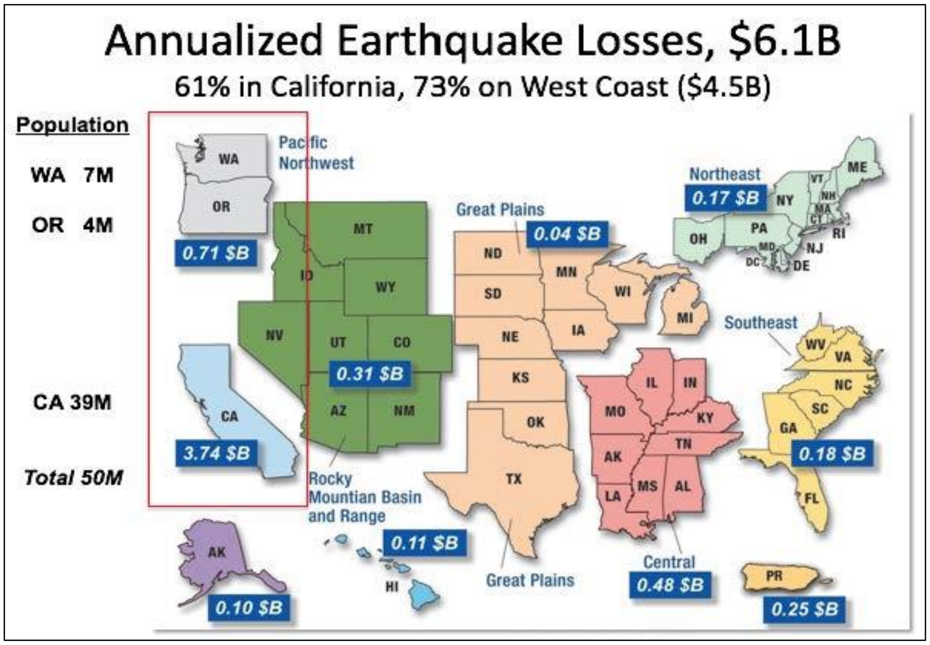
[30] These estimates were prepared in 2017. See Federal Emergency Management Agency (FEMA), *Hazus Estimated Annualized Earthquake Losses for the United States*, 2017, at https://www.fema.gov/sites/default/files/2020-07/fema_earthquakes_hazus-estimated-annualized-earthquake-losses-for-the-united-states_20170401.pdf. The calculated annual losses may be different in 2022.

[31] See FEMA, "National Risk Index," at https://hazards.fema.gov/nri/.

[32] FEMA's expected annualized loss is based on exposure of buildings, agriculture, and population to the specific hazard times the expected annual frequency of the hazard (in this case, annual expected frequency of an earthquake, which is based on the USGS's probability forecasts) times the historic loss ratio (i.e., the expected loss of buildings, agriculture, and population per earthquake). For more information, see FEMA, "Expected Annualized Losses," at https://hazards.fema.gov/nri/expected-annual-loss. FEMA's national risk index for earthquakes estimates the relative risk of a community compared with the rest of the United States for building and population losses due to an earthquake. FEMA compiles data regarding past earthquake locations, previous occurrences, and future probabilities from the USGS National Seismic Hazard Assessment; the Global Significant Earthquake Database produced by the National Oceanic and Atmospheric Administration (NOAA; see NOAA, "NCEI/WDS Global Significant Earthquake Database, 2150 BC to Present," at https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ngdc.mgg.hazards:G012153); and Carl W. Stover and Jerry L. Coffman, *Seismicity of the United States, 1568-1989 (revised),* USGS Professional Paper 1527, 1993, pp. 1-418, at https://doi.org/10.3133/pp1527.

Figure 4. FEMA Annualized Earthquake Losses

(estimates in 2017 dollars)



Sources: ShakeAlert, "ShakeAlert: An Earthquake Early Warning System for the West Coast of the United States," at https://www.shakealert.org/. (ShakeAlert added details about the total loss, West Coast losses, and population.) Original figure and calculations from the Federal Emergency Management Agency (FEMA), *Hazus Estimated Annualized Earthquake Losses for the United States*, 2017, at https://www.fema.gov/sites/default/files/2020-07/fema_earthquakes_hazus-estimated-annualized-earthquake-losses-for-the-united-states_20170401.pdf (hereinafter FEMA, *Hazus*, 2017).

Notes: In the United States, FEMA estimates the total building and building content economic exposure to earthquake hazards is $59 trillion (all estimates presented here are based on calculations completed and published in 2017). These earthquake losses are estimates for buildings only and do not consider the loss of life, other property, other infrastructure, business, government, and other losses. See FEMA, *Hazus,* 2017. Also see FEMA, "What Is Hazus?," at https://www.fema.gov/flood-maps/tools-resources/flood-map-products/hazus/about.

Background and Authority to Issue Earthquake Early Warnings

Since 1930, Congress has authorized programs and appropriated funds for earthquake research (or seismology) to reduce earthquake risks.[33] This earthquake research led to advances in the understanding of Earth processes, improved earthquake instrumentation, and earthquake risk reduction that has led to the development of EEW. Congress expanded earthquake research in the 1960s; the expansion focused on detecting underground nuclear explosions using seismic instruments and finding ways to reduce earthquake risks. Congress increased appropriations to almost $30 million (in 1959-1961 dollars) annually between 1959 and 1961 for the Department of Defense's Project VELA Uniform (VELA) for seismic investigations to support the detection of underground nuclear explosions and to support cooperation among nations to detect nuclear

[33] U.S. Government Accountability Office (GAO), *Need for a National Earthquake Research Program*, B-176621, September 11, 1972, pp. 1-81, at https://www.gao.gov/assets/b-176621.pdf (hereinafter, GAO, *National Earthquake Research*, 1972).

weapons testing. VELA led to improved seismic instruments and seismic networks and accelerated the sharing and standardization of seismic technology and data throughout the world.[34] These advances in research and instrumentation benefitted EEW development.

In the 1960s and the 1970s, there were damaging earthquakes in the United States and the potential for earthquake prediction based on one "predicted" event. The 1964 M9.2 Anchorage earthquake on the Aleutian Arc Subduction Zone, the largest event ever recorded in the United States, caused 9 fatalities, many injuries, and extensive damage in Alaska and generated a tsunami that caused 122 fatalities, many injuries, and damage in Alaska, Hawaii, Washington, Oregon, and California.[35] The 1971 M6.6 San Fernando earthquake caused 64 fatalities, many injuries, and extensive damage (including damage to the lower Van Norman Dam) in Los Angeles County.[36] China evacuated people from the city of Haicheng before the damaging 1975 M7.3 Haicheng earthquake struck on February 4, 1975, saving lives. This was considered a successful earthquake "prediction" at the time. Subsequent evaluation and additional research showed that such an earthquake prediction could not be repeated. There are no precursor physical changes that could be used to predict earthquakes, although research continues to try to understand what may cause an earthquake and whether any physical changes may precede an earthquake.[37]

During the same time frame, Congress conducted hearings that, together with reports and workshops from other groups, called for a coordinated federal program to research (1) earthquake hazards and risk assessments, (2) earthquake prediction and warning of an *imminent* earthquake, and/or (3) earthquake-resistant engineering.[38] Congress passed the Earthquake Hazards Reduction Act of 1977 (P.L. 95-124), which codified a coordinated program to reduce risks by considering these three research directions. It also authorized appropriations for the program, the USGS, and NSF.[39] Congress defined *earthquake prediction* and *earthquake warning* in the House report accompanying the 1977 act as follows: "As defined in the act, an earthquake prediction is a prediction, in definite or probabilistic terms, of the time, place, and magnitude of an earthquake, whereas an earthquake warning means a recommendation that normal life routines should be changed for a time because an earthquake is believed imminent."[40]

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[34] GAO, *National Earthquake Research*, 1972.

[35] For more details about the earthquake and tsunami, see the USGS, "M9.2 Alaska Earthquake and Tsunami of March 27, 1964," at https://earthquake.usgs.gov/earthquakes/events/alaska1964/.

[36] For more details about the earthquake, see the USGS, "50 Years Later an Earthquake's Legacy Continues," at https://www.usgs.gov/news/featured-story/disaster-helped-nation-prepare-future-earthquakes-remembering-san-fernando.

[37] For an overview of the 1975 M7.3 Haicheng earthquake prediction, see USGS, Earthquake Hazards Program, "Repeating Earthquakes," at https://earthquake.usgs.gov/learn/parkfield/eq_predict.php.

[38] GAO, *National Earthquake Research*, 1972; Robert E. Wallace, *Goals, Strategies, and Tasks of the Earthquake Hazards Reduction Program*, USGS, USGS Circular 701, 1974; and U.S. Congress, Senate Committee on Commerce, Subcommittee on Oceans and Atmosphere, *Earthquake Disaster Mitigation Act of 1975*, 94th Cong., 2nd sess., February 19, 1976, No. 94-64, S261-3. Congressional deliberations on earthquake research for risk reduction are recorded in many other hearings after the 1964 M9.2 Anchorage earthquake and before passage of the Earthquake Hazards Reduction Act of 1977 (P.L. 95-124). The particular hearing referenced above covered most aspects of the deliberations, featured witnesses and witness testimony from federal agencies, and included copies of relevant reports.

[39] For more on NEHRP, see CRS Report R43141, *The National Earthquake Hazards Reduction Program (NEHRP): Issues in Brief*, by Linda R. Rowan.

[40] The House report that accompanied P.L. 95-124 is U.S. Congress, House Committee on Science and Technology, *Earthquake Hazards Reduction Act of 1977, Report to Accompany H.R. 6683*, 95th Cong., 1st sess., H. Rept. 95-286, pt. 1, May 11, 1977.

Earthquake prediction and warning about an *imminent* earthquake are not possible based on the current understanding of Earth processes. Therefore, NEHRP's efforts shifted to EEW beginning in the 1980s. Congress directed the USGS to develop an automated, real-time EEW system prototype in the 1997 reauthorization of NEHRP (P.L. 105-47). An automatic seismic hazard warning system warns *high-risk operations,* such as public transit, that an earthquake has been detected and that damaging shaking is coming to the operations' location. This warning allows the operations to take automated actions, such as stopping a train, to reduce risks.

In the NEHRP Reauthorization Act of 2018 (P.L. 115-307), Congress removed statutory language requiring the USGS to develop procedures for making earthquake predictions and replaced it with language requiring NEHRP to develop procedures to issue EEWs. The language states that the USGS should "continue the development of the Advanced National Seismic System, including earthquake early warning capabilities." P.L. 115-307 requires the USGS, in the event of an earthquake, to issue an alert and a warning, when necessary and feasible, to FEMA, NIST, and state and local officials.

Congress authorized the President to direct federal authorities to warn the public about a disaster in the Disaster Relief Act of 1974 (P.L. 93-288, 42 U.S.C. §5132), which was reauthorized and renamed the Robert T. Stafford Disaster Relief and Emergency Assistance Act in 1987 (Stafford Act; P.L. 100-707). Congress directed the President (1) to ensure agencies are able to issue disaster warnings to state and local governments and to use federal agencies to assist states and local officials with disaster warnings,[41] (2) to make available a civilian defense warning system to provide disaster warnings to states and the civilian population in endangered areas, and (3) to cooperate with private or commercial communication systems to provide disaster warnings to states and the civilian population in endangered areas. Congress authorized the President to direct the USGS to provide warnings about earthquakes using civilian defense warning systems and to enter into agreements to use private or commercial communication systems to provide disaster warnings to states and civilian populations in endangered areas.[42] Congress did not specify earthquake early warnings in the Stafford Act. The USGS calls its warnings EEWs, to clarify that they are not earthquake predictions or forecasts but are based on detecting the start of an earthquake and then providing a warning within tens of seconds. In contrast, most severe weather warnings provide hours to days for preparation and protective actions.[43]

The ShakeAlert System

ShakeAlert is the first public EEW system operating in the United States.[44] A public EEW system uses FEMA or other communication pathways to provide alerts to individuals and institutions. ShakeAlert began sending earthquake alerts to communication providers for EEW broadcasts to the public in California in October 2019, in Oregon in March 2021, and in Washington in May 2021. ShakeAlert is available only in these three states. ShakeAlert consists of the following components:

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[41] *Disaster* refers to natural hazards, such as earthquake, flood, hurricane, tornado, landslide, and fire (P.L. 93-288).

[42] Robert E. Wallace, *Goals, Strategies and Tasks of the Earthquake Hazards Reduction Program*, USGS, USGS Circular 701, 1974.

[43] See National Weather Service (NWS), "Hurricane and Tropical Storm Watches, Warnings, Advisories, and Outlook," at https://www.weather.gov/safety/hurricane-ww; NWS, "Understand Tornado Alerts," at https://www.weather.gov/safety/tornado-ww; and NWS, "Storm Prediction Center," at https://www.spc.noaa.gov/.

[44] ShakeAlert, "ShakeAlert: An Earthquake Early Warning System for the West Coast of the United States," at https://www.shakealert.org/; and USGS, "ShakeAlert'" at https://earthquake.usgs.gov/data/shakealert/.

- An earthquake-sensing network of seismic and geodetic stations
- Robust and rapid telemetry (i.e., continuous recording and transmitting of instrument readings to data processing centers)
- Data processing centers to estimate earthquake characteristics and hazards
- Decisionmaking tools to determine if the earthquake may cause damage (i.e., meets shaking intensity thresholds) and to prepare alert messages
- Coordination and cooperative agreements with many communication providers for rapid mass notification of EEWs

Previous EEW system prototypes and earlier versions of the ShakeAlert system in the United States were experimental and sent alerts to specific testers.[45] EEW system development in the United States started in California, because of the state's high earthquake risks, the knowledge of California earthquake hazards, and the established seismic and geodetic networks that could function as part of an earthquake-sensing network. Experimental EEW systems operated in Oakland and Southern California in 1989 and 1997, respectively, as short-term tests of EEW. A prototype EEW system called ShakeAlert began testing in California in 2012 and in the Pacific Northwest in 2015. Congress appropriated funds for these activities primarily through the USGS EHP and NSF research grants and cooperative agreements.[46]

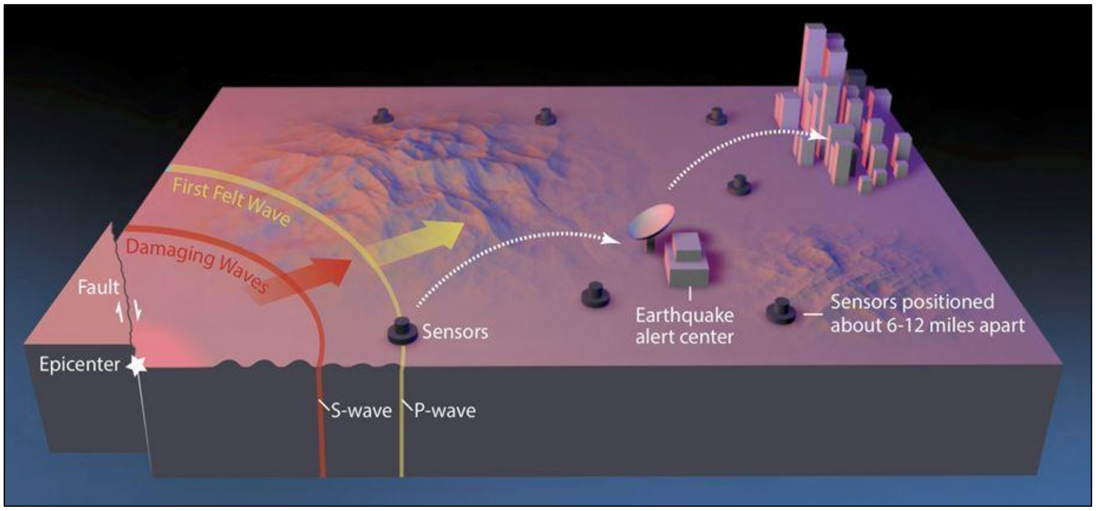
The earthquake-sensing network detects seismic waves that radiate outward from the starting point of an earthquake and sends earthquake-sensing instrument data to the data processing centers (**Figure 5**).[47] The network's intent is to use the faster P-waves to detect the start of an earthquake and prepare an alert before the slower, more damaging S-waves arrive at locations further from the earthquake's epicenter. It is not possible to provide EEW to some locations close to the epicenter, because there is not enough time to complete the EEW process before the shaking arrives. Data processing centers analyze the data and estimate the earthquake's location and magnitude, as well as the area that may receive high-intensity ground shaking. The processing centers send the alert messages containing this information to communication providers.

[45] For a timeline of the development of EEW and ShakeAlert in particular, see Richard Allen, "Earthquake Early Warning Milestones," UC Berkeley, at https://rallen.berkeley.edu/research/EEWmilestones.html; and Sara K. McBride et al., "Evidence-Based Guidelines for Protective Actions and Earthquake Early Warning Systems," *Geophysics*, vol. 87, no. 1 (January-February 2022), pp. WA77-WA102, at https://doi.org/10.1190/geo2021-0222.1, Figure 2 (hereinafter McBride, "Protective Actions," 2022).

[46] USGS, *ShakeAlert Plan*, 2018, p. 6.

[47] Body waves are seismic waves that travel through the Earth's interior. The waves used for earthquake detection for EEW are the primary or compression (P) waves and the secondary or shear (S) waves. P-waves, which travel faster than S-waves, are the first seismic waves to be sensed by instruments deployed at the surface and are the first waves to arrive at a given location. S-waves arrive later than P-waves but carry more energy and cause more intense shaking for a longer time than P-waves. S-waves cause the most damaging ground shaking in most earthquakes that impact communities. An effective EEW system detects the P-waves and determines the earthquake characteristics. This allows an EEW system to provide a warning of high-intensity shaking before the S-waves arrive at locations further away from the earthquake sensing instruments. Surface waves are seismic waves that travel along the surface of the crust; these waves arrive later than the body waves and can contribute to damaging ground shaking, especially for structures that may have been damaged to some extent by the earlier S-waves.

Figure 5. Schematic of the ShakeAlert System



Source: ShakeAlert, "ShakeAlert: An Earthquake Early Warning System for the West Coast of the United States," at https://www.shakealert.org/.

Notes: Once an earthquake starts (star labeled *epicenter* and *fault* on the figure), the ShakeAlert earthquake-sensing network (*sensors* on figure) detects the P-waves (yellow curve shows the P-wave radiating away from the epicenter and arrow indicates the general direction of the waves) at sensors closest to the epicenter. The sensors transmit these data to data processing centers (only one is shown on the figure, labeled *Earthquake alert center*). The centers process the data and, if the earthquake may be damaging, prepare alert messages with information about the earthquake's magnitude and location and what areas may receive intense shaking from the later-arriving, more damaging S-waves (red curve and arrow). Public and private communication pathways convert the alert messages into EEWs and send them to individuals and institutions in endangered areas. On the figure, the nearby city is in the path of the seismic waves; the goal is for everyone in the city to receive an EEW before the S-waves reach the city and cause intense shaking.

Institutions and communication providers use the ShakeAlert-generated messages to prompt protective actions, which reduce earthquake risks and costs (e.g., for repairs or loss of operations) by preventing damage to people and property (**Figure 6**).[48] Some institutions take automated actions based on ShakeAlert messages. These *automated actions* are performed without any human intervention; the ShakeAlert messages are hardwired into critical operations (i.e., through machine-to-machine communications) and prompt automatic protective actions based on the message details. Automated actions may include stopping or slowing trains, opening fire station doors, stopping elevators at a floor and opening elevator doors, preventing vehicles from entering bridges or tunnels, and other actions.[49]

In addition, communication providers use ShakeAlert-generated messages to reduce earthquake risks by transmitting EEWs (**Figure 6**). Emergency communication providers, such as FEMA communication pathways or cell phone EEW applications (apps), receive the ShakeAlert messages and send EEWs to individuals in high-risk areas. These EEWs include the recommended protective action: Drop, Cover, and Hold On (DCHO).[50] **Table 1** lists some other

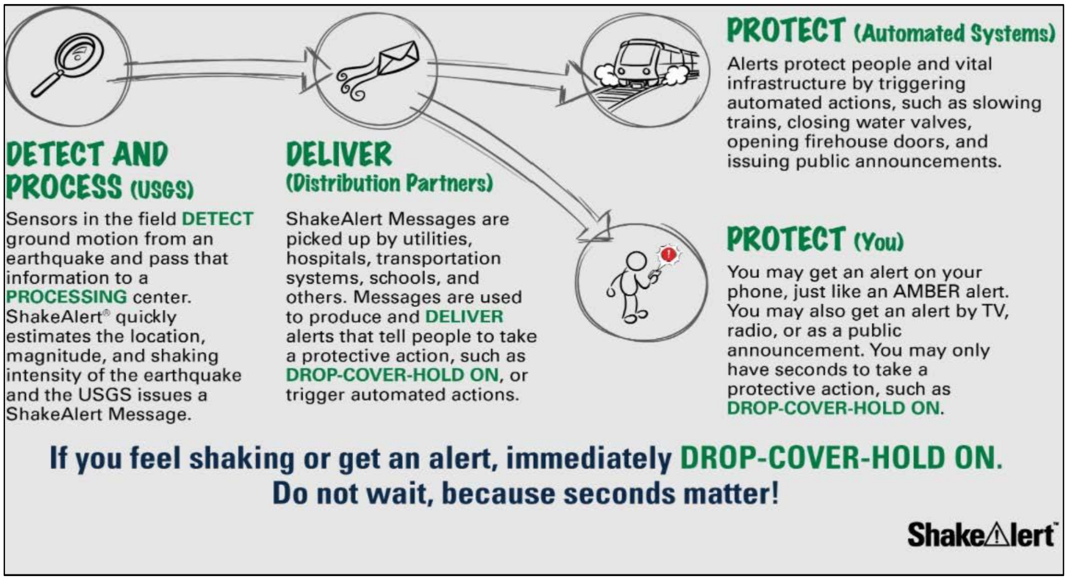
[48] Strauss, "Benefits," 2016.

[49] For example, automatically slowing or stopping a train is one of the most common protective actions to take for an EEW, because the potential to avoid a derailment outweighs the minimal delays caused by stopping a train. EEW systems continue to develop automated or semiautomated alerting for critical structural systems where the application is relatively simple and the cost-benefit calculations and risk-reduction potential are significant.

[50] Drop, Cover, and Hold On (DCHO) is the recommended protective action for an individual on the West Coast because (1) most injuries and fatalities are caused by falling on structures (e.g., stairs), tripping on damaged structures

examples of automated or individual protective actions that may be taken after receiving an EEW to reduce risks.

Figure 6. ShakeAlert System from Detection to Protection



Source: ShakeAlert, "Graphics Library," at https://www.shakealert.org/messaging_toolkit/graphics-library/.

Table 1. Examples of Protective Actions That May Be Taken After Receiving an Earthquake Early Warning

Sector	Sample Protective Action(s)
Construction	Placing cranes and lifts in safe positions and moving people away from hazardous construction sites.
Emergency Management	Alerting first-responders in the field to temporarily retreat to safe spaces, opening doors for emergency vehicles, and starting generators.
General	Alerting the public to prepare physically and psychologically for the impending shaking.
Industrial	Closing valves, slowing or stopping production lines and sensitive processes, and moving people away from hazardous industrial processes.
Medical	Halting dental operations, surgeries, laser procedures, and other medical procedures.
Office	Stopping elevators at the nearest floor and opening their doors, allowing people to move away from windows to interior/safer spaces.
Restaurants	Turning off heat sources and securing or avoiding areas with potentially dangerous equipment, such as deep fryers.

or fallen objects, and/or being hit by falling objects during intense shaking, and DCHO reduces these risks; (2) many structures are built to earthquake-resistant standards in high-risk regions on the West Coast, so the structures should not collapse, making DCHO more effective than evacuation; and (3) individuals are most likely to be inside a structure when an earthquake occurs (i.e., Americans spend most of their time indoors), so DCHO is the most likely situational reaction. Most injuries and fatalities from earthquake hazards occur when people are harmed by damaged structures and infrastructure lifelines. See McBride, "Protective Actions," 2022. For a list of actions to take before, during, and after an earthquake, including a description of DCHO, see FEMA, "Ready, Earthquakes," at https://www.ready.gov/earthquakes; and Occupational Safety and Health Administration, "Earthquakes Guide," at https://www.osha.gov/emergency-preparedness/guides/earthquakes.

Sector	Sample Protective Action(s)
Schools	Warning students and staff to take a protective action such as Drop, Cover, and Hold On.
Transportation	Slowing or stopping trains, stopping aircraft takeoffs and landings, closing vulnerable bridges, and slowing or stopping traffic by turning all traffic signals to red.
Utilities	Opening or closing critical valves in pipelines, shutting down systems, rerouting power supplies, and moving field personnel into safer positions (i.e., places not exposed to power lines or other hazardous conditions).
Vehicles	Instructing alerted drivers to turn on emergency flashers (to warn others) and to slow down.

Source: ShakeAlert, "FAQ," at https://www.shakealert.org/faq/. Modified by CRS.

The ShakeAlert system is a cooperative project led by the USGS, with many partners that are responsible for the system's research and development, operations and maintenance, and/or education and outreach (**Table 2**). These partners include state agencies, universities, and nonprofit organizations that operate NSF facilities. The USGS considers ShakeAlert to be part of the Advanced National Seismic System (ANSS) within the EHP.[51] The USGS prepared a revised implementation plan for ShakeAlert in 2018, which summarized the science, technology, and implementation of ShakeAlert and how the USGS aims to improve the EEW system.[52]

FEMA and NSF indirectly support aspects of ShakeAlert (i.e., Congress does not appropriate funds to these federal agencies specifically for ShakeAlert activities). FEMA provides communication pathways to deliver EEWs to the public and conducts earthquake risk assessments. In addition, Congress authorized FEMA to award hazard mitigation grants to improve ShakeAlert's earthquake-sensing network. Section 1233 of the Disaster Recovery Reform Act of 2018 (Division D of the Federal Aviation Administration Reauthorization Act of 2018, P.L. 115-254) authorized FEMA to provide hazard mitigation assistance through the Hazard Mitigation Grant Program and the Building Resilient Infrastructure and Communities Program for activities that reduce earthquake risk and build EEW capability.[53] FEMA may support improvements to seismic and geodetic networks that are part of ShakeAlert and the purchase and installation of seismometers, GNSS receivers, and associated infrastructure (e.g., telemetry and signal processing) that are part of the ShakeAlert system.[54]

NSF supports earthquake research and earthquake-sensing network operations and maintenance. It does so through research grants to universities and cooperative agreements with seismic or

[51] The Advanced National Seismic System (ANSS) supports basic and applied research to understand and define the structure of the Earth beneath the surface, including mapping faults and understanding earthquakes. ANSS activities contribute to the research and development of EEW. ANSS consists of a backbone network of almost 100 seismic stations distributed throughout the United States, the USGS National Earthquake Information Center, the National Strong Ground Motion network, and 15 regional seismic networks. See the USGS, "ANSS – Advanced National Seismic System," at https://www.usgs.gov/programs/earthquake-hazards/anss-advanced-national-seismic-system.

[52] USGS, *ShakeAlert Plan*, 2018.

[53] FEMA, "Hazard Mitigation Assistance Grants," at https://www.fema.gov/grants/mitigation; and FEMA, "Building Resilient Infrastructure and Communities," at https://www.fema.gov/grants/mitigation/building-resilient-infrastructure-communities.

[54] FEMA mitigation grants may not support any operations and maintenance activities for ShakeAlert. FEMA may support only improvements to ShakeAlert, because the authorization requires FEMA to support EEW capabilities that enable end-user notification. FEMA consulted with the USGS and determined that ShakeAlert is the only system that enables end-user notification. FEMA, "Disaster Recovery Reform Act and Earthquake Early Warning Systems," fact sheet, September 30, 2020, at https://www.fema.gov/sites/default/files/2020-09/fema_drra-earthquake-early-warning-systems_fact-sheet_September-2020.pdf.

geodetic facilities (e.g., the Seismological Facilities for the Advancement of Geoscience, operated by the Incorporated Research Institutions for Seismology; the Geodetic Facilities for the Advancement of Geoscience, operated by UNAVCO Inc.; and the Southern California Earthquake Center, operated by the University of Southern California).[55] The National Aeronautics and Space Administration (NASA) supports the use of geodetic tools for earthquake and tsunami research and for hazards warning and mitigation.[56]

Table 2. ShakeAlert Nonfederal Partners

Institutional Partners Involved in ShakeAlert Research and Development, Operations and Maintenance, and/or Education and Outreach
California Geological Survey (CGS)
California Governor's Office of Emergency Services (Cal OES)
California Institute of Technology (Caltech)
Central Washington University (CWU)
Incorporated Research Institutions for Seismology (IRIS)
Oregon Department of Geology and Mineral Industries (DOGAMI)
Oregon Military Department, Office of Emergency Management (OEM)
Southern California Earthquake Center (SCEC)
Swiss Seismological Service of ETH Zurich
UNAVCO Inc.
University of California, Berkeley (UCB)
University of California, San Diego
University of Nevada, Reno
University of Oregon (UO)
University of Washington (UW)
Washington Military Department, Emergency Management Division (WMD)
Washington State Department of Natural Resources

Sources: USGS, *ShakeAlert Plan*, 2018; USGS, "Earthquake Early Warning – Overview," at https://www.usgs.gov/programs/earthquake-hazards/science/earthquake-early-warning-overview#partners; and ShakeAlert, "ShakeAlert: An Earthquake Early Warning System for the West Coast of the United States," at https://www.shakealert.org/.

Notes: ETH Zurich stands for *Eidgenössische Technische Hochschule* Zürich in German (Swiss Federal Institute of Technology in Zürich, in English).

[55] IRIS, "Seismological Facility for the Advancement of Geoscience (SAGE)," at https://www.iris.edu/hq/sage; UNAVCO, "GAGE Facility," at https://www.unavco.org/what-we-do/gage-facility/; and Southern California Earthquake Center (SCEC), "About the Center," at https://www.scec.org/about.

[56] National Research Council, *Precise Geodetic Infrastructure: National Requirements for a Shared Resource* (Washington, DC: National Academies Press, 2010), at https://doi.org/10.17226/12954 (hereinafter NRC, *Precise Geodetic Infrastructure*, 2010); and NASA, Earth Science, Applied Sciences, "Supporting Earthquake Response and Recovery," at https://appliedsciences.nasa.gov/what-we-do/disasters/earthquakes.

Earthquake-Sensing Network

The ShakeAlert earthquake-sensing network consists of 1,309 seismic stations and about 1,100 geodetic stations in California, Oregon, and Washington (**Figure 7** and **Figure 8**) as of February 2022.[57] Most of these seismic and geodetic stations existed prior to ShakeAlert operations as part of regional networks for research, hazard assessment, natural resource management, and other purposes (**Table 3**). Some stations in these networks now serve an additional purpose: detecting the start of an earthquake to provide EEW. The USGS and ShakeAlert partners aim to add more seismic stations and upgrade more geodetic stations to improve earthquake detection on the West Coast.[58]

ShakeAlert uses diverse telemetry technology, including cellular modem, microwave, and radio, to transmit data from seismic or geodetic stations to data processing centers.[59] The telemetry technology depends on the station location and technology and on the available telemetry systems. In California and Oregon, some stations use their respective state microwave telemetry systems to transmit data. In California, the USGS connected the USGS microwave telemetry systems between Northern and Southern California. The California Governor's Office of Emergency Services (Cal OES) Public Safety Communications system and the University of California, Berkeley, ShakeAlert data processing center are connected with a dedicated telemetry system. The USGS and ShakeAlert partners aim to improve and optimize telemetry for the earthquake-sensing network to support robust and rapid data delivery from the seismic and geodetic stations to the data processing centers under all circumstances.[60] These stakeholders are investigating other telemetry options, including whether new technologies such as the First Responder Network Authority (FirstNet) or a satellite-based data transfer system operated by Starlink may improve telemetry. [61]

[57] Correspondence between CRS and USGS, April 18, 2022.

[58] The USGS aims to add 366 more seismic stations and upgrade 176 geodetic stations to provide adequate coverage and station density to detect earthquakes rapidly and accurately in California, Oregon, and Washington. *ShakeAlert Plan*, 2018; and correspondence between CRS and the USGS, April 18, 2022.

[59] USGS, *ShakeAlert Plan*, 2018.

[60] USGS, *ShakeAlert Plan*, 2018; and correspondence between CRS and the USGS, January 12, 2022.

[61] USGS, *ShakeAlert Plan*, 2018. FirstNet is an independent authority within the U.S. Department of Commerce, National Telecommunications and Information Administration, that provides a dedicated communications network for emergency responders and the public safety community. Chartered in 2012, FirstNet's mission is to ensure the building, deployment, and operation of the nationwide broadband network that equips first responders to save lives and protect U.S. communities. See FirstNet, "FirstNet Authority," at https://www.firstnet.gov/. See also CRS Report R45179, *The First Responder Network (FirstNet) and Next-Generation Communications for Public Safety: Issues for Congress*, by Jill C. Gallagher. Starlink is a commercial company that supports high data rate activities using low Earth orbit satellites. See Starlink, "Starlink," at https://www.starlink.com/.

Table 3. Regional Networks That Contribute to ShakeAlert

Network Name: Location	Partners	Funding Sources	Number of Stations Contributing to ShakeAlert
California Integrated Seismic Network: CA[a]	California Institute of Technology; University of California, Berkeley; California Geological Survey; Cal OES; and USGS	USGS and Cal OES	>832
Pacific Northwest Seismic Network: OR and WA[b]	University of Oregon, University of Washington, IRIS, UNAVCO Inc., and USGS	USGS, Department of Energy, State of Washington, and State of Oregon	>283
Network of the Americas (Geodetic): CA, OR, and WA[c]	UNAVCO Inc.	NSF, NASA, and USGS	>500
Pacific Northwest Geodetic Array: OR and WA[d]	Central Washington University	NSF, NASA, and USGS	>100
Bay Area Regional Deformation Network (Geodetic): Northern CA[e]	University of California, Berkeley; California Institute of Technology; University of Washington; Central Washington University; Lawrence Berkeley National Laboratory; and USGS	USGS	33
USGS Pasadena Office (Geodetic): Southern CA[f]	USGS	USGS	140
USGS Menlo Park Office (Geodetic): Northern CA[f]	USGS	USGS	8

Source: USGS, *ShakeAlert Plan*, 2018.

Notes: Cal OES = California Governor's Office of Emergency Services; IRIS = Incorporated Research Institutions for Seismology; NASA = National Aeronautics and Space Administration; NSF = National Science Foundation; USGS = U.S. Geological Survey.

a. California Integrated Seismic Network, "CISN," at https://www.cisn.org/,

b. Pacific Northwest Seismic Network, "PNSN," at https://pnsn.org/,

c. UNAVCO, "Network of the Americas," at https://www.unavco.org/projects/major-projects/nota/nota.html,

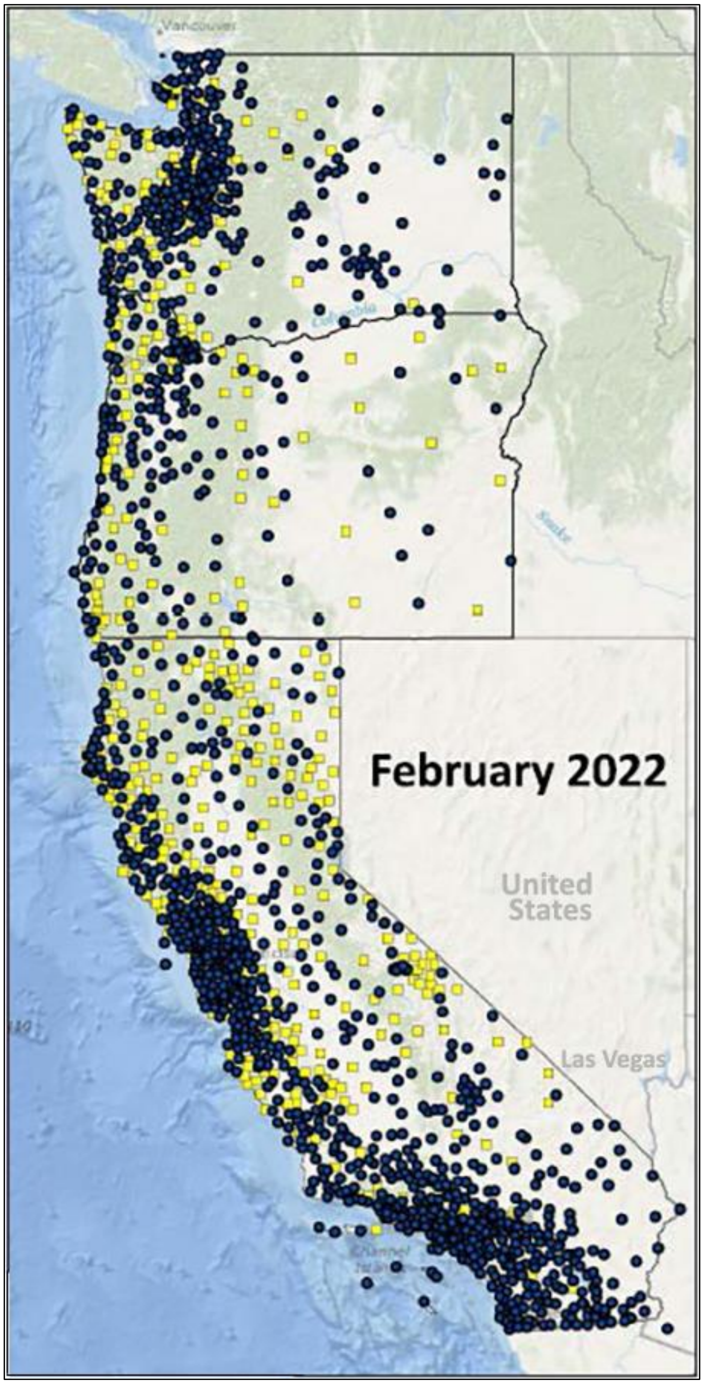
d. Central Washington University, "Pacific Northwest Geodetic Array," at https://www.geodesy.cwu.edu/

e. Berkeley Seismology Lab, "Bay Area Regional Deformation Network," at https://seismo.berkeley.edu/bard/

f. USGS, "USGS Real-Time Deformation Monitoring," at https://www.socalgeodetic.org/.

Figure 7. Seismic Stations Contributing to ShakeAlert as of February 2022

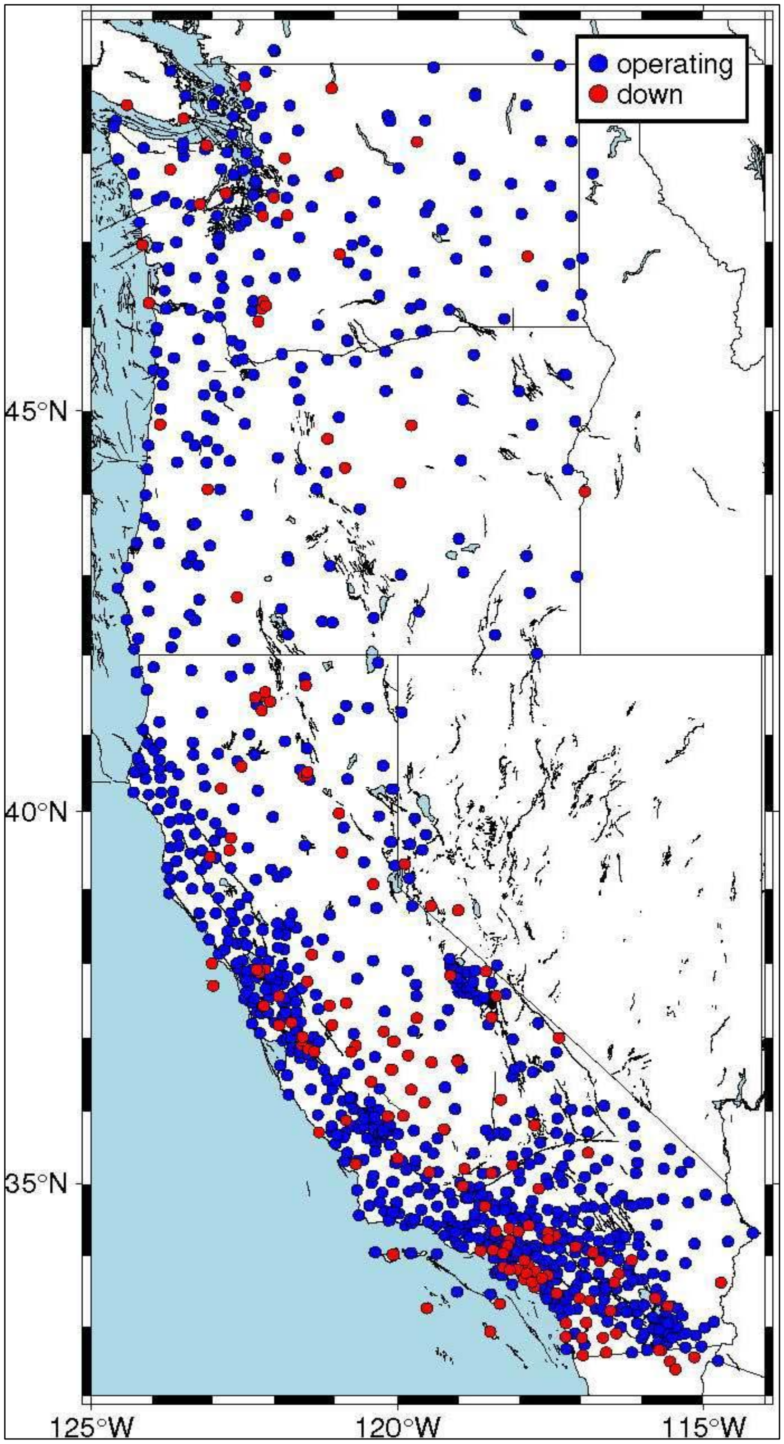
(established and planned seismic stations)



Source: USGS, April 18, 2022.

Notes: ShakeAlert's earthquake-sensing network consists of 1,309 seismic stations (blue dots). The USGS and ShakeAlert partners aim to add 366 seismic stations to the ShakeAlert network (yellow squares). These added stations will be either new stations or upgrades to existing stations in regional networks. The map is from the USGS. Correspondence between CRS and USGS on April 18, 2022.

Figure 8. Geodetic Stations Contributing to ShakeAlert as of February 2022



Source: USGS, April 18, 2022.

Notes: ShakeAlert's earthquake-sensing network includes about 1,100 geodetic stations. The red dots indicate geodetic stations that were not transmitting data when the figure was prepared in February 2022. The USGS and ShakeAlert partners aim to upgrade 176 geodetic stations (not shown on the figure) and add them to the earthquake-sensing network. Mapped faults are delineated by black lines, excluding the state boundaries. The map is from the USGS. Correspondence between CRS and USGS on April 18, 2022.

Data Processing, Analysis, and Alert Message Generation

The seismic and geodetic stations in the ShakeAlert network operate continuously and autonomously. Every second, the stations send real-time data to the data processing centers for analysis. The more stations that detect an earthquake starting at about the same time, the more accurate and rapid the earthquake estimate. ShakeAlert uses the seismic data to detect an earthquake, estimate its characteristics, and determine whether to develop and send alert messages. The USGS and ShakeAlert partners aim to integrate geodetic data into the data analysis system to provide a more effective EEW.[62] As of April 2022, the geodetic data was being transmitted to the testing and development platform at the data processing centers and was used for earthquake analysis on this testing platform.[63] ShakeAlert uses four processing centers to help provide redundancy and reliability. These centers are in Pasadena, CA (operated by the USGS and the California Institute of Technology); Menlo Park, CA (operated by the USGS); Berkeley, CA (operated by the USGS and the University of California, Berkeley); and Seattle, WA (operated by the USGS and the University of Washington). The Berkeley processing center does not deliver ShakeAlert messages to communication providers.[64]

ShakeAlert can generate three types of alert messages with earthquake information for communication providers: (1) location and magnitude; (2) location, magnitude, and a contour map of the area that may receive intense shaking; and (3) location, magnitude, and a gridded map of the area that may receive intense shaking. Providers may subscribe to the message type or types they want to use.[65]

Communication of Earthquake Early Warnings

Once communication providers receive the ShakeAlert-powered alert messages, the providers use various communication pathways (e.g., cell phones, public address systems, or machine-to-machine communications) to deliver EEWs to individuals and institutions. Generally, distributing ShakeAlert messages over different communication pathways increases the chance that people may receive and act on the alerts.[66] The Stafford Act required the USGS to ensure ShakeAlert-powered alert messages are encoded in such a way that they can be sent as EEWs through the

[62] USGS, *ShakeAlert Plan*, 2018, p. 7. The geodetic stations add more spatial coverage by adding more earthquake-sensing stations to the system. The geodetic data may help detect the largest magnitude (M7+) earthquakes on subduction zones more accurately and more rapidly than the seismic data alone. For example, Japan's EEW system underestimated the 2011 M9.1 Tohoku earthquake as an M8.0 partly because of a lack of seismic data near the event and because the system did not use the geodetic data (i.e., the underestimate was significant because an M8.0 is a far less energetic event then an M9.1; see **Appendix** for more information about magnitude and earthquake energy). A post-event analysis indicated that using the real-time geodetic data would have produced a more accurate and higher-magnitude event estimate, leading to a larger tsunami estimate and a larger area to warn. Allen and Melgar, "EEW Advances," 2019; and NRC, *Precise Geodetic Infrastructure*, 2010, p. 48.

[63] Based on research, development, and testing, the data analysis may be improved by adding the raw geodetic data and the Geodetic First Approximation of Size and Timing—Peak Ground Displacement algorithm into the operational data analysis system. See Jessica R. Murray et al., "Development of a Geodetic Component for the U.S. West Coast Earthquake Early Warning System," *Seismological Research Letters*, vol. 89, no. 6 (October 3, 2018), pp. 2322-2336, at https://doi.org/10.1785/0220180162.

[64] USGS, *ShakeAlert Plan*, 2018.

[65] USGS, *ShakeAlert Plan*, 2018, pp. 18-20.

[66] See National Academies of Sciences, Engineering, and Medicine, *Emergency Alert and Warning Systems: Current Knowledge and Future Research*, 2018, at https://doi.org/10.17226/24935.

FEMA Integrated Public Alert Warning System (IPAWS) and to make available ShakeAlert-powered messages to non-FEMA communication providers for distribution as EEWs.[67]

Rapid EEW is intended to provide individuals and institutions tens of seconds to minutes to prepare before intense shaking reaches their location, depending on their distance from the earthquake's epicenter (see **Table 1**).[68] ShakeAlert aims to deliver alert messages in about 4-20 seconds of the earthquake's origin time, depending on the earthquake's characteristics and the station density near the event.[69] The USGS requests that communication providers deliver EEWs to specific areas within seconds and aims for any delays in delivery to be less than five seconds.[70] Geotargeting (i.e., sending EEWs to specific areas) is intended to help reach only those affected by the event; increase confidence in EEWs; limit the strain on commercial communication systems, which may become overwhelmed or limited in the event of an emergency; reduce alerting fatigue; and improve response.[71] In addition, ShakeAlert sets minimum thresholds of magnitude and shaking intensity levels for sending an EEW to allow various communication pathways to limit the EEWs to potentially damaging earthquakes only (**Figure 9**).[72]

[67] For more details about the Integrated Public Alert Warning System, see FEMA, "Integrated Public Alert and Warning System," at https://www.fema.gov/emergency-managers/practitioners/integrated-public-alert-warning-system.

[68] Some individuals or institutions that are close to the earthquake's epicenter may receive no warning or preparation times of less than 10 seconds, which is not enough time to take action. Other individuals or institutions that are far from the earthquake's epicenter may receive one to two minutes of preparation time. For example, many of the most damaging earthquakes in Mexico start on the offshore subduction zone near the western coastline and are hundreds of miles away from large cities. When a subduction zone earthquake is detected on the west coast, Mexico City receives an EEW before the seismic waves travel hundreds of miles to the city, so that people in the city have one to two minutes to prepare for intense shaking to arrive. USGS, *Expected Warning Times*, 2021; Sarah E. Minson et al., "The Limits of Earthquake Early Warning: Timeliness of Ground Motion Estimates," *Science Advances*, vol. 4, no. 3 (2018), at https://doi.org/10.1126/sciadv.aaq0504 (hereinafter Minson, "Limits of EEW," 2018); and Gerardo Suarez et al., "A Dedicated Seismic Early Warning Network: The Mexican Seismic Alert System (SASMEX)," *Seismological Research Letters*, vol. 89, no. 2A (March/April 2018), pp. 382-391, at https://doi.org/10.1785/0220170184 (hereinafter SASMEX, 2018).

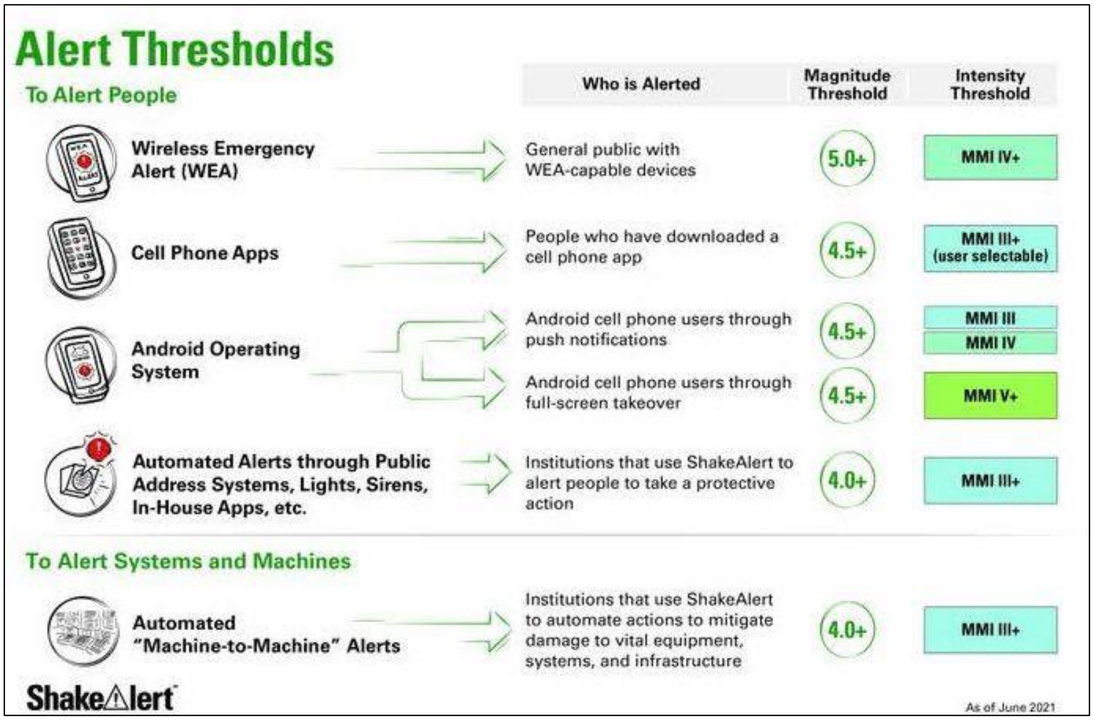
[69] USGS, *Expected Warning Times*, 2021, p. 3.

[70] ShakeAlert, "Become a ShakeAlert System Partner," at https://www.shakealert.org/implementation/partners/.

[71] USGS, *ShakeAlert Plan*, 2018.

[72] USGS, *ShakeAlert Plan*, 2018, pp. 20-21; and Minson, "Limits of EEW," 2018.

Figure 9. Alert Communication Pathways and Minimum Thresholds



Source: USGS, "Earthquake Early Warning Overview," at https://www.usgs.gov/programs/earthquake-hazards/science/earthquake-early-warning-overview.

Notes: ShakeAlert sets minimum magnitude and Modified Mercalli Intensity Scale (MMI; shaking intensity) levels for sending alerts from communication providers as EEWs to people or machines (magnitude threshold and shaking intensity threshold listed above in the right columns). If the earthquake is significant enough to meet these minimum thresholds and thus may cause damage, alerts can be sent as EEWs via five main communication pathways (listed in the left column). The wireless emergency alert (WEA) is a FEMA technology and the USGS sends EEW using this technology. See **Appendix** for more information about magnitude and the MMI shaking intensity levels.

ShakeAlert uses five different communication pathways to send alerts: four to alert people and one to alert systems and machines. The system sets minimum magnitude and shaking intensity (i.e., MMI) levels for sending alerts as EEWs, and the magnitude and MMI minimum thresholds differ for the five different communication pathways (**Figure 9**). ShakeAlert communicates EEWs to individuals via four pathways:

- FEMA Wireless Emergency Alert (WEA) technology to WEA-capable wireless devices
- Cell phone apps to cell phones
- Android operating system software to Android-based cell phones
- Institutional communication pathways (e.g., public address systems in a school or large office building) to individuals working or gathering in these places

ShakeAlert messages are communicated directly to systems and machines through a fifth pathway: established machine-to-machine communication systems. This automated communication allows institutions, such as public transit systems, to take automated protective actions (**Figure 9**).

The amount of time to communicate EEWs via the different communication pathways varies. The fastest machine-to-machine systems and cell phone apps via Wi-Fi or cellular networks communicate EEWs in as little as one second, whereas WEA technology communicates the alerts within several tens of seconds, if at all.[73] The amount of time to communicate EEWs through institutional communication pathways (e.g., public address announcements or institutional systems, such as email and cell phones in buildings) also varies. The fastest alerts are via institutional services connected to Wi-Fi networks (e.g., cell phones or public address systems on Wi-Fi), which can deliver EEWs in a few seconds in some cases.[74]

FEMA Communication Pathways

FEMA delivers public alerts about many hazards or other dangerous situations (e.g., Imminent Threat Alerts) to individuals in targeted locations through IPAWS (**Figure 10**); these alerts provide secure, authenticated emergency and lifesaving information sent by an authorized alerting authority (e.g., state police, local sheriff, National Weather Service, or the USGS).[75] Authorized alerting authorities, once approved by FEMA, purchase FEMA-approved software, which they use to send alerts that comply with FEMA standards (e.g., FEMA's Common Alerting Protocol and Federal Communications Commission [FCC] rules). FEMA must authenticate alerts, such as EEWs, before they are distributed, which could lengthen the delivery time. FEMA distributes the alerts through many communication pathways simultaneously to the area specified by the alerting authority.

Using WEA technology, cellular carriers send alerts over their cellular networks to cell phone users within the targeted area. Cellular carriers AT&T, T-Mobile, and Verizon voluntarily participate in FEMA's WEA program. One benefit of WEA technology is that people need not subscribe to the service; carriers send EEWs to all cell phones operating in the affected area. A challenge with the technology is that it is built into the device's hardware and is not accessible to cell phone app developers, which makes it difficult to upgrade or use with another app.

ShakeAlert is currently using only WEA technology to communicate EEWs among the many IPAWS communication pathways (**Figure 10**). The USGS prepares a FEMA-encoded and FCC-approved EEW that states "Earthquake Detected! Drop, Cover, Hold On. Protect Yourself. – USGS ShakeAlert." FEMA sends these USGS-prepared EEWs to specified locations via cellular networks to wireless devices, such as cell phones.

The USGS proposed some changes to cell phone communications that the FCC approved, including extending alert messages from 90 characters to 360 characters, allowing uniform resource locators (URLs) in messages, sending Spanish language messages, and geotargeting.[76] These new capabilities often require upgrades to all elements of the alerting system. In 2021, the FCC reported that most cell phones in use can receive WEA messages but some cannot (mainly older phones). Some of these WEA-capable phones can receive the longer 360-character

[73] EEWs distributed via WiFi or cellular networks commonly arrive in 1-10 seconds, but various apps are still testing the scaling to large numbers of users. WiFi technology uses radiofrequency waves to transmit information wirelessly. WiFi networks work only within a limited distance and require a modem connected to a wireless router or wireless gateway. Cellular networks use cellular signals to transmit information. Cellular networks work over larger distances where there are enough cellular towers to transmit the cellular signals from towers to devices. The WEA system can deliver EEWs as fast as 4 seconds based on recent tests, but many individuals receive the EEWs after more than 10 seconds or not at all. USGS, *ShakeAlert Plan*, 2018; and USGS, *Expected Warning Times*, 2021, p.3.

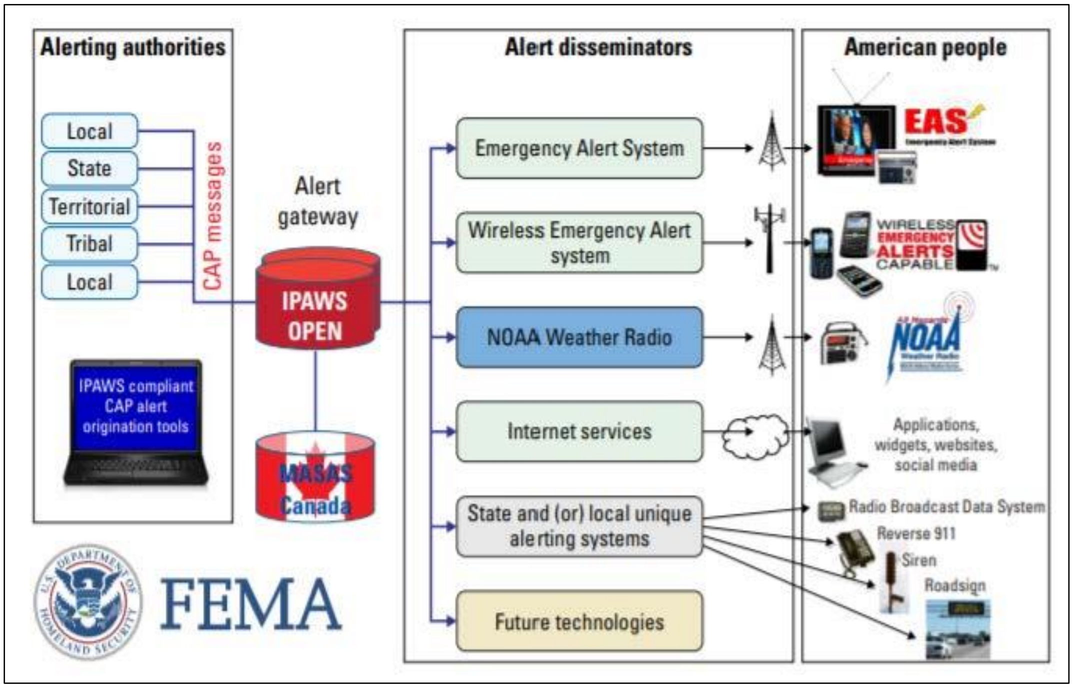
[74] USGS, *Expected Warning Times*, 2021, p. 3.

[75] See FEMA, "Wireless Emergency Alerts," at https://www.fema.gov/emergency-managers/practitioners/integrated-public-alert-warning-system/public/wireless-emergency-alerts. See FEMA's IPAWS website at https://www.fema.gov/emergency-managers/practitioners/integrated-public-alert-warning-system.

[76] USGS, *ShakeAlert Plan*, 2018.

messages and Spanish language messages; a subset of those cell phones can receive the enhanced geotargeted alerts.[77] Further, the FCC found that older WEA-capable alerts had a lower reception rate when FEMA issued a nationwide test alert.[78] Thus, more people may benefit from WEA alerts and EEWs when they upgrade to new, more advanced technologies. In addition, more precise geotargeting may conserve communication bandwidth in an emergency, when communication systems may be overwhelmed or damaged.[79]

Figure 10. FEMA Communication Pathways



Source: USGS, *ShakeAlert Plan*, 2018; and FEMA, "Integrated Public Alert and Warning System," at https://www.fema.gov/emergency-managers/practitioners/integrated-public-alert-warning-system.

Notes: The FEMA Integrated Public Alert and Warning System (IPAWS) OPEN gateway delivers alerts in two main directions. To the left, IPAWS delivers Common Alerting Protocol (CAP)-compliant messages to the authorities listed. To the right, IPAWS delivers alerts to the public via the communication pathways listed under alert disseminators. People receive these alerts on the devices listed in the far right column. Canada's Multi-Agency Situational Awareness System (MASAS) is interoperable with IPAWS and other communication pathways (see Canada's "Welcome to the MASAS Exchange," at https://www.canops.org/masas). Canada and the United States aim to cooperate on EEWs that impact both countries.

Other Communication Pathways

The USGS has agreements with institutions to deliver EEWs using the ShakeAlert messages. The USGS has License to Operate (LtO) partners that are licensed to use the ShakeAlert-powered

[77] The more advanced geotargeted alerts require providers that participate in the WEA program to send alerts to the targeted area with no more than a 0.1 mile overshoot. Federal Communications Commission, *Report: August 11, 2021, Nationwide WEA Test—Wireless Emergency Alerts*, December 2021, at https://www.fcc.gov/document/fcc-releases-report-nationwide-wea-test, p.5 (hereinafter FCC, *WEA Test*, 2021).

[78] FCC, *WEA Test*, 2021.

[79] USGS, *ShakeAlert Plan*, 2018, pp. 23-24.

alert messages, following rules and guidelines set by the USGS.[80] The partners can send EEWs only for earthquakes that meet or exceed the minimum magnitude and shaking intensity thresholds set by ShakeAlert (see **Figure 9**).[81] In addition, the partners must communicate the EEWs rapidly, preferably with delays of less than five seconds.[82] LtO partners use the ShakeAlert messages to create and distribute EEWs via cell phones, internet, radio, television, public address systems, machine-to-machine communication for critical operations, and other means (**Table 4**).[83] As of December 2021, ShakeAlert had 11 LtOs that provided products and services at more than 50 locations.[84] Approximately 20 other organizations are pursuing pilot projects that may result in LtOs.[85]

Table 4. ShakeAlert License to Operate Partners, as of 2021

License to Operate Partner	ShakeAlert-Powered Alerts Communication Services	Sector(s) of Operation
Early Warning Labs LLC	EEWs delivered to individual cell phones via the QuakeAlertUSA application (app) in California and Oregon. EEWs delivered with machine-to-machine automated systems via public address systems, automated opening of parking garages and firehouse doors, and other services.	Education, Emergency Management, Health Care, Mass Notification, Municipal and Residential Buildings, and Transportation
Everbridge	Situational awareness notification that an earthquake has occurred on the West Coast (not an EEW) sent to staff in Public Safety Answering Point facilities in California and Oregon.	Public Safety and Response
Global Security Systems/ALERT FM	EEWs encoded in commercial FM radio to purpose-built devices.	Mass Notification
Google	EEWs delivered to individual Android cell phones via the Android Earthquake Alerts app in California, Oregon, and Washington.	Mass Notification
MetroLink/Rail Pros – Los Angeles Metropolitan Area Transit	EEWs delivered with machine-to-machine automated systems via integration with positive train control systems.	Transportation
RH2 Engineering	EEWs delivered with machine-to-machine automated systems integrated with water and sewage system controls.	Utilities (water)

[80] ShakeAlert, "ShakeAlert License to Operate Partners," at https://www.shakealert.org/implementation/lto/.

[81] See **Appendix** for a description of the magnitude and shaking intensity scales used for EEW.

[82] ShakeAlert, "Become a ShakeAlert System Partner," at https://www.shakealert.org/implementation/partners/.

[83] ShakeAlert, "ShakeAlert License to Operate Partners," at https://www.shakealert.org/implementation/lto/.

[84] The major transportation companies that are License to Operate (LtO) partners using ShakeAlert are San Francisco Bay Area Rapid Transit (BART), with 411,000 average weekday passengers (pre-COVID); Los Angeles Metropolitan Transit Authority (LA Metro), with an average weekday ridership of 344,176; and the Southern California Regional Rail Authority (Metrolink), which averages about 40,000 boardings on a typical weekday. Correspondence between CRS and the USGS, January 12, 2022.

[85] Correspondence between CRS and the USGS, January 12, 2022.

San Francisco Bay Area Rapid Transit District (BART)	EEWs delivered with machine-to-machine automated systems integrated with positive train control systems.	Transportation
SkyAlert	EEWs delivered with machine-to-machine automated systems via public address systems and SkyAlert wireless devices for audio and visual EEWs.	Emergency Management
University of California, Berkeley/MyShake	EEWs delivered to individual cell phones via the MyShake app in California, Oregon, and Washington.	Mass Notification
Valcom	EEWs delivered with machine-to-machine automated systems integrated with public address systems.	Education
Varius, Inc.	EEWs delivered with machine-to-machine automatic response integrated with water and sewage system controls.	Utilities (water), Education

Sources: USGS, January 12, 2022; ShakeAlert.org; and USGS, *ShakeAlert Plan*, 2018. Modified by CRS.

At this point, cell phone apps connected to Wi-Fi or cellular networks are the most common and effective nonfederal communication pathways to warn individuals of the approach of intense ground shaking with enough time to take protective action. Three LtO partner organizations and one state agency have approved cell phone apps to send ShakeAlert-powered EEWs through four apps:

1. Google's Android Earthquake Alerts (based on the Android operating system), which sends ShakeAlert-powered EEWs to Android-based cell phones in California, Oregon, and Washington (about 15.6 million devices)[86]
2. MyShake, available in California, Oregon, and Washington and developed by the University of California, Berkeley (about 1.6 million downloads to devices)[87]
3. QuakeAlertUSA, available in California and Oregon, developed by Early Warning Labs (about 118,000 downloads to devices)[88]
4. ShakeReadySD, developed by San Diego County, which integrates the ShakeAlert-powered alert messages into the county's SD Emergency preparedness app (about 30,000 downloads to devices)[89]

[86] Google developed the Android Earthquake Alerts app, which works in two ways. In California, Oregon, and Washington, the app uses ShakeAlert messages to prepare and send EEWs to Android-based cell phones. Google is a ShakeAlert LtO partner and follows the guidelines set by the license agreement in those states. Beyond the ShakeAlert system, Google's app uses Android-based cell phone data to send EEWs in other countries. See Google's overview of Android Earthquake Alerts at Google, "Earthquake Detection and Early Alerts, Now on Your Android Phone," blog post, April 11, 2020, at https://blog.google/products/android/earthquake-detection-and-alerts/. For more information about how the app works, see *Business World*, "Google Launches Android Earthquake Alerts System," June 17, 2021, at https://www.bworldonline.com/technology/2021/06/17/376367/google-launches-android-earthquake-alerts-system/.

[87] See University of California, Berkeley, "MyShake," at https://myshake.berkeley.edu/.

[88] See Early Warning Labs, "Now Live in California and Oregon," at https://earlywarninglabs.com/mobile-app/.

[89] See ReadySanDiego, "SD Emergency App," at https://www.readysandiego.org/SDEmergencyApp/. The number of downloads for the different apps and the estimate of Android-based devices are from correspondence between CRS and the USGS, January 12, 2022.

Performance: Speed and Accuracy of Earthquake Detection and Alert Messaging

Between October 2019 and December 2021, ShakeAlert provided alert messages for 51 earthquakes.[90] Most of the earthquakes were in California, and all of them were below an M6.2 and caused only mild shaking. Accurate alerts were prepared within 5 seconds of the earthquake's origin time in the best-case scenarios and within 6-20 seconds in other scenarios.[91] ShakeAlert met its performance metrics of accurate and timely alert messages where the seismic station density of the network was sufficient (i.e., there was enough seismic data to rapidly and accurately estimate the earthquake characteristics and shaking intensity and to prepare alert messages).

The ShakeAlert system experienced some issues during the October 2019-December 2021 period. Of the 51 public alerts issued, 2 were false alerts with inaccurate magnitude and/or location. In addition, the system mislocated and underestimated a July 8, 2021, M6.2 earthquake about 39 miles southeast of South Lake Tahoe, resulting in confusion and under-alerting of the shaking intensity in the area impacted by the event (i.e., alerts were not sent to people who experienced ground shaking within the threshold of the EEW system).[92] The earthquake detection was inaccurate because the earthquake was near the edge of the network, where the seismic station density was sparse and inadequate. Further, during this period, ShakeAlert missed five earthquakes (located either in Mexico or offshore, where the earthquake-sensing network was not adequate to detect the event) and sent one false alert for a non-earthquake event.[93]

Communication Pathways Performance: Delivery of Earthquake Early Warnings

ShakeAlert messages for the 51 earthquakes detected between October 2019 and December 2021 were delivered as EEWs to individuals and institutions via multiple communication pathways (**Figure 9**). Machine-to-machine communication pathways, many of which are hardwired to ShakeAlert, and other pathways that use Wi-Fi or cellular networks (including many cell phone apps) generally delivered the alert messages within a few seconds. In general, these communication pathways met the USGS's objective of getting EEWs to individuals and institutions so they had enough time to take protective actions before the intense shaking arrived at their locations.

The USGS issued 11 EEWs via FEMA WEA technology for M5.0+ events between October 2019 and December 2021 (i.e., 11 of the 51 ShakeAlert-detected earthquakes were of M5.0 or larger). Eight of these WEA warnings were sent without delay, and three warnings were not sent due to

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[90] ShakeAlert, "Post ShakeAlert Message Summaries," at https://www.shakealert.org/education-outreach/event-review-files/.

[91] The best-case scenarios occur when there are enough seismic stations that detect the P-waves from an earthquake and can rapidly and accurately estimate the earthquake characteristics. In other scenarios, where fewer seismic stations detect an event, there may be delays in estimating the earthquake characteristics until the P-waves reach other seismic stations that are further away. USGS, *ShakeAlert Plan*, 2018, p. 22; and USGS, *Expected Warning Times,* 2021, p. 3.

[92] Correspondence between CRS and the USGS, January 12, 2022; and ShakeAlert, "Post ShakeAlert Message Summaries," at https://www.shakealert.org/education-outreach/event-review-files/.

[93] Correspondence between CRS and the USGS, January 12, 2022.

problems with the software or interaction with the IPAWS gateway.[94] The USGS and ShakeAlert partners are working with FEMA and the FCC to improve the delivery speed of EEWs.[95]

Experts have generally found that each alerting system (e.g., alerts via television, radio, cell phones, or machine-to-machine communication) has benefits and challenges.[96] EEW apps, for example, deliver EEW alerts faster than other communication pathways; these apps typically deliver EEWs to cell phones within a few seconds of receiving a ShakeAlert message.[97] A downside of these EEW apps is that three of the four require users to download the app to their cell phones (the Google app is built in and does not require owners of Android-based devices to download an app). If users do not download the app, they cannot receive the EEW. Conversely, WEA alerts sent from IPAWS to cell phones reach all operational cell phones in the targeted area; people do not need to opt in or download an app to receive the alert. Further, Wi-Fi or cellular networks must be operational for people to receive EEWs on their cell phones. If an earthquake damages or destroys Wi-Fi or cellular networks, people may not be able to get EEWs on their cell phones. Experts generally assert that multiple communication pathways should be used in case one pathway is damaged or destroyed.[98]

LtOs that provide EEWs through institutional communication pathways have found EEW cell phone apps are the fastest way to warn personnel using electronic devices.[99] Mass notification systems at institutions that use emails, text messages, or reverse 911 for EEWs may not deliver the warning in time for people to take protective action. Communication pathways such as public address systems or sirens in buildings are generally fast enough (i.e., the EEW is delivered within a few seconds) if the systems are connected to Wi-Fi or cellular networks. So far, testing and development by the USGS, ShakeAlert partners, and some LtOs show that EEW communication via television, radio, computer, or social media is too slow to be effective. Work is ongoing to speed up delivery via these other communication pathways.[100]

Public Reaction to Earthquake Early Warnings

EEWs may reduce risks only if the public receives the warnings, believes the warnings, and takes immediate protective actions. Past and ongoing surveys study how much of the public knows about ShakeAlert and how much of the public favors having an EEW system. One 2016 poll in California found that 88% of the sampled population supported building a statewide EEW system in California and 75% were willing to pay an additional tax to fund it.[101] A survey conducted in February 2021 indicated that about 25% of the population of California and less than 12% of the population in Washington and Oregon knew about ShakeAlert.[102] The number of cell phone app

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[94] Ibid.

[95] USGS, *ShakeAlert Plan*, 2018; USGS, *Expected Warning Times*, 2021, p.3 and FEMA National Advisory Council, *Modernizing the Nation's Public Alert and Warning System*, February 15, 2019, at https://www.hsdl.org/?view&did=826793.

[96] FEMA National Advisory Council, *Modernizing the Nation's Public Alert and Warning System*, February 15, 2019, at https://www.hsdl.org/?view&did=826793, p. 7.

[97] USGS, *ShakeAlert Plan*, 2018; and USGS, *Expected Warning Times*, 2021, p. 3.

[98] FEMA National Advisory Council, *Modernizing the Nation's Public Alert and Warning System*, February 15, 2019, at https://www.hsdl.org/?view&did=826793, p. 7.

[99] USGS, *ShakeAlert Plan*, 2018.

[100] USGS, *ShakeAlert Plan*, 2018; and correspondence between CRS and the USGS, January 12, 2022.

[101] Allen and Melgar, "EEW Advances," 2019, p. 364.

[102] Correspondence between CRS and the USGS, January 12, 2022.

downloads, excluding the Android-based app that does not require a download, is less than 2 million. This total may be lower than expected given that the Android-based app is working on about 15.6 million Android-based devices on the West Coast, and Android-based devices make up only about half of the cell phones used on the West Coast.[103] Given that most surveyed Californians in 2016 favored an EEW system, the percentage of people who know about ShakeAlert and have downloaded a ShakeAlert app may be lower than expected.

In addition to studying public knowledge and interest in receiving EEWs from ShakeAlert, the USGS and ShakeAlert partners seek to study how people react to EEWs and whether they find the EEWs valuable. According to previous work in other countries and ongoing ShakeAlert surveys, individuals do not always immediately DCHO. This may occur because individuals pause, wait for confirmation of the event or for other people to react, try to help others first, and for other reasons.[104] The 2021 ShakeAlert survey preliminary results regarding the public's reaction are consistent with the public reaction to EEW systems in other countries, such as Japan and New Zealand.[105] Most respondents (about 70%) to the ShakeAlert survey who have received a warning from ShakeAlert were tolerant of potential flaws in the system, were optimistic about reducing their risk if they received a timely EEW, and saw value in ShakeAlert.[106] Past surveys and current work suggest the public supports an EEW system and the public wants to receive an EEW if they are in harm's way.

ShakeAlert Administration

Responsibility and Governance

The USGS leads the ShakeAlert cooperative project. State, academic, and nonprofit organization partners (**Table 2**) cooperate and coordinate with the USGS on ShakeAlert activities. The USGS considers ShakeAlert activities to be part of ANSS, which is overseen by the USGS EHP.[107] The USGS and ShakeAlert partners coordinate with FEMA and NSF on components of the system and to fulfill related NEHRP responsibilities.[108] The USGS and ShakeAlert partners also coordinate with the National Oceanic and Atmospheric Administration (NOAA) and NASA, because these agencies support research and development that contributes to advancing EEW capabilities.[109]

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[103] Correspondence between CRS and the USGS, January 12, 2022 and Statista, "Subscriber share held by smartphone operating systems in the United States from 2012 to 2022," at https://www.statista.com/statistics/266572/market-share-held-by-smartphone-platforms-in-the-united-states/. According to the website, Apple iOS-based cell phones account for about half of the cell phones used in the United States.

[104] McBride, "Protective Actions," 2022.

[105] Julia S. Becker et al., "Earthquake Early Warning in Aotearoa New Zealand: A Survey of Public Perspectives to Guide Warning System Development," *Humanities and Social Sciences Communications*, vol. 7, no. 138 (2020), at https://doi.org/10.1057/s41599-020-00613-9; and Kazuya Nakayachi et al., "Residents' Reaction to Earthquake Early Warnings in Japan," *Risk Analysis*, vol. 39, no. 8 (2019), pp. 1723-1740, at https://doi.org/10.1111/risa.13306.

[106] Correspondence between CRS and the USGS, January 12, 2022.

[107] USGS, *ShakeAlert Plan*, 2018; and correspondence between CRS and the USGS, January 12, 2022. For more information about ANSS, see footnote 51.

[108] See CRS Report R43141, *The National Earthquake Hazards Reduction Program (NEHRP): Issues in Brief*, by Linda R. Rowan.

[109] NOAA issues tsunami warnings, conducts tsunami research, and conducts geodetic surveys, and these programs help advance EEW capabilities. NOAA's National Weather Service Tsunami Warning Centers (see NOAA/NWS, "U.S. Tsunami Warning System," at https://www.tsunami.gov/) coordinate with ShakeAlert and other EEW

The State of California considers ShakeAlert to be its statewide EEW system, led by the Cal OES in collaboration with the USGS and other ShakeAlert partners. The State of California authorized Cal OES in collaboration with the USGS, California Institute of Technology, University of California, California Geological Survey, Alfred E. Alquist Seismic Safety Commission, and other stakeholders to develop a comprehensive statewide EEW system through a public-private partnership in 2013. The partnership was not authorized to receive appropriations from the California General Fund but sought funding for the development of the statewide system from other sources.[110] The state enacted legislation in 2016 that established the California Safety Fund in the state treasury and allowed appropriations from the General Fund for seismic safety and earthquake-related programs, including the statewide EEW system. In addition, the 2016 legislation established the California Earthquake Early Warning Program within Cal OES and the California Earthquake Early Warning Advisory Board to advise the director of Cal OES.[111]

The Oregon Military Department, Office of Emergency Management, coordinates a statewide public awareness and participation campaign of ShakeAlert in Oregon with the USGS, ShakeAlert partners, and ShakeAlert LtOs.[112] In Washington, the Washington Military Department, Emergency Management Division, coordinates a statewide public awareness and participation campaign of ShakeAlert with the USGS, ShakeAlert partners, and ShakeAlert LtOs.[113]

The USGS is coordinating with Canada's Natural Resources Canada to extend components of ShakeAlert into western Canada and to coordinate cross-border alerts. In addition, the USGS

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development to advance their earthquake detection and tsunami warning decisionmaking when an earthquake triggers a potentially damaging tsunami. (See Tsunami Science and Technology Advisory Panel, *Report and Recommendations Concerning Tsunami Science and Technology Issues for the United States*, NOAA, December 8, 2021, at https://sab.noaa.gov/wp-content/uploads/2022/01/TSTAP-Report_Oct2021_Final_withCoverandLetter.pdf.) NOAA's National Center for Tsunami Research (see NOAA, "National Center for Tsunami Research," at https://nctr.pmel.noaa.gov/index.html) focuses on understanding tsunamis. Because many tsunamis are initiated by earthquakes, some of NOAA's research focuses on understanding earthquakes, earthquake hazards, and earthquake risks. NOAA conducts earthquake research in marine environments (see NOAA, Pacific Marine Environmental Library, "Marine Ecosystem Research," at https://www.pmel.noaa.gov/pmel-theme/marine-ecosystem-research), and NOAA coordinates with the USGS, other federal agencies, and states and local entities for some marine research activities. NOAA's National Geodetic Survey (see NOAA, "National Geodetic Survey," at https://geodesy.noaa.gov/) provides geodetic data, technology, and development that may improve EEW capabilities.

The National Aeronautics and Space Administration's (NASA's) Earth Sciences Division supports earthquake research and development that contribute to EEW capabilities, primarily based on Earth-observing satellite systems (see NASA, "Supporting Earthquake Response and Recovery," at https://appliedsciences.nasa.gov/what-we-do/disasters/earthquakes). NASA's Space Geodesy Program (see NASA, "SGP: Space Geodesy Program," at https://space-geodesy.nasa.gov/about/projOverview.html) operates, maintains, and enhances the Space Geodesy Network and the Global GNSS Network for the definition of the International Terrestrial Reference Frame, measurement of the Earth orientation parameters, and satellite precision orbit determination. The program contributes to the research and development of the geodetic component of ShakeAlert. See also NRC, *Precise Geodetic Infrastructure*, 2010, pp. 48-50.

[110] Earthquake Early Warning System, Senate Bill No. 135 (SB-135, Chapter 342, Statutes of 2013), California Government Code Section 8587.8, at https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201320140SB135

[111] *Earthquake Safety: Statewide Earthquake Early Warning Program and System*, Senate Bill No. 438 (Chapter 803, Statutes of 2016), California Government Code Section 8587.8, 8587.11, and 8587.12, at https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160SB438

[112] Oregon Military Department, Office of Emergency Management, "ShakeAlert in Oregon," at https://www.oregon.gov/oem/hazardsprep/pages/orshakealert.aspx.

[113] Washington Military Department, Emergency Management, "Alert and Warning Notifications, ShakeAlert Earthquake Early Warning", at https://mil.wa.gov/alerts.

aims to collaborate with Mexico's National Center for Prevention of Disasters and the Ensenada Center for Scientific Research and Higher Education in Baja California to coordinate on alerts that may impact Southern California and Baja California, Mexico.

Funding Trends and Estimated Future Costs for ShakeAlert

Congress appropriated funds totaling $162 million between FY2006 and FY2022 to the USGS for EEW capabilities. In addition, the USGS has cooperative agreements and distributes some of its appropriated funds to ShakeAlert partners (see **Table 2**) for research and development, operations and maintenance, and education and outreach components of ShakeAlert. Nonfederal sources of funding, mostly from California state and local agencies, contributed another $84 million for ShakeAlert between 2012 and 2021.

USGS ShakeAlert Funding

Table 5 shows enacted appropriations for EEW within the USGS EHP from FY2006 to FY2022.[114] Congress provided total appropriations of $7.5 million for EEW research, development, testing, and demonstration from FY2006 to FY2014. In addition, Congress provided the USGS with appropriations for operations, maintenance, construction, and repair of critical USGS facilities in the American Recovery and Reinvestment Act (ARRA; P.L. 111-5), and EHP spent $4.4 million of ARRA funds to build EEW-related systems from 2009 to 2011. In FY2015, Congress appropriated $5 million for capital costs to begin to transition the EEW demonstration prototype into an EEW operational capability. In report language accompanying the FY2022 Consolidated Appropriations Act (P.L. 117-103), Congress recommended $28.6 million for ShakeAlert and an additional $1.0 million in congressionally directed spending for the USGS and the State of Alaska to develop a plan to implement ShakeAlert in Alaska.[115]

Table 5. USGS Enacted Appropriations for EEW Activities and ShakeAlert

(amounts in millions of dollars, not adjusted for inflation)

Fiscal Year(s)	Base Funding	Capital Funding
2006-2014	7.5	4.4[a]
2015	1.5	5.0
2016	8.2	—
2017	10.2	—
2018	12.9	10.0
2019	16.1	5.0
2020	19.0	6.7
2021	25.7	—
2022	29.6[b]	
Total	**130.7**	**31.1**

Sources: CRS, with data from USGS, *ShakeAlert Plan,* 2018 and the USGS, January 12, 2022.

[114] USGS, *ShakeAlert Plan*, 2018.

[115] "Joint Explanatory Statement, Division G – Department of the Interior, Environment, and Related Agencies Appropriations Act, 2022," p. H2483 - H2484, accompanying P.L. 117-103, at https://www.congress.gov/117/crec/2022/03/09/168/42/CREC-2022-03-09-bk4.pdf.

Notes: Congress appropriated funds to the USGS Earthquake Hazards Program for EEW capabilities and/or ShakeAlert through regular appropriations, except where noted. *Base funding* covers research and development and operations and maintenance for EEW activities and ShakeAlert. *Capital funding* covers the costs of new equipment and new infrastructure and the costs for installing new stations or upgrading existing stations.

a. Congress appropriated $140 million to the USGS for operations, maintenance, construction, and repair of facilities and systems in the American Recovery and Reinvestment Act (P.L. 111-5), and the USGS spent $4.4 million of that total on new equipment and infrastructure for seismic networks that contribute to EEW capabilities between 2009 and 2011.

b. This base funding includes $1.0 million in congressionally directed spending for the USGS and the State of Alaska to develop a plan to implement ShakeAlert in Alaska.

Other ShakeAlert Funding

No available estimates show the amount of enacted appropriations that federal agencies other than the USGS spent on earthquake-related activities that directly or indirectly support EEW. NSF, through research grants and cooperative agreements, supports research facilitating the development of EEW capabilities and ShakeAlert components; however, these grants and agreements also serve other purposes, and it is difficult to estimate what fraction of these funds supported research that advanced EEW capabilities and ShakeAlert.[116] In addition, FEMA and the FCC are working with the USGS and ShakeAlert partners to improve communication pathways for EEWs.

From 2012 to 2021, ShakeAlert also received other funds (i.e., funds not directly from the federal government) totaling $84 million from states, cities, and a foundation (**Table 6**). These funds supported the development of ShakeAlert system components, education and outreach, and other activities. The largest contributor is Cal OES, which has provided $58.6 million for ShakeAlert. Cal OES funds (1) the installation and upgrading of seismic and geodetic stations in California, (2) improvements in and integration of telemetry for ShakeAlert raw data in the state, (3) a comprehensive public awareness and participation campaign, (4) research and development of various communication pathways (e.g., radio and television) for rapid EEW, and (5) administration and management of the Earthquake Early Warning Program in California. Cal OES estimates supporting these aspects of ShakeAlert in California may cost $17.3 million per year.[117] In addition to Cal OES, the Los Angeles/Long Beach Urban Area Security Initiative provided $5.6 million, mostly for new seismic stations, from funds granted to the initiative by FEMA.[118]

Oregon spent $8.5 million from 2015 to 2020 for ShakeAlert components. The State of Oregon appropriated funds for 15 new seismic stations, the Oregon Department of Geology and Mineral Industries funded 27 new stations, and the Eugene Water and Electric Board purchased equipment for two stations.[119]

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[116] Although NSF is not officially a ShakeAlert partner, it contributes funding that supports research and infrastructure that advances aspects of ShakeAlert. It does so through research grants and cooperative agreements to universities, IRIS, SCEC, and UNAVCO. The USGS expects NSF to continue supporting operations and maintenance for some networks. USGS, *ShakeAlert Plan,* 2018.

[117] Cal OES, *California Earthquake Early Warning Business Plan Update*, 2021, p. 12, at https://www.caloes.ca.gov/EarthquakeTsunamiVolcanoProgramsSite/Documents/CEEWS%20Business%20Plan%20Update%20Final.pdf.

[118] USGS, *ShakeAlert Plan,* 2018, p. 41.

[119] USGS, *ShakeAlert Plan,* 2018.

Table 6. Nonfederal Funding for the ShakeAlert System

(amounts in millions of dollars, not adjusted for inflation)

Time Frame	Source	Amount
2012-2015	Gordon and Betty Moore Foundation	6.5
2014-2016	LA/LB UASI	5.6
2016-2018	Gordon and Betty Moore Foundation	3.6
2016-2021	Cal OES	58.6
2015-2020	Oregon	8.5
2019	Washington	1.2
2012-2021	All Sources	84.0

Sources: CRS, with data from USGS, *ShakeAlert Plan,* 2018; the USGS, January 12, 2022; and Cal OES, *California Earthquake Early Warning Business Plan Update*, 2021, at https://www.caloes.ca.gov/EarthquakeTsunamiVolcanoProgramsSite/Documents/CEEWS%20Business%20Plan%20Update%20Final.pdf.

Notes: Cal OES = California Governor's Office of Emergency Services; LA/LB UASI = Los Angeles/Long Beach Urban Area Security Initiative, which provided funds from the Federal Emergency Management Agency.

2018 Estimate of Costs to Complete ShakeAlert

In 2018, the USGS estimated capital costs to complete ShakeAlert (excluding telemetry) in California, Oregon, and Washington would be $39.3 million (**Table 7**). This estimate included building or upgrading 560 seismic stations for a total seismic network of 1,675 stations; upgrading 475 geodetic stations; and building or upgrading other network infrastructure.[120] The typical cost to install a new seismic station is $52,600-$64,600, and the typical cost to upgrade a geodetic station is $27,300-$54,700.[121] The USGS-estimated annual operations and maintenance budget for ShakeAlert was $28.6 million, without the cost for operations and maintenance of telemetry.[122] In 2018, the USGS estimated the additional cost to build out a telemetry system for ShakeAlert would be $20.5 million and the annual cost for operations and maintenance of the newly built-out telemetry system would be $9.8 million.[123] ShakeAlert partners may cover some of the costs for telemetry, and costs may have changed since 2018. The USGS and ShakeAlert partners have not yet received the capital funding needed to complete ShakeAlert.

[120] Since 2018, 194 new/upgraded seismic stations have been installed and 299 geodetic stations have been upgraded (the costs of these upgrades are shared with other ShakeAlert partners), so the current capital costs are less than $39.4 million. Correspondence between CRS and the USGS, January 12, 2022.

[121] USGS, *ShakeAlert Plan*, 2018, pp. 30-31.

[122] Ibid.

[123] An update to the estimated costs for telemetry was not available as of January 2022. The estimated costs for operations and maintenance may cover any additional upgrades or repairs for the completed ShakeAlert telemetry system going forward.

Table 7. USGS 2018 Estimate of ShakeAlert Costs

(amounts in millions of 2018 dollars)

Component	One-Time Capital Costs	Annual Operations and Maintenance Costs
Seismic Stations	31.2[a]	17.1
Geodetic Stations	6.2[b]	3.5
USGS ShakeAlert Office	1.9	3.0
Research and Development	—	3.2
Communication, Education, and Outreach	—	1.8
Telemetry	20.5[c]	9.8[d]
Total	**59.8**	**38.4**

Source: CRS, with data from USGS, *ShakeAlert Plan,* 2018.

Notes: Figures do not reflect investments made since 2018. Some of the estimated costs listed in this table may be covered by ShakeAlert partners and other federal agencies, such as NSF and FEMA. For example, the USGS assumes NSF will continue to fund the operations and maintenance of the Network of the Americas under a cooperative agreement with UNAVCO and that FEMA hazard mitigation grants may cover the costs of new or upgraded seismic or geodetic stations. See USGS, *ShakeAlert Plan*, 2018, pp. 30-32.

a. CRS calculated that the 194 new seismic stations installed since 2018 at an estimated $52,600 per station may reduce this estimated cost by $10.2 million. Furthermore, this estimated cost may change, because only 366 new stations are needed as of April 2022 and because ShakeAlert partners or FEMA may cover the costs of some new stations.

b. The remaining one-time capital cost for upgrades may be different than the 2018 estimate shown because 299 geodetic stations have been upgraded (some of the costs of these upgrades were covered by other ShakeAlert partners). Only 176 geodetic stations needed upgrades as of April 2022.

c. The one-time capital costs to complete the telemetry needed for the ShakeAlert system on the West Coast is an estimate of the USGS costs. The cost may change if ShakeAlert partners, FEMA, and/or NSF cover some of the costs of telemetry upgrades. See USGS *ShakeAlert Plan*, 2018, p. 42, for full details of this cost estimate.

d. The annual operations and maintenance cost is for the new telemetry only (i.e., the $20.5 million of new telemetry costs estimated in the previous column).

Comparison of ShakeAlert with Other Earthquake Early Warning Systems

Comparing ShakeAlert with other EEW systems may help stakeholders improve the ShakeAlert system, consider alternative components or technology, and coordinate and cooperate on advancing EEW throughout the world (**Figure 11**). Two types of EEW system are used today. One type uses an earthquake-sensing network consisting of seismic and/or geodetic stations spatially distributed around active faults for optimal earthquake detection. These networks can generally rapidly and accurately detect P-waves and provide effective EEWs. The second type uses a fixed or crowd-sourced cell phone network to detect accelerations caused by earthquakes.[124] Cell phones have miniature accelerometers and Global Navigation Satellite

[124] Most cell phone-based networks cannot detect the first arriving P-waves, but rely on detecting the stronger and later arriving S-waves. This means that the EEW is delayed and that the cell phones used to detect the S-waves provide no

System (GNSS) receivers that are not as accurate or sensitive as seismic or geodetic instruments, respectively, but cell phones can function as approximate earthquake detectors. In addition, cell phones provide a communication pathway and may send EEWs to other cell phones using apps via Wi-Fi or cellular networks.

The USGS and ShakeAlert partners may consider how EEW systems in other countries are working and how countries might share earthquake understanding, risk reduction, and any techniques to better detect and mitigate earthquake hazards. China, India, Italy, Japan, Mexico, Romania, South Korea, Taiwan, and Turkey have regional to nationwide public-alerting EEW systems that use standard earthquake-sensing networks. Austria, Chile, Costa Rica, El Salvador, Greece, Iceland, Italy, Israel, New Zealand, Nicaragua, Slovenia, Spain, and Switzerland are testing similar EEW systems.[125] Canada aims to begin testing ShakeAlert as soon as components are established and operating.[126]

A comparison of ShakeAlert with standard earthquake-sensing networks used in other countries may help reveal the optimal location, deployment, station technology, telemetry technology, and data analysis techniques for earthquake detection and the most effective communication pathways for EEWs. Mexico City established the first public EEW system in 1991.[127] Today, Mexico's earthquake-sensing network uses fewer than 100 seismic stations to cover an area comparable to the area of California, Oregon, and Washington combined. Mexico's system provides EEWs to Mexico City and a few other cities primarily via tens of thousands of radios and thousands of sirens installed throughout urban areas. In contrast, Japan's EEW system, established in 2006, uses more than 4,000 seismic stations and more than 1,000 geodetic stations on land and on the seafloor, covering an area comparable to the area of California. Japan provides EEWs nationwide through multiple communication pathways including television, radio, and cell phones. In general, ShakeAlert is larger and more sophisticated than Mexico's system and smaller and less sophisticated than Japan's system.

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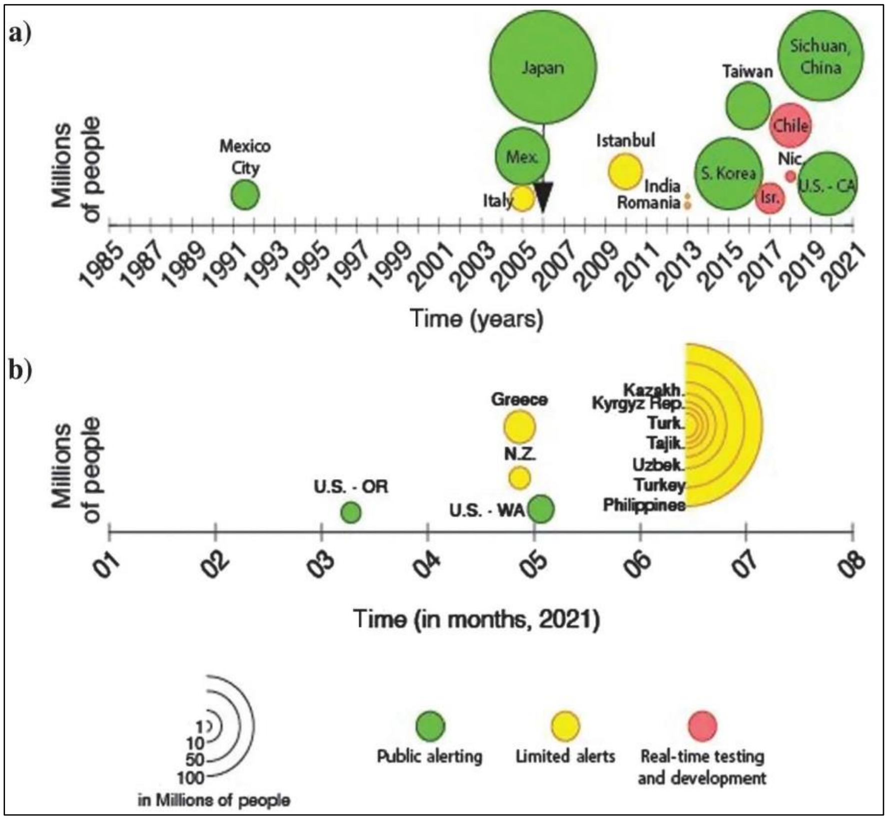
warning to their owners in advance of intense ground shaking. Benjamin A. Brooks et al., "Robust earthquake early warning at a fraction of the cost: ASTUTI Costa Rica," *AGU Advances*, vol. 2 (May 2021), e2021AV000407, pp. 1-17, https://doi. org/10.1029/2021AV000407.

[125] Gemma Cremen and Carmine Galasso, "Earthquake Early Warning: Recent Advances and Perspectives," *Earth Science Reviews*, vol. 205 (June 2020), pp. 1-15, at https://doi.org/10.1016/j.earscirev.2020.103184.

[126] Canada is developing an EEW system at the federal level through Natural Resources Canada. Canada faces earthquake risks on the west coast because of the Cascadia Subduction Zone (CSZ), which also affects the United States. Canada is working with ShakeAlert to extend the ShakeAlert system into Canada and to cooperate on earthquake detection and warning across the CSZ. For the latest information about Canada's EEW system, see Meghomita Das, *Engaging Communities with Canada's Earthquake Early Warning System*, Temblor, December 16, 2021, at https://doi.org/10.32858/temblor.224.

[127] SASMEX, 2018.

Figure 11. Timeline of Public EEW by Country or Region and Population Size Alerted



Source: Sara K. McBride et al., "Evidence-Based Guidelines for Protective Actions and Earthquake Early Warning Systems," *Geophysics*, vol. 87, no. 1 (January-February 2022), WA77-WA102, at https://doi.org/10.1190/GEO2021-0222.1.

Notes: Limited alerts have been sent in Costa Rica and El Salvador but are not shown on this graphic.

Issues for Congress

ShakeAlert has been operating in California since October 2019 and in Oregon and Washington since 2021. Given that the system is relatively new, additional information to assess ShakeAlert's performance and effectiveness may be useful to Congress. An assessment could examine information on improvements in the earthquake-sensing network and data analysis, the communication of EEWs, and funding. Seismic and geodetic networks that are now components of ShakeAlert's earthquake-sensing network were established for other purposes; they have been used for ShakeAlert while continuing to serve these other purposes. An evaluation of whether these components are effective for EEW and how these components might be used effectively for multiple purposes, perhaps with further coordination among the component operators, also may be useful for Congress. For example, the Network of the Americas, operated by UNAVCO Inc., supports basic research; the network's operations and maintenance are funded through a cooperative agreement with NSF.[128] In addition, NOAA's National Geodetic Survey uses hundreds of the geodetic stations in the Network of the Americas to help define the National

[128] UNAVCO, "Network of the Americas," at https://www.unavco.org/projects/major-projects/nota/nota.html.

Spatial Reference System.[129] Thus, the Network of the Americas supports research, EEW, and surveying with funding from different federal agencies.

As part of an evaluation, Congress could direct the USGS to analyze ShakeAlert's performance and provide recommendations for improving, expanding, or contracting the current system. Any evaluation may consider the USGS and ShakeAlert partners' aim to increase the size of the earthquake-sensing network on the West Coast, as discussed in the 2018 USGS ShakeAlert Plan.[130] According to the USGS, the planned size would ensure rapid and accurate earthquake detection for effective EEW on the West Coast. The USGS analysis of the performance of ShakeAlert from October 2019 to December 2021 shows that some earthquakes were missed or miscalculated because of inadequate station coverage. The USGS indicates that more seismic stations plus the integration of the geodetic data into the data processing may improve the performance of ShakeAlert on the West Coast. Further, the USGS and ShakeAlert partners aim to improve the data algorithms and data processing in order to prepare more timely and accurate alert messages.

Congress may consider expanding ShakeAlert into other states or specific regions (i.e., some parts of some states). For example, the 2018 USGS ShakeAlert Plan aims to expand ShakeAlert into Alaska, Hawaii, and Nevada. Congress directed the USGS and the State of Alaska to develop an implementation plan for ShakeAlert in Alaska in FY2022 appropriations.[131]

Currently, most of FEMA's communication pathways are not fast enough for effective EEWs. Congress may consider requesting FEMA to evaluate its communication pathways and make suggestions about how FEMA may improve its technology and techniques to meet the challenge of rapid, targeted mass notification for earthquakes.[132] In addition, FEMA may be able to evaluate whether these improvements may be applied for rapid warning about other hazards, such as further developing communication protocols for rapid and targeted mass notification for tornadoes.[133] Another potential area for oversight is related to how federal communication pathways operate in coordination or in parallel with nonfederal communication pathways to provide the most effective disaster warnings to states and civilian populations in endangered areas. In particular, the continued growth of cell phone EEW apps for public warnings may create issues regarding security, privacy, accuracy, reliability, accessibility, and authority. Congress may consider how agreements between federal agencies, such as the USGS's LtOs, and nonfederal communication providers address these issues. These oversight and policy considerations may lead to changes in NEHRP or the Stafford Act, which in turn may impact funding and funding priorities.

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[129] NOAA, "National Geodetic Survey," at https://geodesy.noaa.gov/INFO/WhatWeDo.shtml.

[130] USGS, *ShakeAlert Plan*, 2018.

[131] Explanatory Statement, Division G – Department of the Interior, Environment, and Related Agencies Appropriations Act, FY2022 to accompany H.Rept. 117-83 for P.L. 117-103.

[132] For example, see FEMA National Advisory Council, *Modernizing the Nation's Public Alert and Warning System*, February 15, 2019, at https://www.hsdl.org/?view&did=826793 and the recent contract awarded to AT&T to modernize FEMA's IPAWS, AT&T Communications, "FEMA Awards AT&T 4 EIS Contracts Valued at $167M/5-Years to Modernize Its Communications Capabilities," press release, February 15, 2022, at https://www.prnewswire.com/news-releases/fema-awards-att-4-eis-contracts-valued-at-167m5-years-to-modernize-its-communications-capabilities-301482531.html.

[133] See Cliff Mass, "A Critical Gap in Tornado Warning Technology: Lessons of the Recent Tornado Outbreak," *Cliff Mass Weather Blog*, December 12, 2021, at https://cliffmass.blogspot.com/2021/12/a-critical-gap-in-tornado-warning.html.

The USGS notes that ShakeAlert has not yet received all of the funding estimated to complete the system or to support annual operations and maintenance in the future.[134] If Congress chooses to continue to provide funding for ShakeAlert, there are a range of options to consider, such as annual appropriations or through shared costs similar to those that support other observing networks in the United States that are a mix of federal- and state-funded initiatives (e.g., NOAA Continuously Operating Reference Stations and USGS Streamgaging Network).[135] Other funding options for consideration may include funding aspects of ShakeAlert through established NSF or FEMA federal grants, contracts, or cooperative agreements or through new NSF or FEMA federal grants, contracts, or cooperative agreements. In addition, Congress may consider policy options that would enable NOAA or NASA to contribute funds for ShakeAlert as well as research and development for EEW capabilities.

Congress may consider policy options that would improve insight into how federal funds are used to support ShakeAlert and that support other related activities. The USGS, NSF, NIST, and FEMA receive appropriations for earthquake hazards risk reduction through NEHRP or for research and development related to hazard mitigation objectives; however, except for those identified by the USGS for EEW, how other agencies used appropriated funds for ShakeAlert is difficult to track, because those funds were not specifically appropriated for ShakeAlert.

[134] USGS, *ShakeAlert Plan*, 2018, p. 30 – 32.

[135] NOAA, "National Geodetic Survey, The NOAA CORS Network (NCN)," at https://geodesy.noaa.gov/CORS/ and USGS, "USGS Streamgaging Network," at https://www.usgs.gov/mission-areas/water-resources/science/usgs-streamgaging-network.

Appendix. Earthquake Magnitude, Shaking Intensity Scale, and Hazards

Earthquake magnitude is determined for every observed earthquake and often estimated for older events that happened before earthquake-sensing instruments existed in order to compare these events to current events and to estimate the possible recurrence rate of earthquakes on a fault.[136] Magnitude is rapidly estimated for earthquake early warning (EEW), and the estimated magnitude may change as more data are collected or because the earthquake may continue to "grow" with time (i.e., the movement along a fault may continue over seconds to minutes leading to a larger area of movement and a larger magnitude event). A changing magnitude estimate can complicate EEW and can make EEW less effective in reducing risks because the warning must be rapid, leaving little to no time to reassess an estimated magnitude.

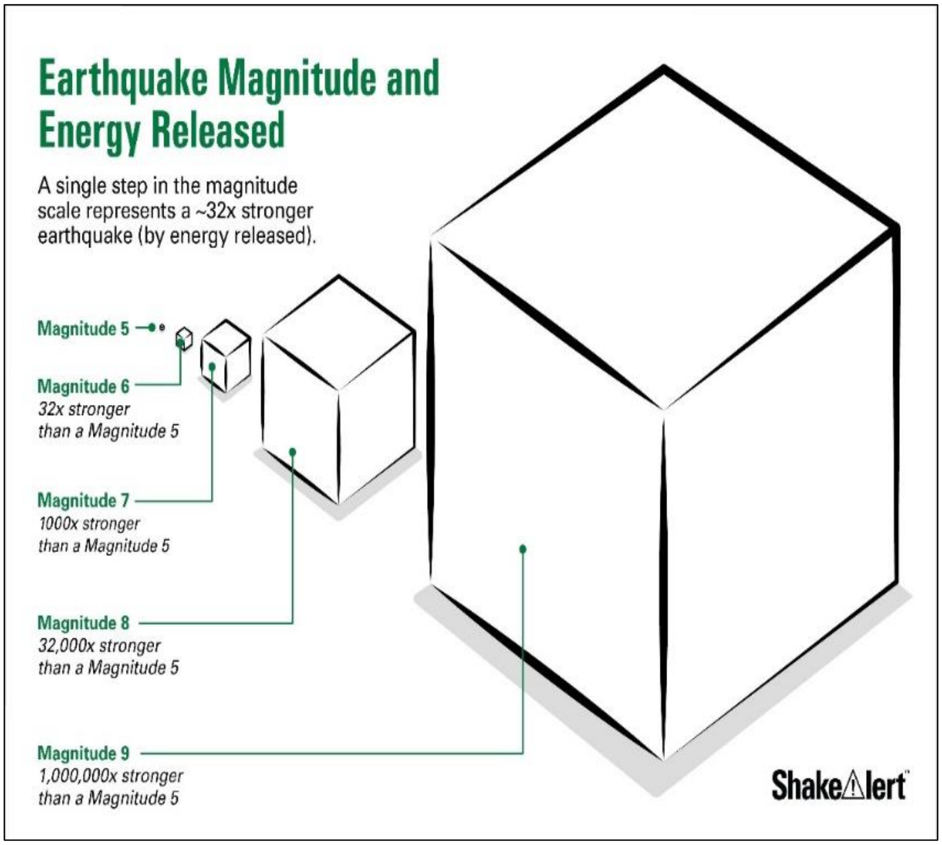
For the public, specifying the magnitude provides a way to understand the "size" of the event using a familiar parameter and to compare the event to previous newsworthy events. For earthquake scientists, magnitude provides a measurement of the length and area of the fault that slipped and the strength of the rock involved in the rupture. These parameters improve an understanding of what causes an earthquake and whether the fault is more or less likely to have an earthquake over a specified future period. Magnitude can be calculated in different ways, and this report cites moment magnitude (M). Moment magnitude is based on the strength of the rock, the fault surface area that ruptures, and the amount of slip along the fault. This magnitude calculation may be the closest to the public's perspective that the earthquake magnitude represents the "size" of the earthquake, given that a longer and more extensive fault may produce a larger magnitude event because there is more length and area that can slip, producing a larger moment magnitude event.

Magnitude can be converted into the energy released by the earthquake. The energy released increases by about 32 times for each single step in magnitude (**Figure A-1**), so an M9.0 event is much more energetic than an M8.0 event. An M9.0 event may cause surface shaking that is much more intense, covers a larger area, and is of a longer duration than surface shaking from an M8.0 event. The public may not fully understand that each magnitude step means a much more energetic earthquake that may cause much more intense ground shaking. However, for EEW and other earthquake notifications for the public, it is important to quickly estimate the magnitude and determine where and how much intense shaking the earthquake may cause. In the case of the 2011 M9.1 Tohoku earthquake, Japan's EEW system underestimated the magnitude as an M8.0, leading to no warning or less warning (i.e., less intense shaking over a smaller area was expected and the larger area that was impacted by the tsunami were not anticipated) for a much more energetic event.[137]

[136] U.S. Geological Survey (USGS), "Magnitude Types," at https://www.usgs.gov/programs/earthquake-hazards/magnitude-types.

[137] For more information about the 2011 M9.1 Tohoku earthquake and the magnitude underestimate, see Richard M. Allen and Diego Melgar, "Earthquake Early Warning: Advances, Scientific Challenges and Societal Needs," *Annual Review of Earth and Planetary Sciences*, vol. 47 (2019), pp 361-388 (see p. 374), at https://doi.org/10.1146/annurev-earth-053018-060457 (hereinafter, Allen and Melgar, "EEW Advances," 2019) and National Research Council, *Precise Geodetic Infrastructure: National Requirements for a Shared Resource* (Washington, DC: National Academies Press, 2010), at https://doi.org/10.17226/12954.

Figure A-1. Earthquake Magnitude and Energy Released



Source: The figure is from ShakeAlert, "ShakeAlert Graphics Library," at https://www.shakealert.org/messaging_toolkit/graphics-library/.

Note: For more details about magnitude and the amount of energy released for a given magnitude, see USGS "Earthquake Magnitude, Energy Release and Shaking Intensity," at https://www.usgs.gov/programs/earthquake-hazards/earthquake-magnitude-energy-release-and-shaking-intensity.

An earthquake shaking intensity scale, called the Modified Mercalli Intensity (MMI) scale, is used for EEW and in post-earthquake assessments to compare and describe earthquake intensity on the surface with one consistent, comparable parameter.[138] The MMI scale depicts the intensity of the shaking based on how intensely people feel the shaking and the amount of damage the shaking causes to structures (**Table A-1**). The scale is empirical and is based on previous observations. For example, light shaking of MMI intensity IV refers to people indoors feeling the shaking. For intensities greater than V, the expected experiences refer to the potential impact of the shaking on structures. For example, violent shaking of MMI IX refers to structures that have substantial damage.

[138] For more details, see USGS, "The Modified Mercalli Intensity Scale," at https://www.usgs.gov/programs/earthquake-hazards/modified-mercalli-intensity-scale.

Table A-1. Modified Mercalli Intensity Scale

Intensity	Shaking	Description
I	Not felt	Not felt except by a very few under especially favorable conditions.
II	Weak	Felt only by a few persons at rest, especially on upper floors of buildings.
III	Weak	Felt quite noticeably by persons in doors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.
IV	Light	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	Moderate	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI	Strong	Felt by all, many frightened. Some heavy furniture moved; a few instances of a fallen plaster. Damage slight.
VII	Very strong	Damage negligible in buildings of good design and construction; slight to moderate in well-build ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
VIII	Severe	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
XI	Violent	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X+	Extreme	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.

Source: Douglas D. Given et al., *Revised Implementation Plan for the ShakeAlert System: An Earthquake Early Warning System for the West Coast of the United States*, USGS, Open-File Report 2018–1155, 2018. Modified by CRS.

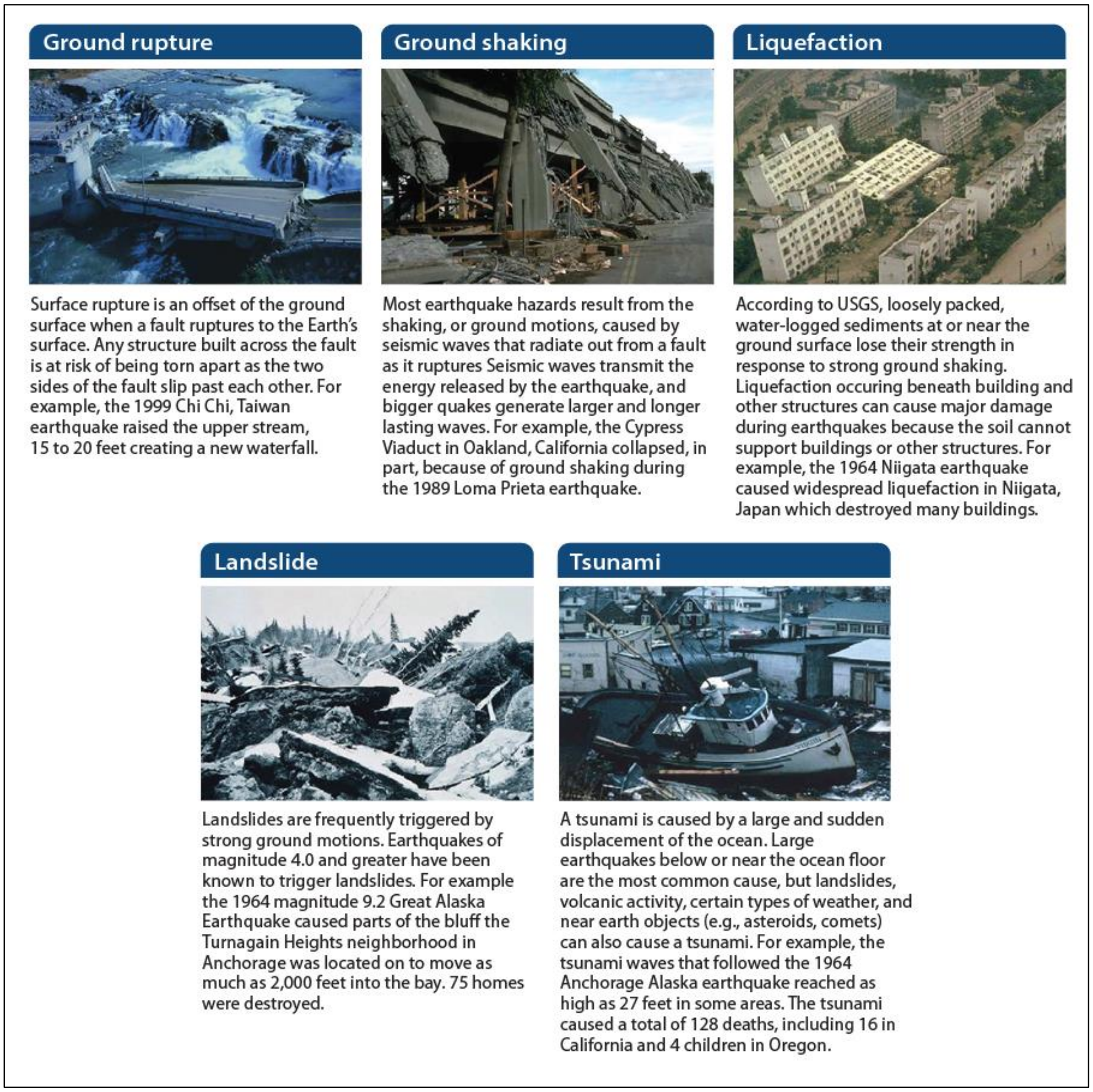
Earthquake hazards include ground movement, ground displacement, ground shaking, and liquefaction (**Figure A-2**).[139] The location, depth, type of fault, and magnitude of the earthquake determine whether any of these hazards may occur at or near the surface, whether the event may cause damage, and where the event may cause damage. Higher-magnitude earthquakes that release more energy and earthquakes at shallow depth may cause damaging surface hazards.[140] An earthquake can trigger other natural hazards, such as tsunamis, landslides, fires, floods, or volcanic eruptions. Earthquake hazards can damage property, such as structural cracks, structural collapse, fires, explosions, floods, loss of power, loss of water supplies, loss of communication, and other damage. Earthquake hazards can cause injuries and fatalities. People are injured or killed mostly by tripping and falling during ground shaking or by being hit or trapped under fallen objects or shake-damaged structures.[141] Subsequent hazards caused by the earthquake, such as tsunami waves, fires, and floods, may injure or kill more people and damage more structures after the earthquake.

[139] Liquefaction occurs when earthquake-induced ground shaking causes loose, weak, or water-saturated soils or rocky materials to lose their strength. When liquefaction happens around structures, such as buildings or bridges, these structures can be damaged or collapse because the foundations of these structures are no longer supported. For more information about liquefaction, see the USGS, "What is Liquefaction?" at https://www.usgs.gov/faqs/what-liquefaction

[140] There is no minimum or maximum earthquake depth used to determine whether ground shaking, ground displacement/movement, or liquefaction may occur; however, observations of past earthquakes suggest earthquakes at shallower depths of 0-50 kilometers (0-31 miles) may cause surface damage, depending on their magnitude and other factors. See the USGS, "What Depth Do Earthquakes Occur?" at https://www.usgs.gov/faqs/what-depth-do-earthquakes-occur-what-significance-depth.

[141] See Occupational Safety and Health Administration "Earthquakes," at https://www.osha.gov/emergency-preparedness/guides/earthquakes for more details.

Figure A-2. Earthquake Hazards



Source: U.S. Government Accountability Office (GAO), EARTHQUAKES Progress Made to Implement Early Warning System, But Actions Needed to Improve Program Management, GAO-21-129, March 2019 (modified by CRS).

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