On the Feasibility of Implementing an Earthquake Early Warning (EEW) System in Utah

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EXECUTIVE SUMMARY

The Utah Legislature, in the 2022 General Session, appropriated funding to study the feasibility of implementing an Earthquake Early Warning (EEW) system in Utah. Funding was provided to the three primary agencies in the Utah Earthquake Program—the Utah Division of Emergency Management (UDEM), the Utah Geological Survey (UGS), and the University of Utah Seismograph Stations (UUSS). The study consisted of four main activities: (1) reviewing the history and development of EEW systems within the U.S. and around the world; (2) assessing the potential performance of an EEW system in Utah; (3) determining what enhancements to the existing Utah seismic network would be needed to implement an EEW system; and (4) conducting an online survey of Utah stakeholders to assess their knowledge of and potential interest in an EEW system.

After a significant earthquake occurs, an EEW system can provide seconds to tens of seconds of warning before the onset of strong ground shaking. This time window, although brief, allows for actions that can potentially reduce economic losses, injuries, and deaths from the shaking—trains can be slowed or stopped, safety controls at critical facilities and utilities can be activated, students can take cover under desks, elevators can stop at the nearest floor, and so on. Thus, EEW systems have become increasingly popular in the U.S. and worldwide in areas that routinely experience large earthquakes, such as California and Japan, and in areas where large earthquakes are less common, such as Oregon and South Korea.

In partnership with the three U.S. states (California, Oregon, and Washington) with the highest seismic risk, the U.S. Geological Survey (USGS) began operating a public EEW system named ShakeAlert in 2019. Utah has the fourth highest seismic risk among U.S. states, with an annualized earthquake loss estimate of $367 million. Seismic risk in Utah is severe because its population and infrastructure are concentrated along the Wasatch Front, directly adjacent to the Wasatch fault zone that has generated 26 magnitude 6.5+ earthquakes in the last 6,500 years. There is a 43% or higher probability of another large (magnitude 6.75+) earthquake in the Wasatch front within the next 50 years. A magnitude 7.0 earthquake along the Salt Lake City segment of the Wasatch fault zone is expected to cause 2,000–2,500 deaths, 7,400–9,300 serious injuries, and over $33 billion in short-term economic losses. Damage estimates for large earthquakes on the other four central segments of the Wasatch fault zone (Nephi, Provo, Weber, and Brigham City) are also high, with economic losses in the billions of dollars. The question we address in this report is how an EEW system could help mitigate future earthquake losses in Utah.

In partnership with the USGS, the UUSS maintains a network of over 200 seismograph stations throughout Utah. These stations continuously record ground motion as small as 1 nanometer at a rate of one hundred times per second. Seismologists use these data to detect and locate about 1,500 earthquakes annually in the Utah region. The UUSS processing system currently generates alerts and notifications to stakeholders and the public. This system, however, was not designed for EEW and the notifications are generally distributed within a few minutes of the earthquake origin time, much slower than the few seconds needed for an EEW system. Significant enhancements to the existing Utah seismic network are required to operate an EEW system in Utah.

Our primary recommendation is that the State of Utah should pursue a partnership with the USGS to expand the ShakeAlert EEW system to the region around the Wasatch fault zone. ShakeAlert currently operates in California, Oregon, and Washington, and discussions on expanding it to Alaska, Hawaii, and Nevada are ongoing. Expanding ShakeAlert to Utah would leverage the hundreds of millions of dollars that have been invested in its technical development and allow for formal cost-sharing with the federal government. Based on historical data, shaking alerts would likely be issued relatively infrequently, perhaps once every two years along the Wasatch Front, potentially providing up to 15–30 seconds of warning in advance of noticeable ground shaking and up to 5–15 seconds of warning in advance of strong ground shaking.

Importantly, the existing seismic network along the Wasatch Front is near the density required for the ShakeAlert system to function reliably. Relatively few new seismograph stations would need to be installed and many existing stations could be upgraded to develop a prototype ShakeAlert system. In this scenario, upgrade costs would primarily involve improving the speed and robustness of the telemetry systems that transmit the data from the individual seismograph stations to the processing hub at the University of Utah. Establishing a partnership with the USGS ShakeAlert project would allow Utah to leverage the existing ShakeAlert knowledge base in terms of data flow, cybersecurity, and sociological studies on how best to engage the public so that effective action is taken once an alert is received.

In many cases, seismic risk in Utah is best reduced by either retrofitting or replacing vulnerable structures such as unreinforced masonry buildings and older infrastructure such as aqueducts. Given how common these structures are in Utah, with over 140,000 unreinforced masonry buildings along the Wasatch Front alone, this process will be both expensive (tens of billions of dollars) and time-consuming (decades). Implementation of an EEW system in Utah represents an opportunity to work in parallel with these efforts and reduce the seismic risk on a shorter time frame. If made a priority, we anticipate that a fully functional EEW system could be operational along the Wasatch Front by 2030, with capitalization costs near $5 million and annual costs for operations and maintenance near $1 million. By adopting the ShakeAlert framework, both costs could be eligible for cost-sharing under a state-federal partnership with the USGS.

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1. INTRODUCTION

Earthquakes are a serious threat to Utah's population, infrastructure, and economy. Seismic hazard in Utah is highest along the north-south trending Intermountain Seismic Belt (ISB), although significant seismicity occurs throughout the state (Fig. 1.1). In an average year, 1,500 earthquakes are detected and characterized in Utah. Most of these earthquakes are small and cause no damage. Only about 20 earthquakes per year are felt by Utah residents (Fig. 1.2); however, geologic studies have found evidence for at least 26 large-magnitude earthquakes along the five central segments of the Wasatch fault zone in the last 6,500 years (*Duross and others*, 2016; *Utah Seismic Safety Commission*, 2022). These paleoearthquakes (pre-historic) had magnitudes near 7.0 (*Valentini and others*, 2020), 90 times more energetic than the magnitude 5.7 Magna, Utah, earthquake that occurred on 18 March 2020 (*Pang and others*, 2020). Based on the historical geological data, present-day seismicity, and other geophysical observations, seismologists estimated a 43% chance of a large (M6.75+) earthquake occurring along the Wasatch Front for a 50-yr period beginning in 2014 (*Wong and others*, 2017). In 2015, it was estimated that a magnitude 7.0 earthquake on the Salt Lake City segment of the Wasatch fault would lead to 2,000–2,500 deaths, 7,400–9,300 serious injuries, and over $33 billion in short- term economic losses (*Earthquake Engineering Research Institute*, 2015).

In early 2023, the Federal Emergency Management Agency (FEMA) published new estimates of earthquake risk for all 50 states, two U.S. territories, and the District of Columbia (*FEMA*, 2023). In that report, Utah was ranked as the fourth riskiest state with an annualized earthquake loss of $367 million. Only California, Washington, and Oregon had higher loss estimates. Similarly, Utah was ranked the fourth riskiest state in annualized estimates of earthquake related casualties, displaced households, and debris generated. Seismic risk in Utah is severe because over 85% of Utah's 3.4 million residents live in the Salt Lake City-Provo-Orem urban corridor, directly adjacent to the Wasatch fault zone (Fig. 1.1). A second contributing risk factor is the widespread presence of unreinforced masonry structures (URMs), which are prone to failure during moderate to strong ground shaking. Building codes were changed in the 1970's to prohibit construction of new URMs, however there remain approximately 140,000 URMs along the Wasatch Front (*FEMA*, 2021). For context, as of 2006, there were about 26,000 URMs in California's high seismic hazard zones, which comprised regions near historically active faults, such as Los Angeles, San Francisco, and San Diego, and included more than 75% of the state population (*California Seismic Safety Commission*, 2006).

To prepare Utah for its next major earthquake it is important to adopt and enforce seismic building codes requisite for the expected shaking. Modern engineering practices design buildings to protect life safety during strong ground shaking. Thus, the most effective way to reduce seismic risk in Utah is by replacing or strengthening the legacy stock of URMs and other vulnerable infrastructure. Unfortunately, this process is expensive and time consuming. For instance, the 2004–2008 seismic retrofit of the Utah Capitol cost $260 million. Likewise, the ongoing seismic retrofit of The Church of Jesus Christ of Latter-day Saints Temple in downtown Salt Lake City is expected to take at least five years and be comparably expensive. The total value of buildings on the 119 K-12 school campuses in Utah recently identified as having URM structures is almost $2 billion (*Applied Technology Council*, 2022). It will take several decades for the URM problem in Utah to be solved.

A parallel approach to mitigating seismic risk in Utah is the implementation of an Earthquake Early Warning (EEW) system. EEW systems work by quickly identifying when an earthquake is underway, and transmitting an alert to surrounding regions before the strong ground shaking arrives. EEW systems take advantage of electronic communications being faster than seismic waves. Warning times in Utah would be in the range of seconds to tens of seconds, which could allow trains to slow down or stop, utility companies and industry to apply safety measures, and children in school buildings to take cover beneath their desks. A Utah EEW system will not negate the need for infrastructure upgrades and URM replacement and, vice versa, URM replacement will not negate the usefulness of EEW. Most earthquake-related injuries and casualties in the U.S. result from falling objects. Warnings to take cover under a sturdy table or desk before shaking starts can help protect people from structural failure in URMs and from unsecured objects or furnishings in all structures.

In collaboration with state agencies, universities, and private companies, the federal U.S. Geological Survey (USGS) currently operates the ShakeAlert EEW system in California, Oregon, and Washington. ShakeAlert was developed over the last 17 years (2006–present) with about $216 million in combined funds (*Congressional Research Service*, 2022). Now that ShakeAlert has been implemented along the West Coast of the United States, studies are being conducted about its possible expansion to other high-risk states, such as Alaska, Hawaii, and Nevada. For instance, in federal fiscal year 2022, the U.S. Congress appropriated $1 million to the USGS to develop a ShakeAlert implementation plan for Alaska (*Congressional Research Service*, 2022). Expansion of ShakeAlert into Utah would leverage the previous and ongoing developmental work and potentially allow the State of Utah to share the costs of operating an EEW system with the federal government, perhaps similar to the existing 50/50 financial partnership between the USGS and the University of Utah Seismograph Stations (UUSS) for routine earthquake monitoring in Utah.

In this report, we present a feasibility study for implementing an EEW system in Utah. We mainly focus on the

Wasatch Front Region, which has the highest seismic risk as well as the highest density of existing seismograph stations in Utah, but also consider central and southwestern Utah. In Section 2, we briefly describe how EEW systems work and what benefits they provide. We also document their distribution within the U.S. and around the world. In Section 3, we explore the potential operation of an EEW system in Utah, including how often it might be used. This section presents EEW scenarios for the M5.7 2020 Magna, earthquake; hypothetical M7 earthquakes along the Wasatch and Oquirrh-Great Salt Lake fault systems; the 1934 M6.6 Hansel Valley earthquake; the 1901 M6.5 Richfield earthquake; and a hypothetical M6.7 earthquake on the Hurricane fault system. In Section 4, we describe what network upgrades would be required to implement and operate an EEW system along the Wasatch Front. It includes a brief discussion of the associated costs. In Section 5, we describe the results from a survey of Utah stakeholders that was conducted to gauge interest in a Utah EEW system. Entities surveyed included state agencies, municipal agencies, large private sector employers, school districts, and emergency responders. In Section 6, we list the major findings and recommendations from the study.

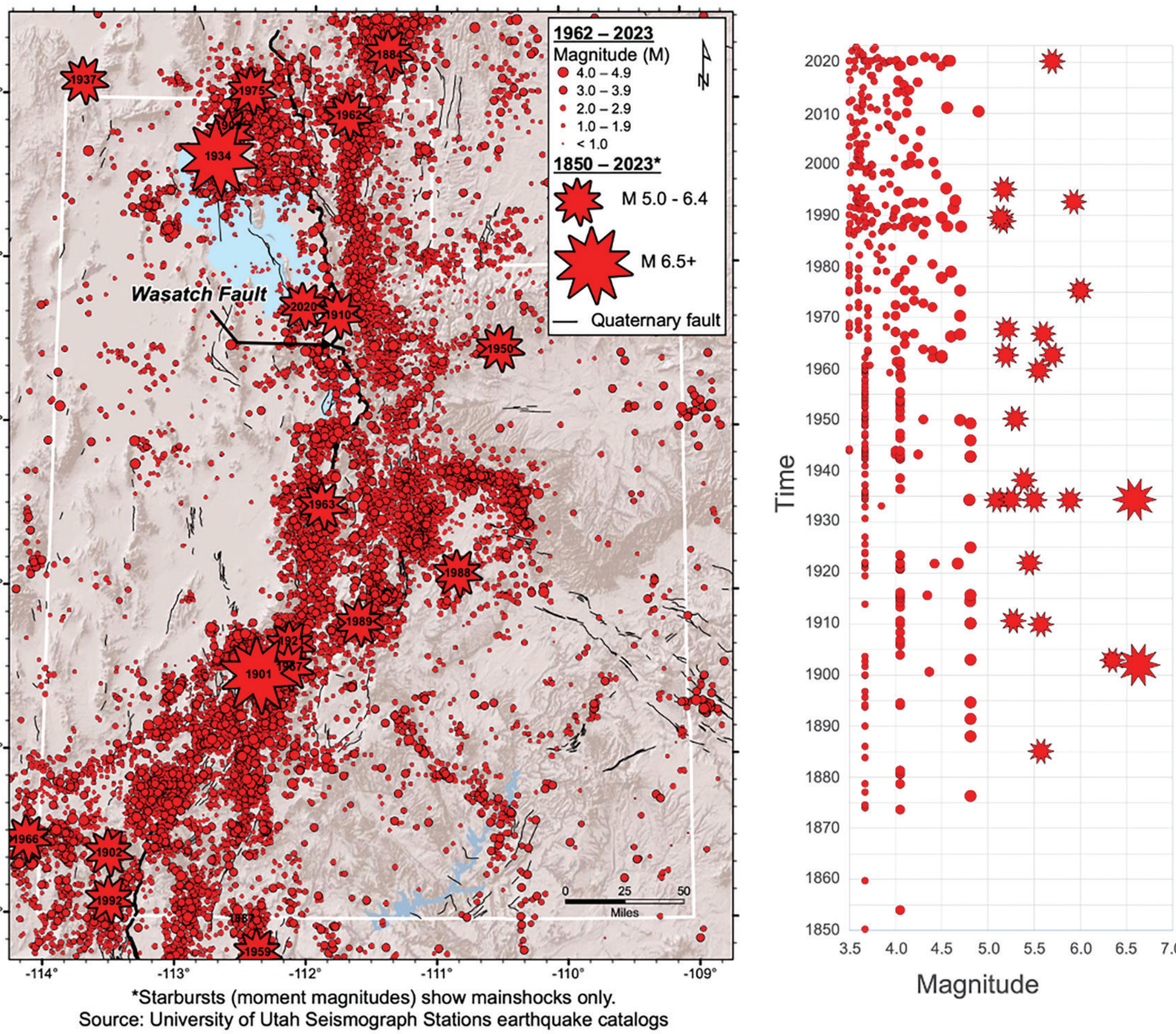


Figure 1.1. (left) *Earthquake epicenters in the Utah region from 1850 through 31 March 2023. Circle size is proportional to earthquake magnitude, and stars represent larger (M5+) earthquakes. The north-south trend of earthquakes is part of the Intermountain Seismic Belt (ISB), which stretches from Arizona in the south to Montana in the north and generally follows the Interstate 15 corridor in Utah.* ***(right)*** *The history of M3.5+ earthquakes in the Utah region.*

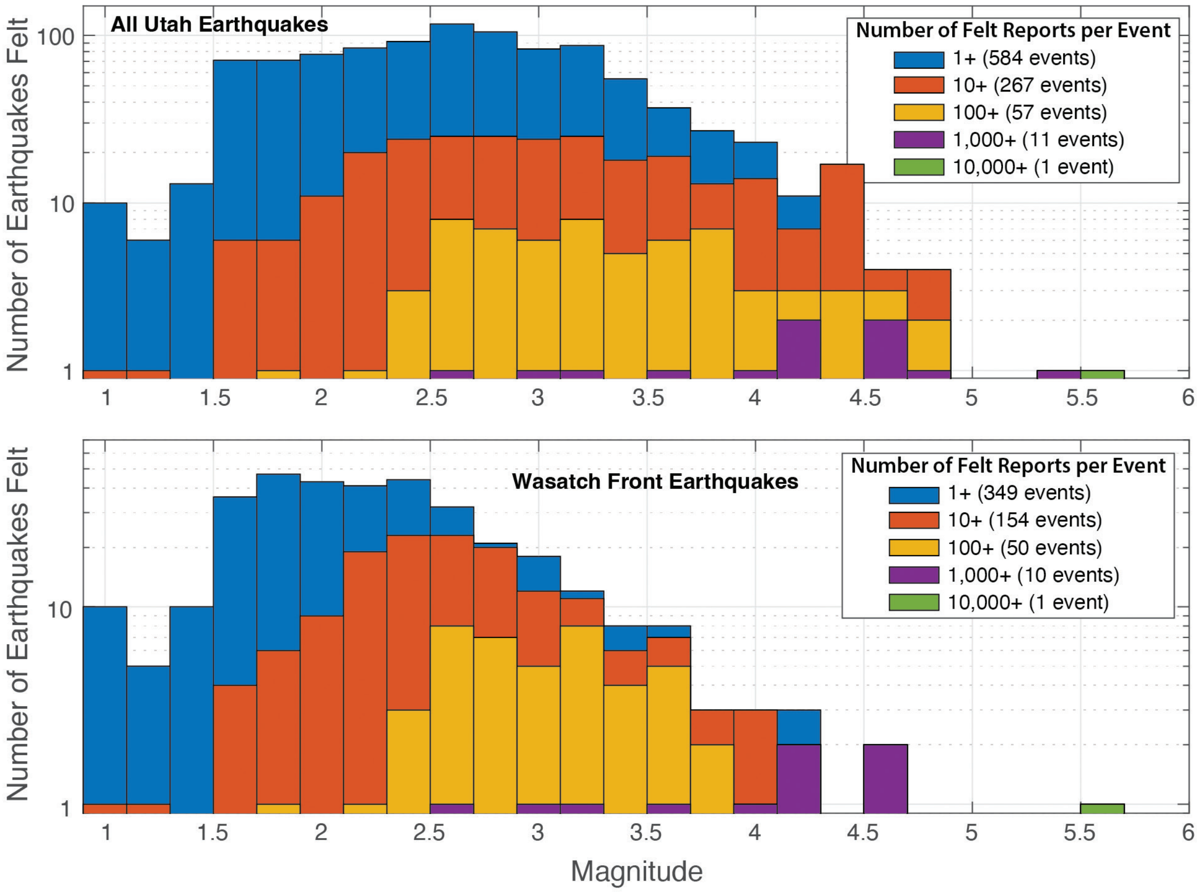
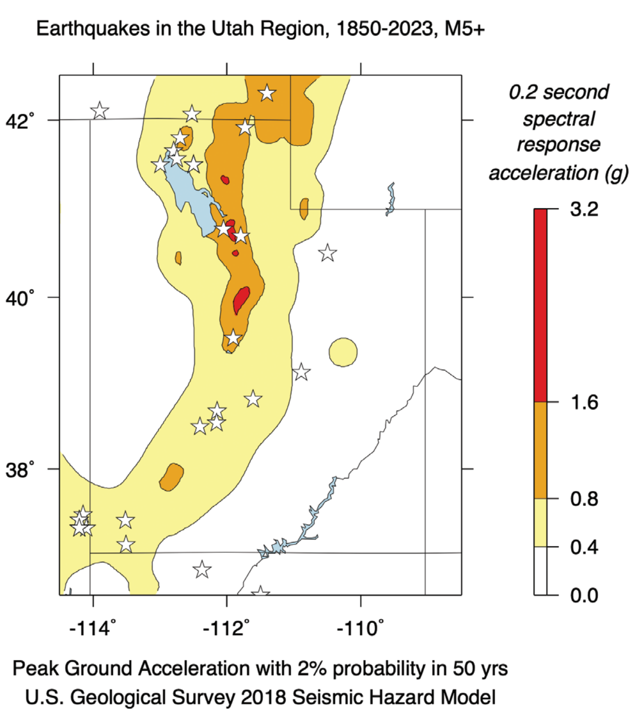


Figure 1.2. (top) *Histogram of earthquakes detected in 2000–2022 that had USGS Did-You-Feel-It (DYFI) reports within Utah, color-coded by the number of reports per earthquake. This figure shows that earthquakes as small as magnitude 2.5 are often felt by over 100 people, although those that feel these small earthquakes are typically located very close to the epicenter.* ***(bottom)*** *As in the top panel but restricted to felt reports within the Wasatch Front Region.*



State Ranking of Utah in Measures of Earthquake Risk[1]

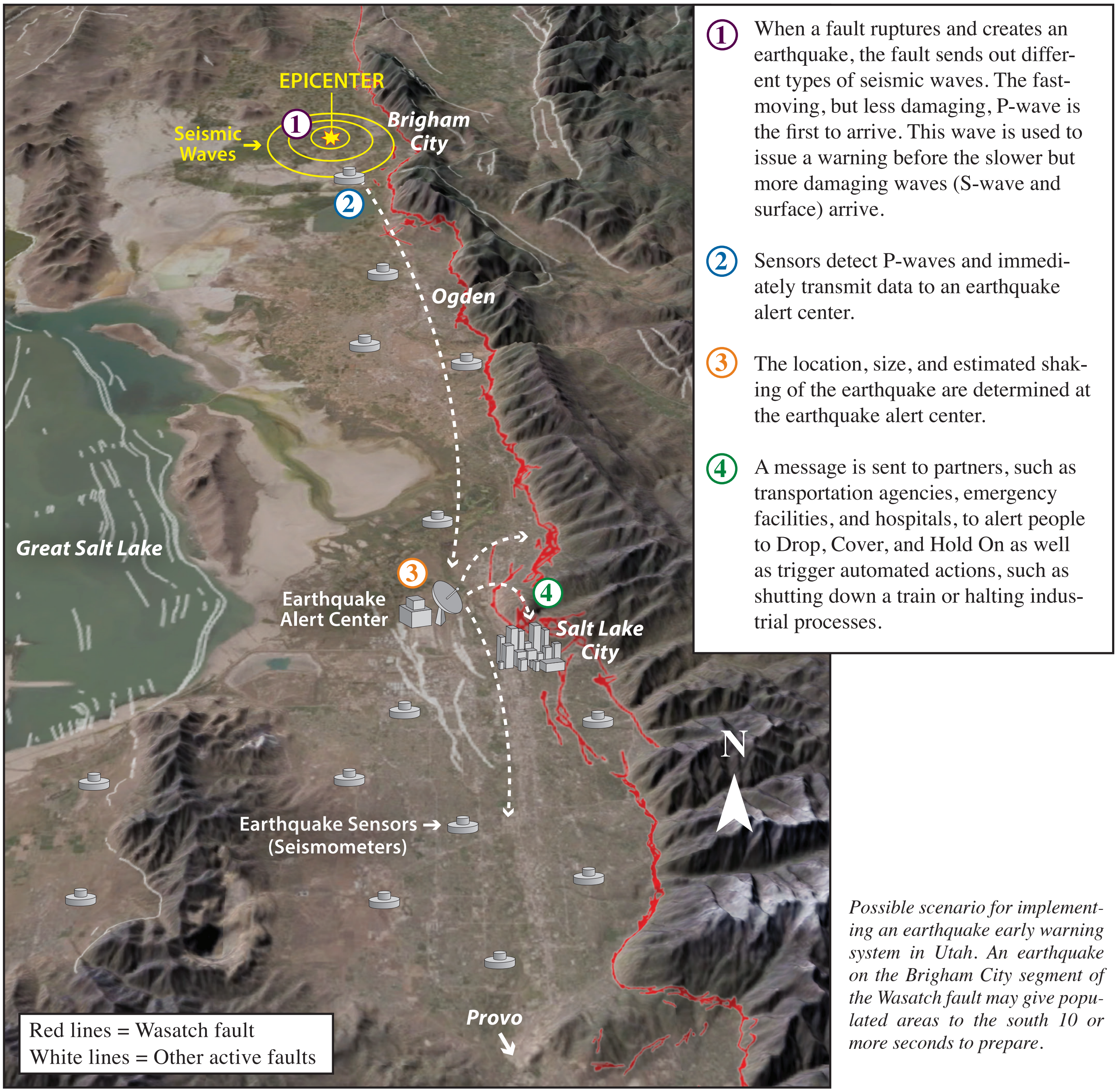
	National Ranking	Regional Ranking[2]
Annualized Earthquake Loss	4	1
Annualized Earthquake Loss Ratios	4	1
Estimates of Debris	4	1
Displaced Households	4	1
Annualized Shelter Requirements	4	1
Annualized Casualties	4	1

[1]Data from FEMA P-366 HAZUS Estimated Annualized Earthquake Losses for the United States (2023).
[2]FEMA's Rocky Mountain Basin and Range seismic region includes: MT, ID, WY, NV, UT, CO, AZ, and NM.

Figure 1.3. (left) *Map of seismic hazard in Utah. Higher accelerations correspond to higher hazard. The 31 earthquakes with magnitudes of 5.0 or larger that have occurred in the Utah region since 1850 are shown with white stars. Ten additional M5+ earthquakes occurred just outside the plot bounds.* ***(right)*** *Results of recent FEMA analysis of earthquake risk. California, Oregon, and Washington are the only states with higher seismic risk than Utah. The annualized earthquake loss estimate for Utah is $367 million.*

2. OVERVIEW OF EARTHQUAKE EARLY WARNING SYSTEMS

Earthquake Early Warning (EEW) aims to quickly detect seismic waves from an earthquake and use that information to issue alerts to more distant regions, providing a few seconds to tens of seconds of warning time prior to the arrival of strong shaking (Fig. 2.1). EEW systems rely on transferring information quickly from one location to another, as the data need to be processed, alert regions defined, and alerts issued prior to the onset of strong shaking. A single earthquake produces different types of seismic waves. The P wave is the fastest seismic wave and is the first to be recorded at a seismic station, followed by the slower but more damaging S wave (Fig. 2.2). Some EEW methods are designed to detect the smaller P-wave signals (*Allen and others*, 2009), although



Possible scenario for implementing an earthquake early warning system in Utah. An earthquake on the Brigham City segment of the Wasatch fault may give populated areas to the south 10 or more seconds to prepare.

Figure 2.1. *Illustration of how an earthquake early warning system could work in Utah. Image used with permission from* Utah Seismic Safety Commission *(2022).*

this can be problematic because seismic noise (e.g., wind or traffic) might be misconstrued as an earthquake signal. Other EEW methods strive to detect a certain level of ground shaking that could occur during the P or S wave. Methods that focus on levels of ground shaking can be more robust but have the disadvantage that their detection times tend to be slower, in turn making the alerts slower (*Böse and others*, 2023).

There are two main classes of EEW systems: on-site and network-based (*Allen and others*, 2009). On-site systems rely on processing data at a single or small group of seismograph stations and broadcast alerts to a specific facility or nearby region. They essentially act as P wave detectors. Network systems rely on data from an array of seismograph stations that are processed together, and broader alert regions are derived based on the system as a whole. Most EEW systems, including the ShakeAlert system, are network-based. A notable example of an on-site system is the P-Alert system of low-cost accelerometers in Taiwan that complements the network-based EEW system (*Wu and others*, 2016, 2021). On-site systems may be more prone to false alarms and missed detections than network-based systems.

Earthquake detection methods used in network-based EEW can be divided into two end members. The first is a source-based method that calculates and reports the earthquake magnitude and epicenter (latitude and longitude only), while the second is a ground motion- based method that directly reports the locations of strong shaking. The second method sidesteps the need to estimate the earthquake magnitude or epicenter. Ground motion-based methods were initially developed in response to difficulties in accurately characterizing the 2011 M9.0 Tohoku- Oki, Japan, earthquake sequence (*Kodera and others*, 2021).

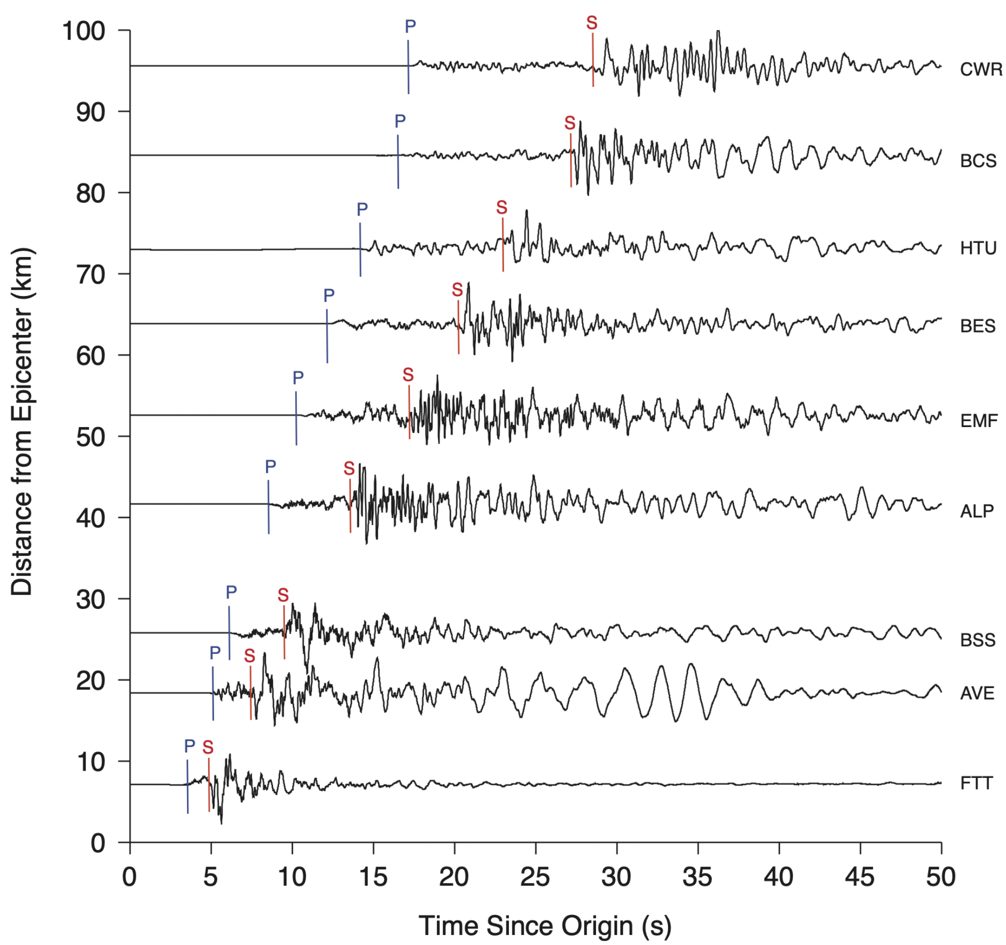


Figure 2.2. *Waveforms from the 2020 M5.7 Magna, Utah, earthquake. Each trace shows ground velocity in the north-south direction at a particular seismograph station (station code listed on right). The earthquake P-wave arrival is shown with a dark blue line, and the S-wave arrival is shown with a red line. Note how the separation between the P and S waves increases with distance. In some cases, the strongest ground motion occurs after the S-wave arrival, such as at stations AVE, BES, and CWR. The long "ringing" observed at station AVE is created by energy resonating in the soft sediments underneath the station. Seismograms for each station are normalized for clarity; the true amplitude decreases rapidly with distance.*

The concept of EEW is old, having been proposed for California as early as 1868 by J. D. Cooper (*Cremen and Galasso*, 2020). The first operational EEW system was developed in 1989 for use in Mexico (*Espinosa Aranda and others*, 1995) and has been systematically refined over the years (*Allen and others*, 2009; *Allen and others*, 2018; *Cochran and Husker*, 2019; *Santos- Reyes*, 2019). The pace of EEW system deployments around the globe has recently increased and robust systems are operational in Japan, Mexico, South Korea, and Taiwan (*Allen and Melgar*, 2019). The ShakeAlert EEW system in California, Oregon, and Washington is also currently operational, and further testing is ongoing to reduce false and missed alerts. Additional EEW systems are rolling out globally, initially issuing alerts to select user groups (such as in Canada, India, Turkey, Romania, and China). Some of these systems send alerts to cell-phone-based app partners and/or Android operating systems (*https://crisisresponse.google/android-alerts/*) to push alerts to end users. For example, the MyShake app receives an earthquake feed from the U.S. ShakeAlert system and uses this earthquake source information to disseminate an alert (*Allen and others,* 2020). In 2007, fewer than 150 million people had potential access to EEW, but this number has grown to over 400 million as of 2021 (*Allen and Stogaitis*, 2022). Because seismicity within these regions is typically widespread, most of these EEW systems are network-based. Collectively, what is learned at one location can be leveraged elsewhere. For example, the United Nations sponsored two key documents: (1) *Developing Early Warning Systems: A Checklist*; and (2) *Global Survey of Early Warning Systems* and suggested that these documents be updated with a summary of protective actions related to hazard and warning systems (*McBride and others*, 2022).

The initial development of the U.S. EEW system that is now called ShakeAlert began with a focus on California in 2006 and was initially developed through a collaboration between the USGS, the California Institute of Technology, and UC Berkeley (Kohler *et al.*, 2018; Table 2.1). This system expanded over the last 17 years and now covers California, Oregon, and Washington (*Given and others*, 2014, 2018). The ShakeAlert EEW system currently uses two source-based methods (called EPIC and FinDer; *Kohler and others*, 2018; *Kohler and others*, 2020) but will soon add a geodetic method to determine large magnitudes (GFAST-PGD, *Murray and others*, 2018). ShakeAlert is also considering incorporating a ground motion-based method called PLUM (*Cochran and others*, 2019; *Böse and others*, 2023). Initial research suggests that combining source-based with ground motion-based methods could be beneficial, in that one method might detect an earthquake that the other method missed (*Böse and others*, 2023). An important component of the ShakeAlert system is the inclusion of social science researchers who can provide quantitative results on societal needs, understanding, and knowledge about what to do when receiving an EEW alert (*McBride and others*, 2022). Iteratively working with social scientists provides an avenue to learn how best to teach people to protect themselves when they receive an alert.

Table 2.1. *Timeline for the West Coast USGS ShakeAlert EEW system.*

History of ShakeAlert along the West Coast of the USA
2006: Development began (USGS, Caltech, UC Berkeley)
2011: Moore Foundation Award for West Coast development
2016: Production prototype online for California
2017: Expansion to include alerts for Oregon and Washington
2018: Initial beta rollout in California
2019: Public rollout in California
2021: Functional for the West Coast (CA, WA, OR)

ShakeAlert uses ground motion data from several project partners, including Canada and Mexico. Prior to ingesting data from new partners, the seismic data (and eventually geodetic data) are vetted and must pass data quality and telemetry tests; the system must also correctly ignore spurious signals and distant earthquakes (*Cochran and others*, 2018). ShakeAlert is currently collaborating with Canada to develop a Canadian EEW system for British Columbia, the Ottawa River Valley, and the Saint Lawrence Seaway. The Canadians are augmenting their existing seismic network and are using the ShakeAlert software at Canadian processing centers, which will be interconnected with the U.S. system. They are scheduled to go live in April 2024.

In this report, we refer to various time intervals in the EEW process that contribute to the total amount of time between the start of the earthquake and the receipt of a shaking alert (Alert Latency), and the amount of time between the receipt of an alert and the onset of strong shaking (Warning Time). We use a simplified description of the EEW time model in *Behr and others* (2015), as an overview of ShakeAlert's source-based data processing (Fig. 2.3). The initiation of the earthquake is known as the Origin Time (OT). The first stage in the alert process is the time required for the earthquake P waves to travel from the earthquake hypocenter (underground initiation point) to the four closest seismograph stations (P-wave travel time; Purple zone in Fig. 2.3). This time interval is dependent on the seismic network configuration and the location and depth of the earthquake. Next, there is Data Latency that encompasses the time it takes the data logger at a given seismograph station to digitize the data, send it to the data processing center, and receive these data into the data center queue (Gray zone in Fig. 2.3).

Once these data arrive at the data processing center, there is a time interval required for the system to detect the P-wave arrivals, determine if there is an earthquake, estimate its location and size, estimate the resulting ground motions, and prepare and send out an alert, if applicable (Processing Time; Blue zone

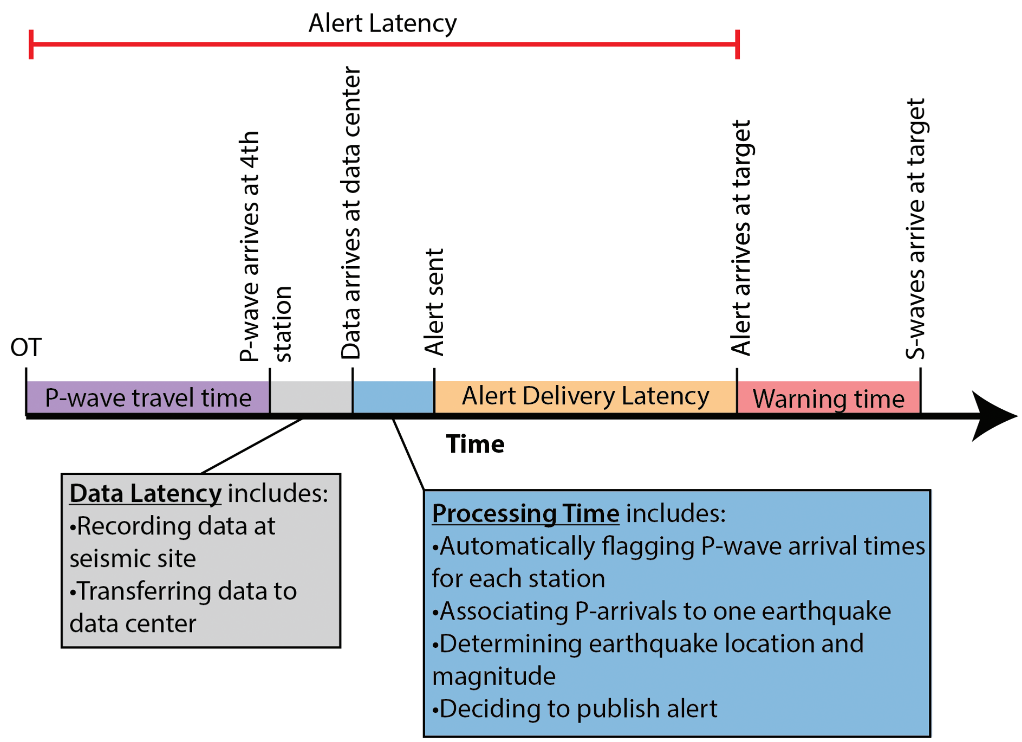


Figure 2.3. *Schematic of the times and latencies that contribute to overall alerting and Warning Time in an EEW system for the sourced-based detection method currently used by ShakeAlert. The time from the start of the earthquake, Origin Time (OT), to when the P wave arrives at the fourth closest station (purple; P-wave travel time), the time to record and transmit the data (gray; Data Latency), the time to process the event (blue), and the transmit time for an alert to reach the target (orange; targets are facilities and the public) all contribute to how much Warning Time (red) a target will have to take protective action beore the stronger S waves and surface waves arrive.*

in Fig. 2.3). The time from sending the alert until it is received at target locations is the Alert Delivery Latency (Orange zone in Fig. 2.3). This latency is dependent on the delivery method used (for example, smartphone apps or emergency alerts). Here, we define the total time between the earthquake origin time and the receipt of the alert as the Alert Latency, which is the sum of the P-wave travel time, the Data Latency, the Processing Time, and the Alert Delivery Latency (Fig. 2.3).

We define the Warning Time (Red zone in Fig. 2.3) as the amount of time a target location has time to take protective action (i.e., the time between receiving an alert and the onset of shaking from the earthquake S wave passage). Here, we assume that the maximum ground shaking occurs at, or a short time after, the S wave arrival. The Warning Time depends not only on the system performance, but also on the location of the individual or facility at the time they receive the alert and the method used to send the alert.

Given a long enough Warning Time, several actions are possible that can provide economic and life safety benefits (see https://www.shakealert.org/education-and-outreach/case-studies/). For instance, it has been suggested that it would take an able-bodied person 5–10 s to perform the recommended drop, cover, and hold-on action once receiving an alert (*Porter and James*, 2018), which can prevent significant injuries. Other potentially automated actions could be rapidly initiated, such as slowing down trains and shutting off pipelines and other critical infrastructure. In the context of California, financial savings from these types of actions are discussed in *Strauss and Allen* (2016) and include the example of preventing the derailment of a single commuter train with a potential savings of $33 million. *Tan and others* (2022) reviewed 70 recent scientific papers on EEW and documented several indirect benefits of EEW in addition to personal protective action and pre-programmed shutdown actions. They found that EEW systems can promote a culture of preparedness, increase public confidence in management of critical facilities such as nuclear reactors, and provide situational awareness for emergency responders. However, since EEW is a relatively new technology, studies have mostly focused on potential EEW benefits rather than observed EEW benefits (*Wald*, 2020). A notable exception is described in *Strauss and Allen* (2016):

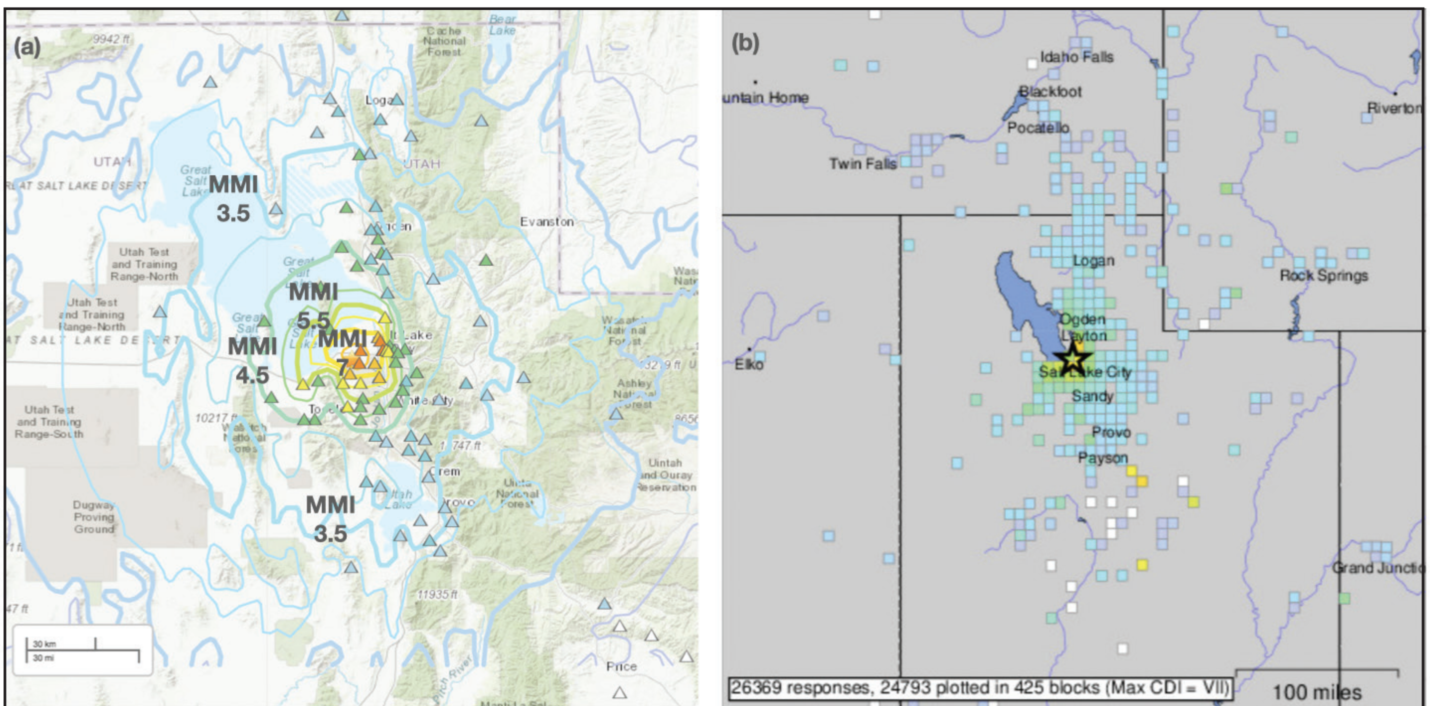
> *"One of the best documented returns on investment for private industry is that of the OKI semiconductor factory in Miyagi Prefecture, which experienced $15 million U.S. in losses due to fire, equipment damage,*

and loss of productivity in two moderate earthquakes (M 7.1 and 6.4) in 2003. They invested $600,000 U.S. in retrofits and EEW controls to automatically shut down hazardous chemical systems and manipulate sensitive equipment into a safe position. In two similar subsequent earthquakes, the losses were reduced to only $200,000 U.S. (Allen et al., 2009), a savings of $7.7 million U.S. per earthquake ...”

3. POTENTIAL PERFORMANCE OF EARTHQUAKE EARLY WARNING IN UTAH

The primary question we address in this section is “How would an EEW system perform in Utah?”. To answer this question, we assess how much warning can be expected for the types of earthquakes likely to occur in Utah, how many Utah residents are expected to receive the alerts, and how often alerts are expected to be issued.

We first explore what would have happened during the 2020 M5.7 Magna, Utah, earthquake had a fully functioning EEW system been in place. The shaking that Utah residents experienced during this earthquake is well known from over 26,000 felt reports and acceleration measurements from over 80 nearby seismometers. These data can be combined with existing geological knowledge to produce a ShakeMap (*Worden and others, 2020*), which presents a smooth and continuous map of the maximum level of shaking experienced throughout the region (Fig. 3.1). Descriptions and examples of shaking intensity levels are shown in Fig. 3.2. We can then compare the map of experienced shaking with estimated Warning Times from a fully functioning EEW system.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 3.1. *ShakeMap for the 2020 M5.7 Magna, Utah, earthquake. Colors represent the level of shaking expected at each location.* ***(a)*** *The shaking levels are calculated using a combination of seismic data, geologic data, and felt reports. Each triangle is the location of a seismograph station that recorded shaking from the earthquake.* ***(b)*** *Summary of the USGS Did-You-Feel-It responses. The legend at the bottom shows color-coding levels for both images, where warm colors indicate more intense shaking than cool colors.*

Because digital communication is fast, the Alert Latency is relatively constant over the source region. The time needed to transmit a digital message from Magna to downtown Salt Lake City (~11 miles or 18 km) is not appreciably different from the time needed to transmit a message from Magna to Logan (~71 miles or 115 km). In contrast, earthquake S-wave arrival times increase with distance away from the epicenter. An S wave from Magna would arrive in Salt Lake City after ~5 s but would take ~34 s to reach Logan. Thus, the farther away from where the earthquake initiated (epicenter), the longer the Warning Time. However, the level of shaking at a location diminishes as the distance from the epicenter increases. Therefore, it becomes easier to alert people to progressively smaller ground motion. Conversely, alerting people to progressively larger ground motion becomes more difficult. The locations nearest the epicenter, where shaking is generally strongest, constitute a No-Alert Zone because the earthquake S-wave travel time is shorter than the Alert Latency. For instance, for the 2020 M5.7 Magna earthquake, it would not have been possible to alert residents of downtown Salt Lake City (Fig. 3.3).

An EEW system in Utah would be most beneficial for larger earthquakes, magnitude six or higher, which produce strong and long shaking throughout a large region, like the 26 paleoearthquakes that occurred along the Wasatch fault zone in the last 6,500 years. We do not have seismic data or felt reports for the paleoearthquakes, but we can simulate their shaking using what we know about Utah geology and observations of magnitude 7 earthquakes that occurred in regions of the world with similar geology and tectonics as Utah. These synthetic, or scenario, ShakeMaps can be used in conjunction with expected earthquake S-wave arrival times to calculate the Warning Times and shaking levels at target locations.

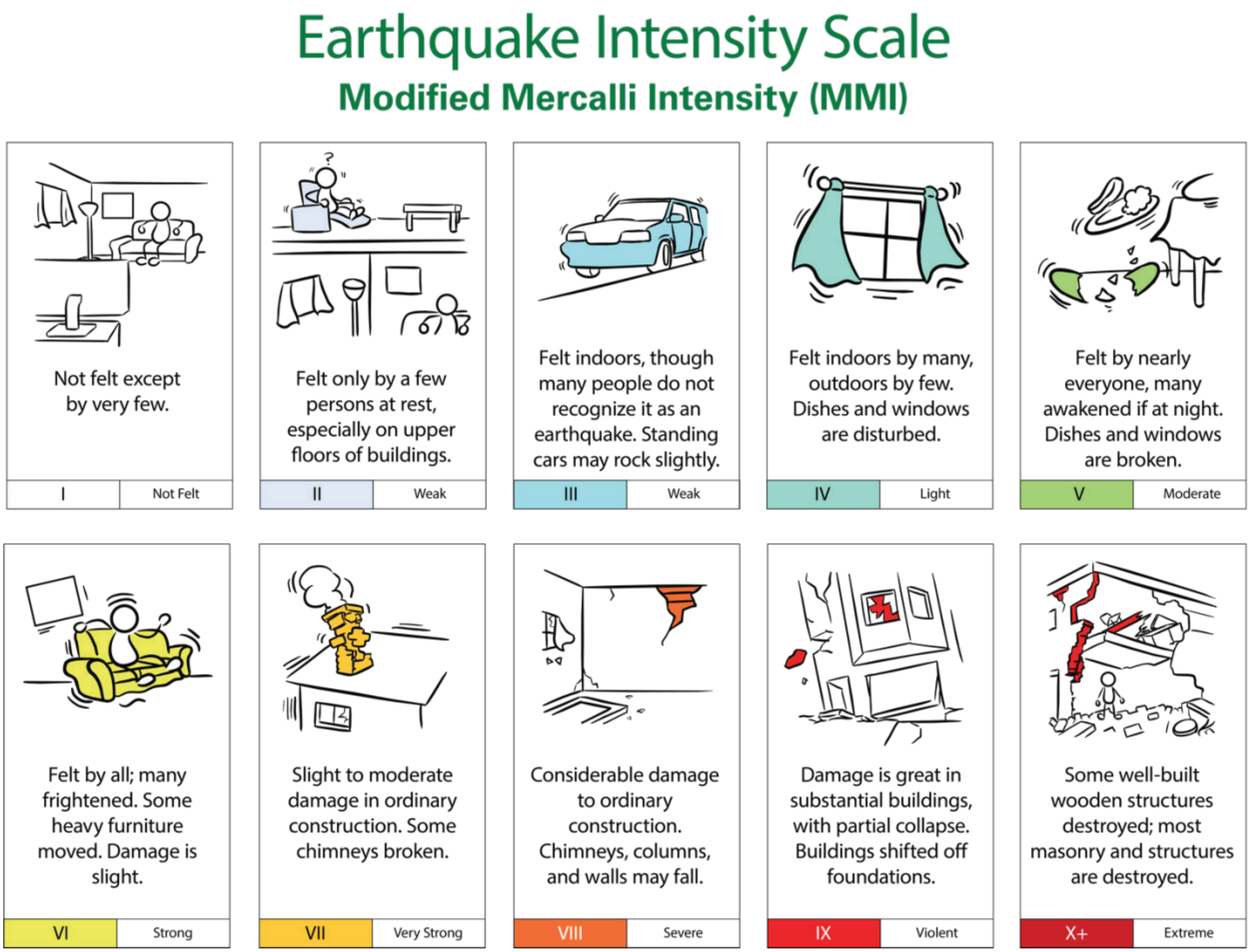


Figure 3.2. *Descriptions of shaking intensity used in the Modified Mercalli Intensity (MMI) system. Public domain image created by the USGS Earthquake Hazards program. The full caption in the lower right panel* (Extreme, X+) should read "Some well-built wooden structures are destroyed; most masonry and frame structures destroyed with foundations. Rails bent.

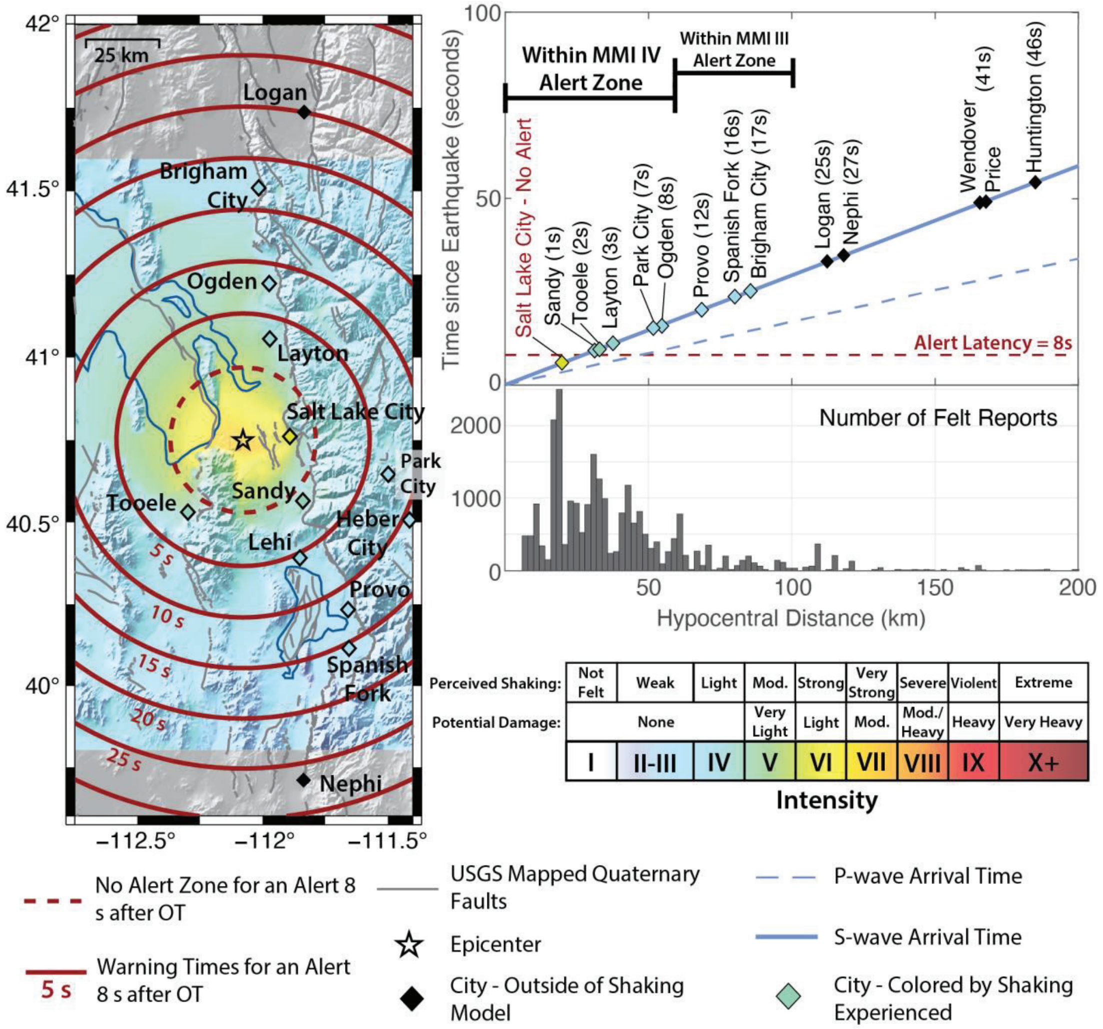


Figure 3.3. *Estimated Warning Times for the 18 March 2020 M5.7 Magna, Utah, earthquake had an EEW system been operational. The concentric red circles on the map indicate how much Warning Time would have been provided at a given location before shaking associated with the earthquake S wave began. The dashed red circle is the No-Alert Zone for an alert latency of 8 s. Colors indicate the maximum intensity of the experienced shaking based on seismograph measurements and felt reports. The upper right panel summarizes the Warning Times and the shaking intensity for select cities. The lower right panel shows the number of felt reports logged at the USGS by distance from the earthquake. For the cities located outside of the ShakeMap, we cannot be sure if they experienced shaking above the intensity threshold for alerting, and thus, we cannot be sure if they would have been alerted.*

We present EEW simulations for expected M7 earthquakes on the Salt Lake City and Brigham City segments of the Wasatch fault zone. These are the two most overdue of the five central segments of the Wasatch fault zone, with neither having produced a large earthquake within the last 1,000 years (*Wong and others*, 2017). The next scenario we examine is a hypothetical M7 earthquake on the Oquirrh-Great Salt Lake fault zone, just west of the Wasatch fault zone but still within the Wasatch Front area. The fourth scenario we examine is a simulation of the 1934 M6.6 Hansel Valley earthquake—the largest Utah earthquake since settlement in 1847 (*Doser*, 1989). This scenario allows us to explore the EEW implications of an earthquake slightly west of the Wasatch Front, where the seismic hazard is not quite as high but is still significant. The fifth scenario simulates shaking for the 1901 M6.5 earthquake near Richfield, in central Utah. The sixth and final scenario simulates shaking for a hypothetical M6.7 earthquake on the Hurricane fault zone in southwestern Utah.

In the following earthquake scenarios, we assume an Alert Latency (time between when the earthquake occurs, and an alert is received) of 8 seconds (s). We can calculate the time it takes for the earthquake S waves to arrive at a location from the scenario earthquake and subtract the 8 s Alert Latency to estimate the Warning Time for a given location (Red zone in Fig. 2.3). The 8 s Alert Latency presupposes a fully functioning EEW system along the Wasatch Front Region and is justified as follows.

Previous EEW studies determined that a seismic station spacing of 6–12 miles (10–20 km) is optimal for performance (*Kuyuk and Allen,* 2013), thus we can estimate the earthquake P- wave travel time (Purple zone in Fig. 2.3) based on the current UUSS seismic network and an idealized 12-mile (20-km) spacing between stations in the UUSS network. For the scenario earthquakes explored here, the fastest possible P-wave travel time from the scenario epicenter and depth to the four closest stations varies from 2.1 to 3.5 s. Data Latencies (Gray zone in Fig. 2.3) in ShakeAlert are typically around 1 s, and ShakeAlert requires Data Latencies for each seismic station to be less than 3.5 s. Processing times for ShakeAlert algorithms (Blue zone in Fig. 2.3) range from less than a second to several seconds. Based on these statistics, we assume that the combined Data Latency and Processing Time (time to process the event and disseminate the warning) is 4 s, as previously suggested (*Kuyuk and Allen*, 2013; *Ogweno and others*, 2021). The largest uncertainty in the Alert Latency is in the Alert Delivery Latency (Orange zone in Fig. 2.3).

ShakeAlert uses a variety of alert delivery methods: smartphone apps, Google push notifications for Android OS, and wireless emergency alerts (WEAs; like an AMBER alert) sent by the FEMA Integrated Public Alert & Warning System. The Alert Delivery Latency is highly dependent on the delivery method and varies by alerting event. It can be less than one second for devices connected to the internet (i.e., cell phones on Wi-Fi, machine-to-machine alerts) to more than 10 s for WEA alerts (*McGuire and others*, 2021). A test of WEA alert telemetry delays in California found a median delivery latency of 6–12 s (*McBride and others*, 2023) and cellular delivery is in the range of 1–10 s (*McGuire and others*, 2021). A test of the Alert Delivery Latency for the MyShake app to 100 phones yielded a median delay of 2.8 s (*Allen and others*, 2020). ShakeAlert requires their non-WEA alert delivery partners to have an Alert Delivery Latency of less than 5 s. Here, we assume an ideal Alert Delivery Latency of 1 s, though we note that this can be higher. Adding the 4 s Data Latency and Processing Time and 1 s Alert Delivery Latency to the P-wave travel times of our scenario earthquakes yields total Alert Latencies of 7.1–8.5 s. For simplicity, we assume a constant Alert Latency of 8 s in the following scenarios. Since 2020, the average time for ShakeAlert to send an alert (does not include Alert Delivery Latency) for earthquakes with magnitude 3.5 or greater is 11.64 ± 7 s (personal communication, E. Cochran). Our assumed 8 s Alert Latency is consistent with that range.

Warning Time is calculated as the amount of time between when the alert is received and when the S waves arrive at a given location. It is possible that the shaking could exceed the ground motion threshold for alerting before or after the S wave arrives, depending on the size and characteristics of the earthquake. Modeling when the seismic waves would surpass the ground motion threshold at each location is complex and beyond the scope of this study, thus we assume the ground motion threshold is exceeded with the S-wave arrival for simplicity and consistency.

3.1. Seven Utah Earthquake Early Warning Scenarios

3.1.1. EEW Scenario for the 2020 M5.7 Magna Earthquake

Within Utah, the most recent moderate sized earthquake was the 18 March 2020 M5.7 Magna earthquake (*Pang and others*, 2020; Fig 3.3). It was felt as far away as Idaho Falls, Idaho, to the north; Rock Springs, Wyoming, to the northeast; and Grand Junction, Colorado, to the east, with over 26,000 felt reports submitted to the USGS (see *earthquakes.usgs.gov/data/dyfi*). The maximum horizontal acceleration recorded during the earthquake was 0.43 g (43% of gravity), corresponding to a level of VIII on the Modified Mercalli Intensity (MMI) scale (*Wong and others*, 2021; Fig. 3.3.). Salt Lake City experienced strong shaking but would have been in the No-Alert Zone, and thus too close to the epicenter to receive a timely alert. Residents of Sandy, Tooele, and Layton would have received up to 1–3 s of warning ahead of light-to- moderate shaking (dishes and windows are disturbed or broken; Fig. 3.2). This would not be enough time for people to take protective measures (drop, cover, hold on), but may be enough time for automatic systems to perform preventative actions. Lehi, Park City, and Ogden would have received up to 5–8 s warning ahead of light shaking. More distant cities, such as Provo, Spanish Fork, and Brigham City, would have had up to 12 s or more of warning. This would be enough time for people to take protective measures, but the shaking experienced at these locations was weak-to-light (felt, some disturbance to household items).

EEW systems only issue alerts to areas where the predicted shaking exceeds some threshold, i.e., people located in an area where shaking is very light or not felt will typically not receive an alert. Importantly, ShakeAlert is not responsible for issuing alerts. Instead, ShakeAlert's project partners issue alerts. These project partners currently include the Wireless Emergency Alert (WEA) system, cell phone apps, Android push notifications, public announcement systems, and machine-to-machine actions for MMI III (M4–5+). The threshold to issue an alert to WEA messaging is MMI IV (M5+). In the case of the 2020 Magna event, Logan and Nephi are located outside of the observed ShakeMap but appear to still be within the MMI III region (Fig. 3.3; Intensity = III). Wendover, Price, and Huntington are likely outside the MMI III zone and therefore would not receive an alert. Had the 2020 Magna earthquake grown to M7.0, these more distant cities with potentially longer warning times would have experienced stronger shaking.

3.1.2. EEW Scenario for an M7.0 Earthquake in Salt Lake City

To explore how an EEW system would behave for a large earthquake, we use the earthquake hypocenter and ShakeMap from a previously computed simulation of an M7 earthquake along the Salt Lake City segment of the Wasatch fault zone (*Earthquake Engineering Research Institute*, 2015). In this scenario, Salt Lake City and the nearest suburbs, where the shaking and corresponding damage are expected to be severe, are in the No-Alert-Zone (Fig.3.4). Layton, Park City, and Tooele would receive up to 3–5 s warning before experiencing very strong shaking in Layton (slight to moderate building damage), strong shaking in Tooele (slight damage, furniture moved) and moderate shaking in Park City (dishes and windows broken). This could be enough time for people to start to take protective action, and for automatic safety measures to be implemented in these cities. Ogden, Provo, and Spanish Fork would have up to 8–14 s of warning before strong shaking. Brigham City would have up to 17 s warning before moderate shaking, where household items could be damaged. Seismic wave amplitudes are enhanced in valleys, thus Ogden would experience a higher degree of shaking than Park City, even though it is farther from the earthquake.

3.1.3. EEW Scenario for an M7.0 Earthquake in Brigham City

The second hypothetical earthquake we investigate is located near Brigham City, Utah (Fig. 3.5; *Pankow and others*, 2013). Based on geologic studies of paleoearthquakes, the Brigham City segment of the Wasatch fault zone is considered overdue for a magnitude 6.5–7.0 earthquake. There is evidence of four such earthquakes along this fault segment in the last 6,500 years, with the most recent oc-

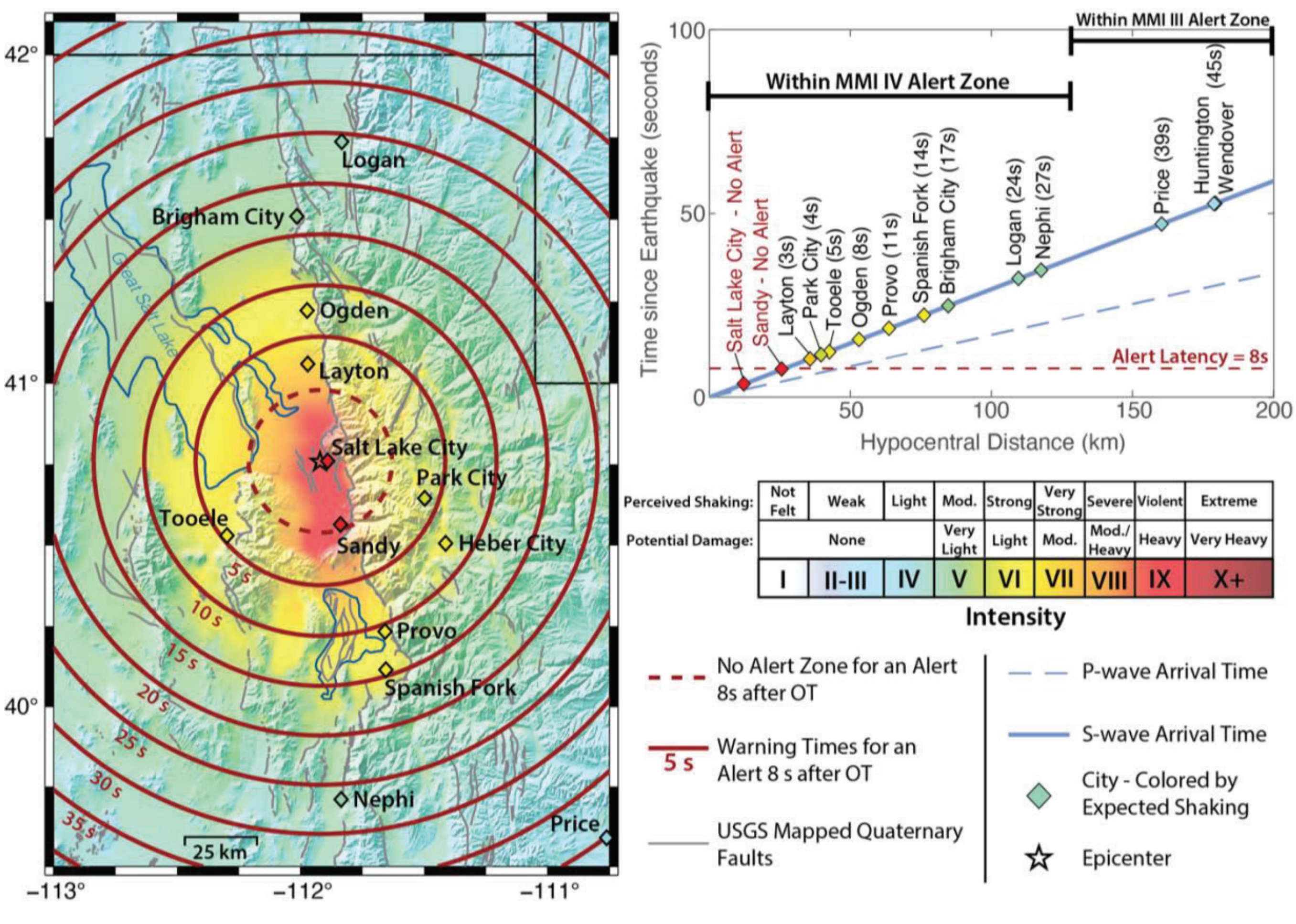


Figure 3.4. *Warning Times for a potential M7.0 earthquake on the Salt Lake City segment of the Wasatch fault zone. The Salt Lake City scenario earthquake source is located at 40.76°N, 111.92°W, 7 mi (12 km) depth (EERI, 2015). The concentric red circles on the map indicate how much Warning Time would be provided before shaking associated with the earthquake S wave begins. The dashed red circle is the No- Alert Zone for an alert latency of 8 s. Colors indicate the maximum intensity of expected shaking modeled for the potential earthquake. The upper right panel summarizes the Warning Times and the expected shaking intensity for select cities.*

curring over 2,000 years ago (*USSC*, 2022). As of 2014, there was a 5.6% probability of an M 6.75+ earthquake on this segment within the next 50 years (*Wong and others*, 2016). A second reason for selecting this location is to ensure we have a range of geographically realistic scenarios. Note that although we use the same magnitude as the M7.0 Salt Lake City scenario earthquake, the expected pattern of shaking is noticeably different. The peak intensity is lower, but the region of severe shaking (VIII) is broader. Differences like these are caused by variations in geology as well as differences in the depth of the earthquake below the ground surface. For an earthquake on the Brigham City segment, the nearest cities of Logan, Ogden, and Layton could receive 1–6 s of Warning Time in advance of very strong-to-severe shaking and moderate-to-heavy damage (slight-to-considerable building damage). This is not a substantial amount of time, particularly for Ogden (1 s warning), but people could start to take protective action, and automatic safety measures could be performed. Salt Lake City would receive 16 s of warning ahead of moderate shaking and very light damage (broken dishes, windows). Brigham City is located too close to the rupturing fault segment to receive a timely alert. Tooele, Sandy, and Lehi are outside the modeled ShakeMap, so we cannot determine what intensity they would experience and if they were within the alert region. The lowest intensity of the ShakeMap is MMI 3.59, thus some of these cities may still be within the MMI III alert region.

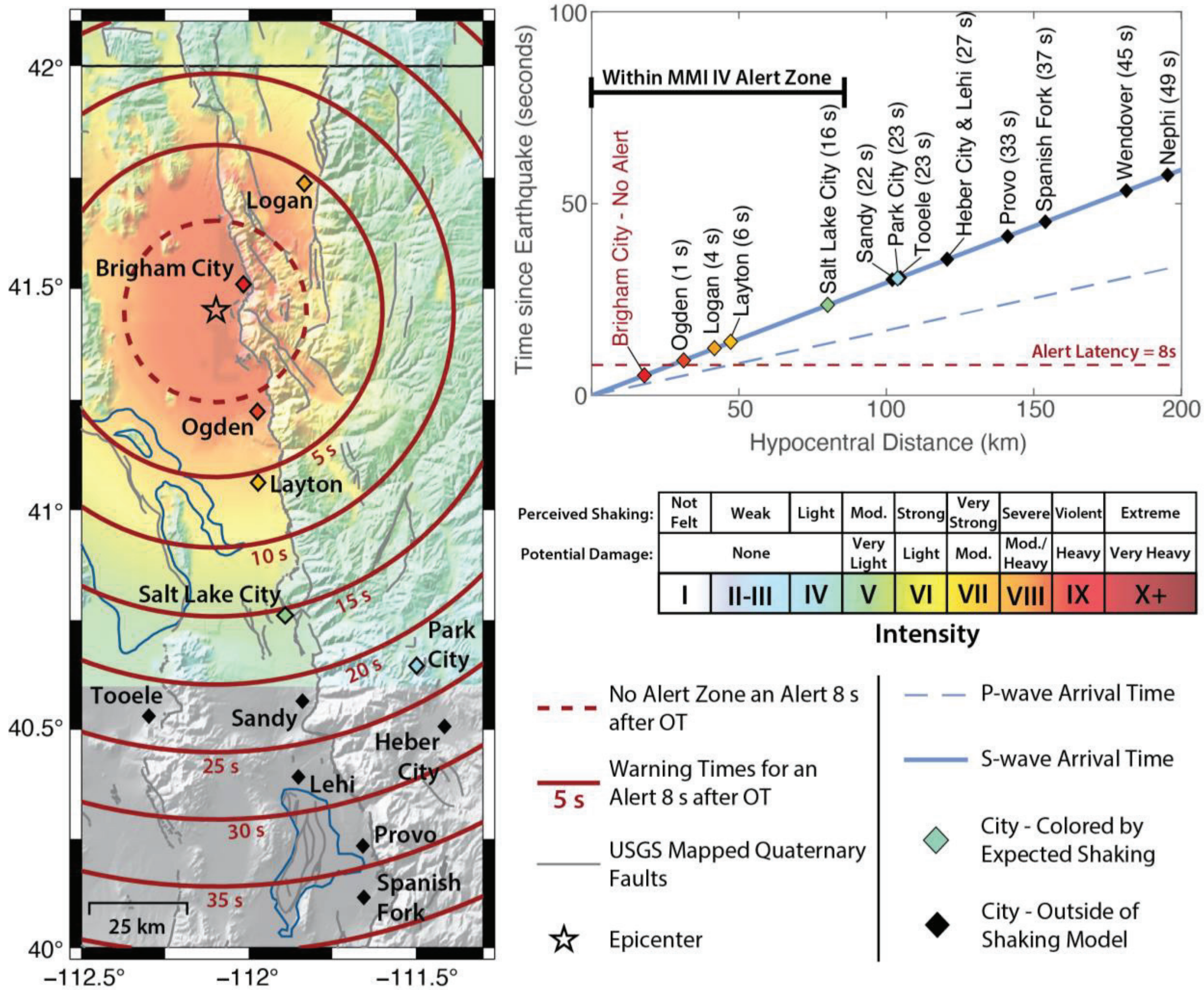


Figure 3.5. *Warning Times for a potential M7 earthquake on the Brigham City segment of the Wasatch fault zone. The Brigham City scenario earthquake source is located at 41.45°N, 112.1°W, 7 mi (15 km) depth (*Pankow and others*, 2013). The concentric red circles on the map indicate how much Warning Time would be provided at that location before shaking associated with the earthquake S wave begins. The dashed red circle is the No-Alert Zone for an alert latency of 8 s. Colors indicate the maximum intensity of expected shaking modeled for the potential earthquake. The upper right panel summarizes the Warning Times and the expected shaking intensity for select cities. For the cities located outside of the predicted ShakeMap, we cannot be sure if they would experience shaking above the intensity threshold for alerting, and thus cannot be sure if they would be alerted.*

3.1.4. EEW Scenario for an M7.0 Earthquake on the Oquirrh-Great Salt Lake Fault Zone

Although the Wasatch fault zone represents the biggest threat for a large earthquake along the Wasatch Front, there are additional faults in the area that pose a risk of generating earthquakes of magnitude 6+. The Oquirrh-Great Salt Lake fault zone, Stansbury fault zone, and West Cache fault zones are all included in the 57% (43%) probability estimate for a magnitude 6+ (M6.75+) earthquake in the Wasatch Front Region (*Wong and others*, 2017). We use a hypothetical earthquake rupture and predicted ShakeMap to assess the EEW potential for a magnitude 7.0 earthquake on the Oquirrh-Great Salt Lake fault zone (Fig. 3.6; *Pankow and others*, 2013). For this rupture scenario, Salt Lake City, Tooele, and Layton are the closest to the earthquake epicenter and are expected to experience very strong-to-severe shaking and moderate-heavy damage. They could receive 2–3 s of Warning Time to begin to take protective action and initiate automated actions. Sandy, Ogden, and Lehi are expected to experience strong shaking and light damage and would have 6–10 s of Warning Time. This would potentially be enough time to drop, cover, hold-on and perform automatic safety measures. Farther from the earthquake, Park City, Brigham City, and Provo would receive at least 12–17 s of warning before light-to-moderate shaking (broken dishes, windows). Logan, Nephi, and farther cities are outside of the modeled ShakeMap, and it cannot be determined if they are within the MMI III alert region.

3.1.5. EEW Scenario for the M6.6 1934 Hansel Valley Earthquake

Additional faults that could cause shaking along the Wasatch Front exist in the region outside of those included for the 50-year probability estimates, such as the Hansel

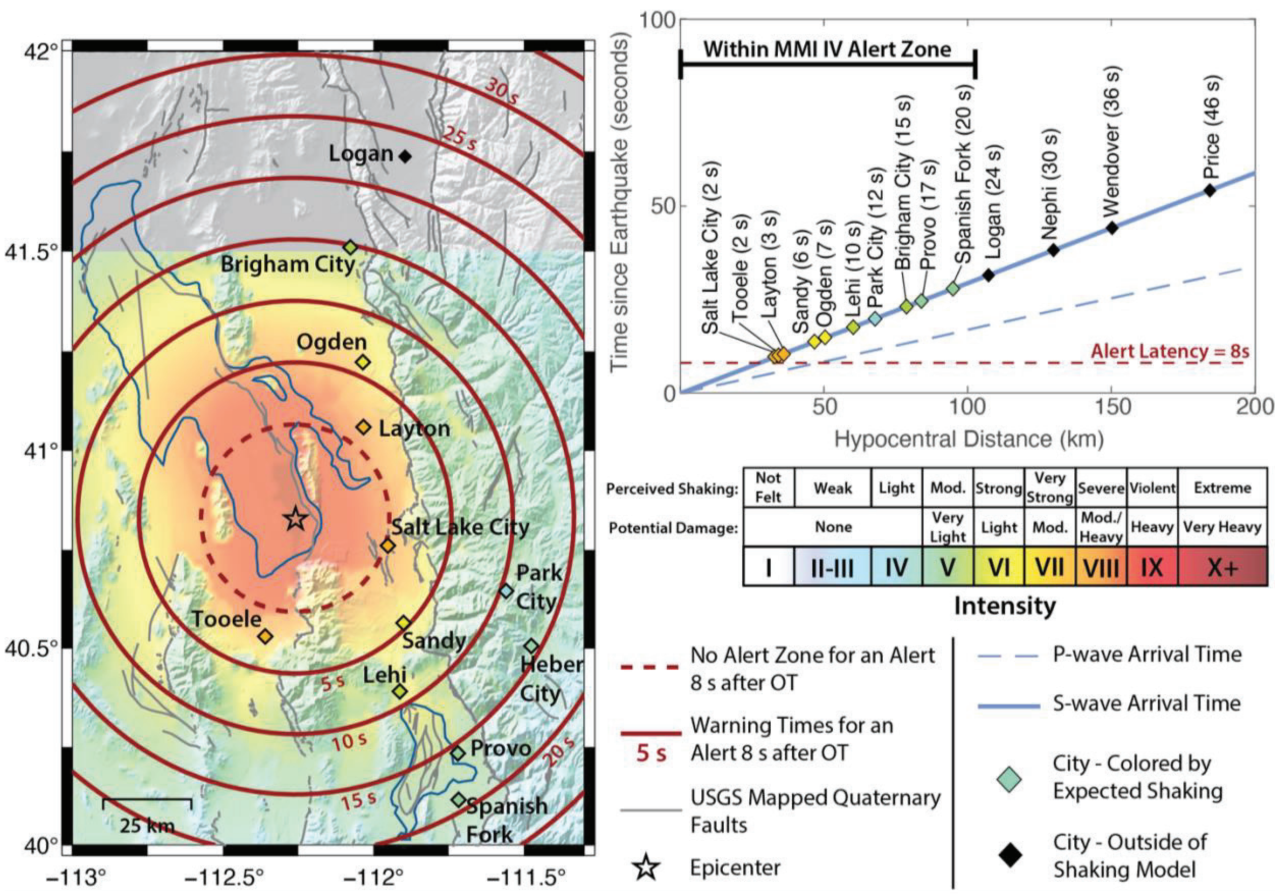


Figure 3.6. *Warning Times for a hypothetical M7 earthquake on the Oquirrh-Great Salt Lake fault zone. The Great Salt Lake fault zone scenario earthquake source is located at 40.83°N, 112.26°W, 4 mi (7 km) depth (*Pankow and others*, 2013). The concentric red circles on the map indicate how much Warning Time would be provided at that location before shaking associated with the earthquake S wave begins. The dashed red circle is the No-Alert Zone for an alert latency of 8 s. Colors indicate the maximum intensity of expected shaking modeled for the hypothetical event (*Pankow and others*, 2013). The upper right panel summarizes the Warning Times and the expected shaking intensity for select cities. For the cities located outside of the predicted ShakeMap, we cannot be sure if they would experience shaking above the intensity threshold for alerting, and thus, we cannot be sure if they would be alerted.*

Valley fault zone, north of the Great Salt Lake. The 1934 M6.6 earthquake in the Hansel Valley is the largest recorded earthquake in Utah and was felt in Idaho, Montana, Nevada, and Wyoming (*Doser*, 1989). Two casualties resulted from the earthquake, and it caused significant property damage (such as chimney collapses in brick buildings), rockslides, the formation of springs and associated calving, and water emissions from fissures. Surveys found that in some regions, the surface subsided by up to 40 cm (*Doser,* 1989). The EEW scenario for this earthquake is shown in Fig. 3.7 (*Pankow and others*, 2013). For an earthquake like the 1934 M6.6 Hansel Valley earthquake, Brigham City, Logan, Ogden, and Layton would have received more than 9 s of warning before the onset of moderate shaking and very light damage (broken household items, windows). Salt Lake City and regions farther south would have received at least 29 s of warning in advance of weak-to-light shaking. We cannot determine if the cities outside the modeled ShakeMap are within the MMI III alert region, though some of the closer cities may be.

3.1.6. EEW Scenario for the M6.5 1901 Richfield, Utah, Earthquake

The Wasatch fault zone is not the only dangerous fault in the Intermountain Seismic Belt (ISB); in 1901 an M6.5 earthquake occurred in central Utah near Richfield, with a felt area of about 50,000 square miles (*Christensen and Nava*, 2012). No casualties were reported following this earthquake, but there were numerous near misses from collapsing walls and ceilings. Structural damage occurred in Richfield, Beaver, Joseph, and Elsinore, including cracks in walls, downed chimneys, roof damage, and broken windows. Large ground disturbance was reported in the areas

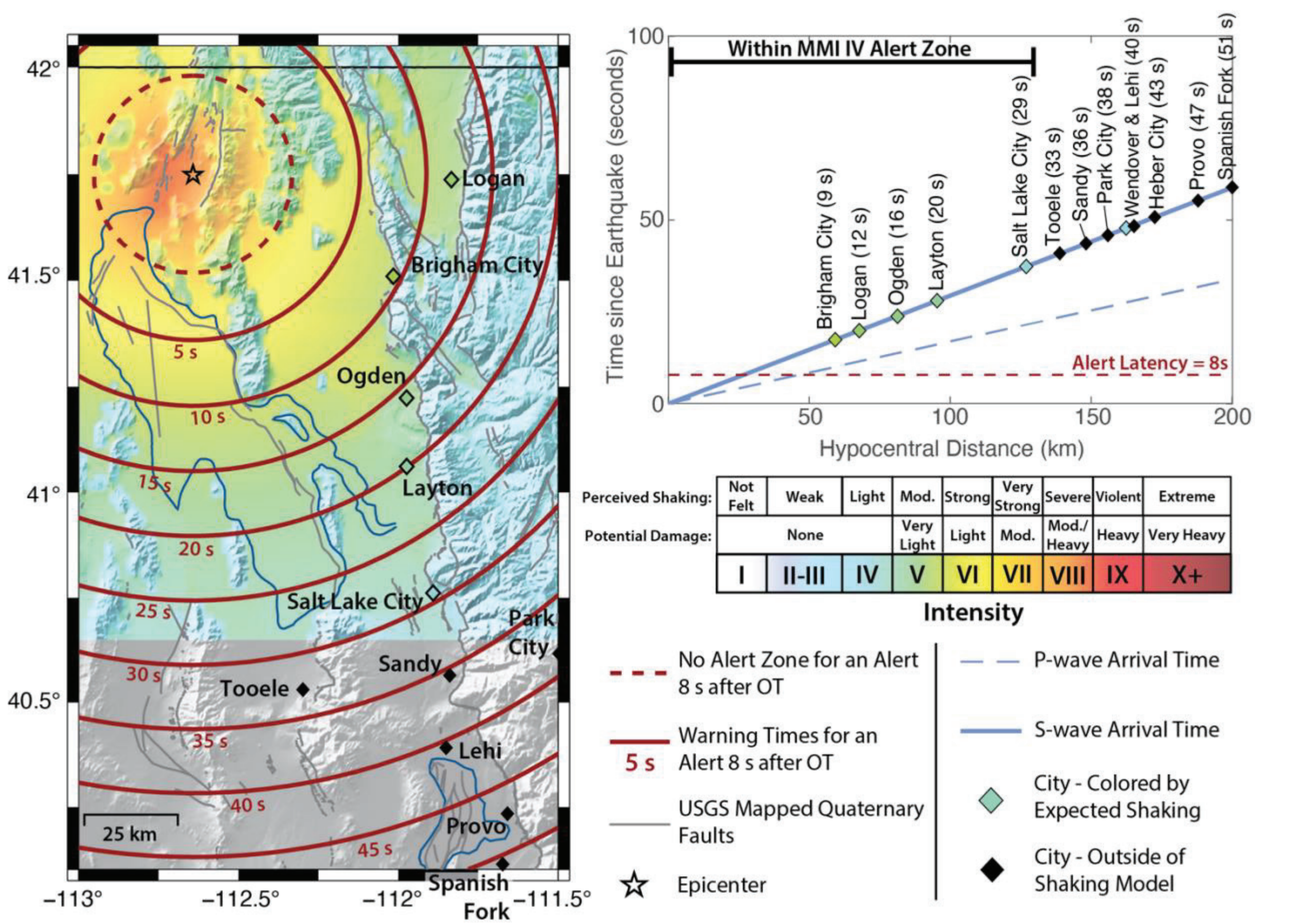


Figure 3.7. *Estimated Warning Times for a potential earthquake like the 1934 M6.6 Hansel Valley earthquake. The Hansel Valley scenario earthquake source is located at 41.75°N, 112.64°W, 5 mi (9 km) depth (*Pankow and others*, 2013). The concentric red circles on the map indicate how much Warning Time would be provided at that location before shaking associated with the earthquake S wave began.*

The dashed red circle is the No-Alert Zone for an alert latency of 8 s. Colors indicate the maximum intensity of expected shaking modeled for the scenario earthquake. The upper right panel summarizes the Warning Times and the estimated shaking intensity for select cities. For the cities located outside of the predicted ShakeMap, we cannot be sure if they would experience shaking above the intensity threshold for alerting, and thus we cannot be sure if they would be alerted.

surrounding Richfield, and some roads and canyons were rendered impassable from fallen rocks (*O'Brian and Nava,* 1997). A predicted ShakeMap for this earthquake (*Pankow and others,* 2013) with potential EEW performance is presented in Figure 3.8. Richfield, Annabella, Elsinore, and Aurora are all within the No-Alert Zone and are modeled to have experienced very strong and severe shaking. Salina and Fillmore would only receive 1–2 s of warning before very strong shaking causing damage to buildings. This is not much Warning Time but may be enough to initiate automatic protective processes. Gunnison and Loa would have 7 and 9 s, respectively, of warning before moderate-to-strong shaking and light damage (broken household items, furniture moving, slight building damage), giving enough time for people to drop, cover, hold-on and for automatic processes to operate. Circleville, Beaver, Delta, Ephraim, Milford, and Sugarville would all have more than 12 s of warning, and up to 22 s for Mt. Pleasant, before shaking arrived and caused damage to household items. We cannot be sure if the cities outside of the modeled ShakeMap are within the MMI III alert region, but some of them likely are.

3.1.7. EEW Scenario for an M6.7 Earthquake on the Hurricane Fault Zone

The Hurricane and Washington fault zones in southwest Utah run along and through the populous cities of Hurricane, Washington, and St. George. This area is continuing to grow and has the potential for large earthquake ruptures. In 1992, an M5.8 earthquake occurred on the Washington fault zone near St. George. Though no casualties or injuries were reported, there was extensive damage due to a landslide caused by the shaking: State Route-9 was closed, hillside homes were destroyed, telephone poles and lines were swept away, and a waterline was damaged beneath a road. A landslide scarp in Springville was up to 50 ft high. A historical building in Hurricane (~12 mi away) received extensive structural damage, and cars were damaged from a rolling boulder in Toquerville (~16 mi away; *O'Brian and Nava*, 1997). A ShakeMap was generated for a hypothetical M6.7 earthquake on the Anderson segment of the Hurricane fault zone, east of Washington and southwest of Hurricane

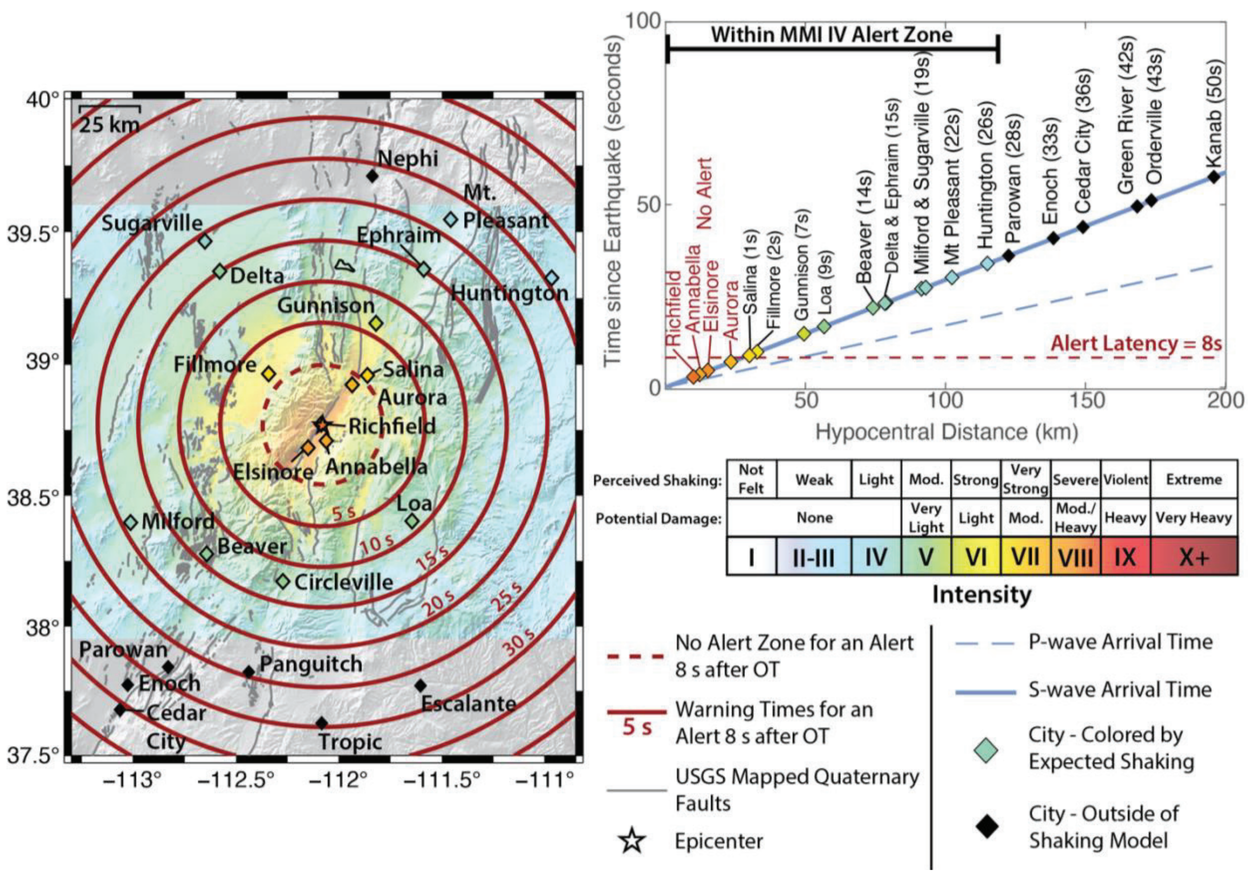


Figure 3.8. *Estimated Warning Times for a potential earthquake like the 1901 M6.5 Richfield, UT earthquake. The Richfield scenario earthquake source is located at 38.77°N 112.08°W, 6 mi (10 km) depth (*Pankow and others*, 2013). The concentric red circles on the map indicate how much Warning Time would be provided at that location before shaking associated with the earthquake S wave began. The dashed red circle is the No-Alert Zone for an alert latency of 8 s. Colors indicate the maximum intensity of expected shaking modeled for the scenario earthquake. The upper right panel summarizes the Warning Times and the estimated shaking intensity for select cities. For the cities located outside of the predicted ShakeMap, we cannot be sure if they would experience shaking above the intensity threshold for alerting, and thus, we cannot be sure if they would be alerted.*

(*Pankow and others*, 2013), and we present a corresponding estimate of the EEW performance (Figure 3.9). If such an earthquake were to occur with a fully-functioning EEW system, Washington, Hurricane, St. George, Toquerville, and Ivins would all be within the No-Alert Zone and experience very strong-to- violent shaking. Enterprise, Cedar City, Orderville, Kanab, and Enoch would receive 10–16 s of warning ahead of moderate-to-strong shaking and light damage. The earthquake would be felt, and household items would be disturbed in Parowan, Panguitch, Tropic, Beaver, Milford, and Circleville. These locations would receive 21–38 s of warning, which would be enough time to take protective action. All the cities shown on the map are within the MMI III alerting region.

3.2. Expected Frequency of Alerts in the Wasatch Front

The benefit of an EEW system depends in part on how often it can be used successfully. Our results show that a Utah EEW system could provide substantial economic and lifesaving benefits for earthquakes like the large paleoearthquakes that occurred on the Wasatch fault zone over the last 6,500 years. In 2014, it was determined that within the next 50 years there was a 43% chance of a large earthquake (M6.75+) occurring in the Wasatch Front and a 57% chance of a smaller but still damaging (M6.0+) earthquake (*Wong and others*, 2017). Given the high seismic risk and the hazard mitigating effect of EEW systems, even a single use of an EEW system for a damaging earthquake within the next few decades would likely pay for itself in terms of reduced losses (*Strauss and Allen*, 2016). The annualized earthquake loss just for the Salt Lake City region is $174 million (*FEMA*, 2023), whereas a Wasatch Front EEW system could likely be constructed for $5 million and operated for less than about $1 million per year, as discussed later.

An EEW system could also be beneficial for smaller earthquakes that generate little damage. Recent work has

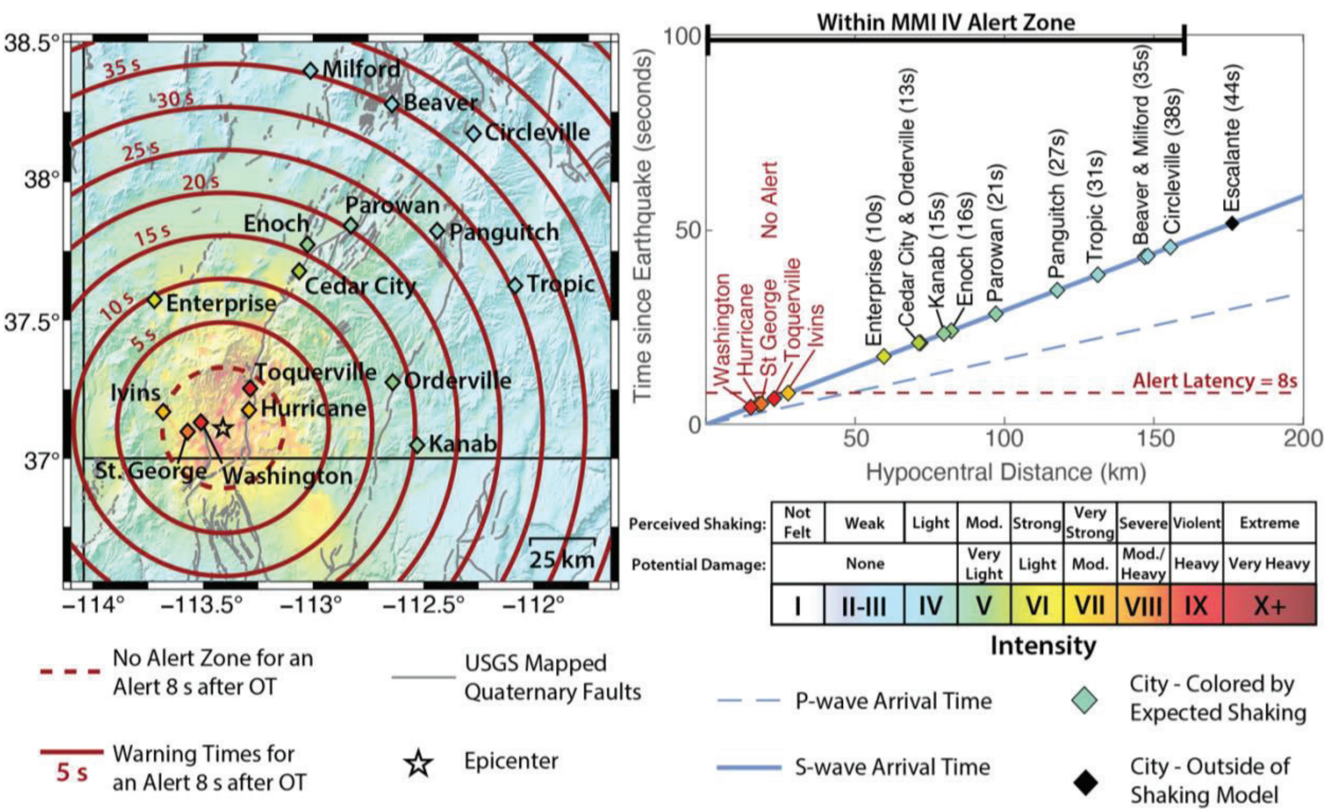


Figure 3.9. *Estimated Warning Times for a potential M6.7 earthquake on the Anderson segment of the Hurricane fault zone in southwestern Utah. The Anderson segment scenario earthquake source is located at 37.11°N, 113.41°W, 7 mi (12 km) depth (*Pankow and others*, 2013). The concentric red circles on the map indicate how much Warning Time would be provided at that location before shaking associated with the earthquake S wave began. The dashed red circle is the No-Alert Zone for an alert latency of 8 s.*

Colors indicate the maximum intensity of expected shaking modeled for the scenario earthquake. The upper right panel summarizes the Warning Times and the estimated shaking intensity for select cities. For the cities located outside of the predicted ShakeMap, we cannot be sure if they would experience shaking above the intensity threshold for alerting, and thus, we cannot be sure if they would be alerted.

shown strong public interest in being warned before shaking occurs, even if the shaking is not strong enough to cause significant damage (*Bostrom and others, 2022*). Because smaller earthquakes occur more often than larger earthquakes, we can expect an EEW system to be activated more often for non-damaging earthquakes. We can use the recent history of earthquakes near the Wasatch Front to estimate their frequency and the corresponding ShakeMaps to estimate their felt areas to get a sense of how often an EEW system would generate alerts for relatively small earthquakes. The key issue is whether the felt area, here defined by the MMI II contour on a ShakeMap, is significantly larger than the No-Alert Zone, which is the region within ~15 miles (25 km) of the earthquake epicenter.

The modern, instrumental earthquake catalog maintained by the UUSS began in 1962. Since then, there have been 14, 27, and 66 earthquakes with magnitudes (M) greater than or equal to 4.5, 4.0, and 3.5, respectively, within or directly adjacent to the Wasatch Front (defined here as 39.65–42.05°N and 111.30–112.95°W, Fig. 3.10). Therefore, on average there is an M ≥ 3.5 earthquake every ~1 (0.96) year, an M ≥ 4.0 earthquake every ~2 (2.26) years, and an M ≥ 4.5 earthquake every ~4 (4.35) years. Of the 31 earthquakes with M ≥ 3.5 since 2002, when ShakeMaps were first implemented in Utah, only one earthquake has been recorded as not being felt. It is extremely uncommon for earthquakes with M ≥ 3.5 to go unfelt along the Wasatch Front.

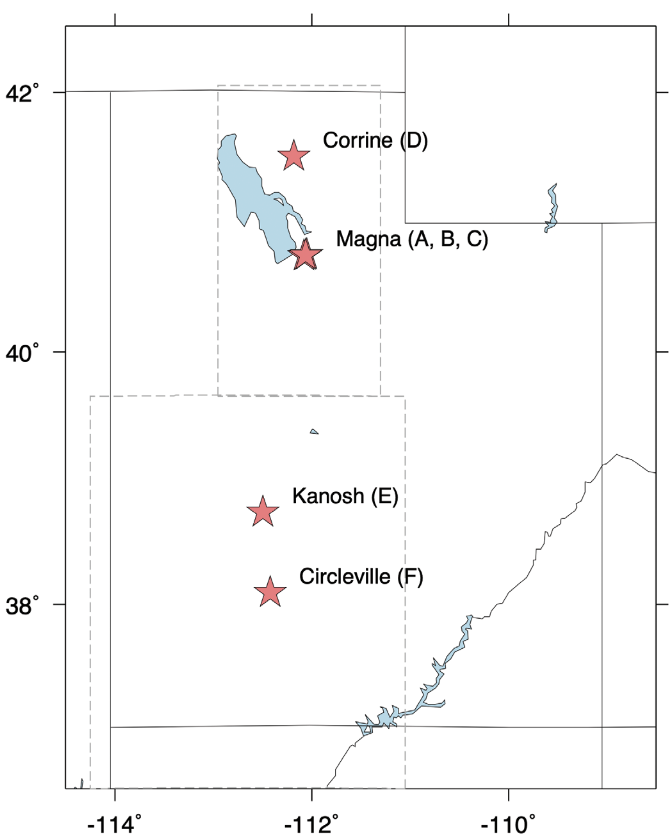


Figure 3.10. *Locations of six recent small earthquakes (**A–F**) in Utah used to estimate the size of felt regions defined by MMI II contours on ShakeMaps. The upper dashed gray box bounds the Wasatch Front Region (Section 3.2), and the lower dashed gray box bounds the central and southern segments of the ISB (Section 3.3).*

We consider data from the following three recorded earthquakes (date, time, latitude, longitude, depth, magnitude, location) to estimate plausible Warning Times for small earthquakes in the Wasatch Front:

A: 2020/03/18, 14:57:41, 40.755°N, 112.047°W, 5.2 mi (8.3 km), M3.6 near Magna

B: 2020/03/18, 13:10:16, 40.748°N, 112.080°W, 4.3 mi (6.9 km), M4.0 near Magna

C: 2020/03/18, 19:12:23, 40.751°N, 112.059°W, 6.6 mi (10.7 km), M4.6 near Magna

All three earthquakes were part of the 2020 M5.7 Magna aftershock sequence with epicenters about 6 miles (10 km) west of downtown Salt Lake City (Fig. 3.10). For earthquake A, the intensity contour representing a felt earthquake (MMI II) stretches as far south as Riverton at ~17 miles (27 km), and as far west as Tooele at ~20 miles (32 km). Alerts at these locations are barely possible with expected Warning Times of 0–1 s and 1–2 s before the S-wave related shaking begins. For earthquake B, the felt region stretches as far south as Saratoga Springs, ~30 miles (49 km) for which we could expect up to 6–7 s of Warning Time, and as far north as Hooper, ~29 miles (46 km) for which we could expect up to 5–6 s of Warning Time. For earthquake C, the felt region stretches as far south as Payson, ~53 miles (85 km) for which we could expect up to 17 s of Warning Time, and as far north as Brigham City, ~52 miles (83 km) for which we could expect up to 16–17 s of Warning Time.

The above Warning Times were calculated assuming 8 s of Alert Latency and that earthquake S waves travel at 2.1 mi/s (3.4 km/s). Here, we are neglecting the effect of earthquake depth. If we accounted for depth, the Warning Times would be slightly longer. As expected, the Warning Time grows with distance, and the felt area grows with magnitude. Importantly, the number of residents in the warning zone also grows with magnitude since the area of the No- Alert Zone remains relatively constant as the magnitude increases. We can expect actual Warning Times to vary somewhat because felt areas are not solely a function of magnitude. They also depend on how the earthquake ruptured (fault orientation, the direction of rupture, and resulting stress changes), as well as regional variations in propagation efficiency (attenuation) and geology (site effects). An example of this phenomenon is given by a recent earthquake (date, time, latitude, longitude, depth, magnitude, location):

D: 2022/11/12, 13:45:07, 41.513°N, 112.181°W, 6.3 miles (10.1 km), M3.6 near Corinne

that occurred about 6 miles (10 km) west of Brigham City (Fig. 3.10). In this case, the MMI II contour stretches as far south as Bountiful, ~47 miles (75 km), for which we could expect 14–15 s of Warning Time, even though it has the same magnitude as earthquake A, which yielded only 0–2 s of Warning Time for the MMI II contour.

Given the above considerations, we estimate that an EEW system along the Wasatch Front could be expected to provide alerts in advance of noticeable ground shaking about every two years on average. However, its use would cluster in time because earthquakes tend to cluster in mainshock-aftershock sequences. If we assume an EEW system had been in place for the last 61 years (since 1962), that it issued alerts for all 27 M4+ earthquakes along and near the Wasatch Front, and that it did not issue alerts for any of the smaller earthquakes, then 26% or 7 of the alerts would have been issued during a ~1-month period associated with the 2020 M5.7 Magna earthquake sequence. The longest dry spell with no alerts would have been 17 years, corresponding to the time between an M4.2 earthquake near Herriman in 1992 and an M4.0 earthquake near Riverside in 2009.

3.3. Earthquake Early Warning Outside of the Wasatch Front

While the Wasatch Front is the logical starting point for EEW in Utah based on the estimated hazard (Fig. 1.3), expansion to the south and west along the ISB (Fig. 1.1), generally following the Interstate 15 corridor, would be beneficial. This region lacks the compelling paleoseismic record of the Wasatch fault zone; however, it is seismically active and contains relatively well-mapped faults (such as the 155-mile [250-km] long Hurricane fault zone) capable of generating large earthquakes (*Lund and others*, 2006). Since 1900, there have been 20 earthquakes with magnitude 5.0+ within the region, including an M6.6 earthquake near Marysvale in 1901, and an M6.3 earthquake near Pine Valley in 1902 (*Arabasz and others*, 2016). Metropolitan areas in southwestern Utah have been among the fastest growing areas of the country, with the St. George region in Washington County doubling in size between 2000 and 2022 (*https://utah.reaproject.org*). Rapid growth is expected to continue, and the population in Washington County is projected to reach 464,000 by 2060 (*University of Utah*, 2022). Therefore, seismic risk in the region is rapidly increasing, and a repeat of the 1902 M6.3 Pine Valley earthquake today would cause considerable damage.

The UUSS maintains seismograph stations throughout Utah, but the station and population density are the highest within the Wasatch Front Region. Constructing an EEW system in southwestern Utah would be more expensive. Propagation of seismic energy in this region is roughly like that along the Wasatch Front. Considering two recent earthquakes (time, latitude, longitude, depth, magnitude, location) in the region (Fig. 3.10):

E: 2019/02/20, 07:05:35, 38.738°N, 112.497°W, 5.1 miles (8.2 km), M4.0, near Kanosh

F: 2020/10/03, 11:47:43, 38.092°N, 112.420°W, 5.2 miles (8.3 km), M4.4, SW of Circleville

we observe that for earthquake E, the MMI II contour (felt region) stretched as far east as Richfield at 22 miles (36 km) with a Warning Time of 2–3 s, and for earthquake F, the MMI II contour stretched southwest to St. George at 93 miles (150 km) with a Warning Time of 36–37 s. Since 1962, there have been 51 earthquakes in this region (defined here as 36.50 to 39.65°N and 111.05 to 114.25°W, Fig. 3.10) with magnitudes 4.0+. Assuming that the No-Alert Zones for these events would have been significantly smaller than the felt regions, an EEW alert would have been issued every ~1.2 years, more frequently than along the Wasatch Front. But given the lower population density in this region, the number of residents receiving the alerts would be smaller. The longest dry spell with no alerts would have been almost seven years, corresponding to the time between an M4.2 earthquake near Levan in 2003 and an M4.1 earthquake near Cedar City in 2010.

3.4. Caveats

Although we follow methodologies used in previous EEW feasibility studies (e.g., *Kuyuk and Allen*, 2013; *Ogweno and others*, 2019), our modeling is necessarily simplified compared to what may happen during operation of an EEW system (*Wald*, 2020). In practice, for large earthquakes, as more data are processed, ShakeAlert sends multiple alerts to account for the temporal evolution of the predicted shaking. The earliest alerts may underpredict shaking or be otherwise inaccurate. Earthquakes are also more complicated than what we have assumed in these examples. Large earthquakes often have directivity effects that can alter the shaking experienced depending on the direction relative to the fault, and algorithms for predicting ground motions are an active area of research.

There are also choices to be made by EEW operators about what ground motion threshold should be used for alerting. Currently, ShakeAlert generates alerts for predicted ground motion intensities of MMI III or greater, depending on the delivery method (*shakealert.org*). Lower thresholds could lead to more false alerts, while higher thresholds could lead to more missed alerts. In general, EEW systems should be viewed as another tool to help reduce economic losses and improve personal safety, not as a panacea.

4. NEEDS FOR IMPLEMENTING EARTHQUAKE EARLY WARNING IN UTAH

In this section, we explore how well the current UUSS seismic network would perform as an EEW system and what changes need to be made to realize the benefits presented in Section 3. We first summarize the current UUSS network and earthquake analysis process and evaluate individual stations in terms of existing ShakeAlert acceptance criteria. We then assess the seismic wave travel times for potential earthquakes, given the current network configuration and status. Lastly, we evaluate what improvements to the network are required to maximize the EEW benefit in Utah. We use a method that "scores" potential locations where new seismic stations can be deployed by how much benefit they provide to the network (*Hotovec-Ellis and others*, 2017). In this way, we can identify key areas for station upgrades or new station installations and evaluate the corresponding return in EEW performance. The changes that can be made to a seismograph network to maximize the Warning Time at a given location are to decrease the P- wave travel time to the four closest stations with denser station coverage, decrease the Data Latency with upgraded telemetry and adjusted station settings, and decrease the Processing Time with improved EEW algorithms (Fig. 2.3).

4.1. Current Seismic Monitoring Capabilities

Earthquakes in Utah are detected, located, and characterized by the University of Utah Seismograph Stations (https://quake.utah.edu). In an average year, about 1,500 earthquakes in Utah are large enough to be recorded, analyzed, and cataloged. The UUSS disseminates the locations and magnitudes of Utah earthquakes to the public via X (formally Twitter), web posting, and quarterly reports. Utah earthquake information is shared with the USGS, which redistributes the information to a broader audience via the Advanced National Seismic System (ANSS) Comprehensive Catalog (*Guy and others*, 2015; *USGS and EHP*, 2017). Since 2001, funding for UUSS operations in Utah has been provided by an almost 50/50 state-federal partnership, with the federal portion coming from the USGS under the auspices of the ANSS (*USGS*, 2017). During the most recent state fiscal year (July 1, 2022 – June 30, 2023), the Utah Legislature appropriated $818,000, and during the most recent federal project year (Feb. 1, 2022 – Jan. 31, 2023), the USGS contributed $849,429 via a cooperative agreement.

The UUSS currently operates 217 seismograph stations in Utah (Fig. 4.1), 129 of which are in the Wasatch Front Region (Fig. 4.2a, b). Ground motions at these 217 stations are continuously recorded, mostly at 100 samples per second, and transmitted to the UUSS Earthquake Information Center (EIC). Transmission methods include microwave radio, internet, and cellular modem. Seismic data received at the EIC are processed with the ANSS Quake Monitoring Software (AQMS) system (*Hartog and others*, 2022) to detect, locate, and calculate the magnitude of these earthquakes. When an automatically detected earthquake is larger than a predetermined magnitude threshold (usually M3.0), alerts are issued, and notifications are sent to UUSS personnel and a short list of stakeholders. On average, the alert is issued almost four minutes after the earthquake origin time (Fig. 4.3), much too late to be useful for EEW. The delay is partially caused by a trade-off between detection speed and magnitude accuracy in AQMS data processing. The UUSS is investigating decoupling the duration magnitude requirement from the earthquake detection protocol, which could improve Alert Latencies by tens of seconds but would still be too slow for EEW.

The UUSS uses three types of seismic sensors (i.e., seismometers) in network operations: broadband (records a wide range of seismic wave frequencies), short-period (records locally generated, high-frequency seismic waves), and strong motion (records large ground motions from larger earthquakes). A single seismograph station may have one, two, or all three types of sensors. Short-period sensors are not used in EEW systems because large earthquakes tend to have ground motions beyond the scale of these sensors, saturating the signal, and the sensors do not record lower frequency waves accurately. Furthermore, most of the UUSS short-period stations record only vertical, not horizontal, components of motion. Broadband sensors can also saturate if they are too close to the earthquake epicenter, but they can still be used in EEW if they are far enough away to record the full range of ground motion. Strong motion sensors typically do not saturate and are well suited for deployment in urban areas as part of an EEW system. Of the 129 seismograph stations along the Wasatch Front, 89 have a broadband or strong motion sensor appropriate for use in an EEW system.

Each seismograph station must be investigated for data quality and performance before being incorporated into an EEW system. Poor data quality can render a seismic site unusable or even hinder the EEW system by creating false alerts or incorrect magnitude estimates. High background noise can mask the earthquake signal, increasing the time for the system to detect an earthquake and, subsequently, the time to issue an alert, or prevent detection entirely. Similarly, if a site becomes inoperable (no data) or if data take too long to transmit (large Data Latency) to the EIC, the time to release an alert will increase and could be too late to be of benefit. Sites where there are frequent electronic spikes or glitches in the data can cause the system to falsely issue an earthquake detection. A high recording offset (i.e., DC bias) increases the likelihood of saturating the recording scale, making it impossible to determine the maximum ground motions for magnitude estimation and ground-motion based detection. Subsequently, when the ground motions are so high that their recordings become saturated, the derived earthquake magnitudes will be much smaller than the true values.

We compare recent UUSS station performance with the acceptance metrics currently used in the ShakeAlert West Coast U.S. system. We examine (1) percent data availability and DC, or mean, bias using the Seismological Facility

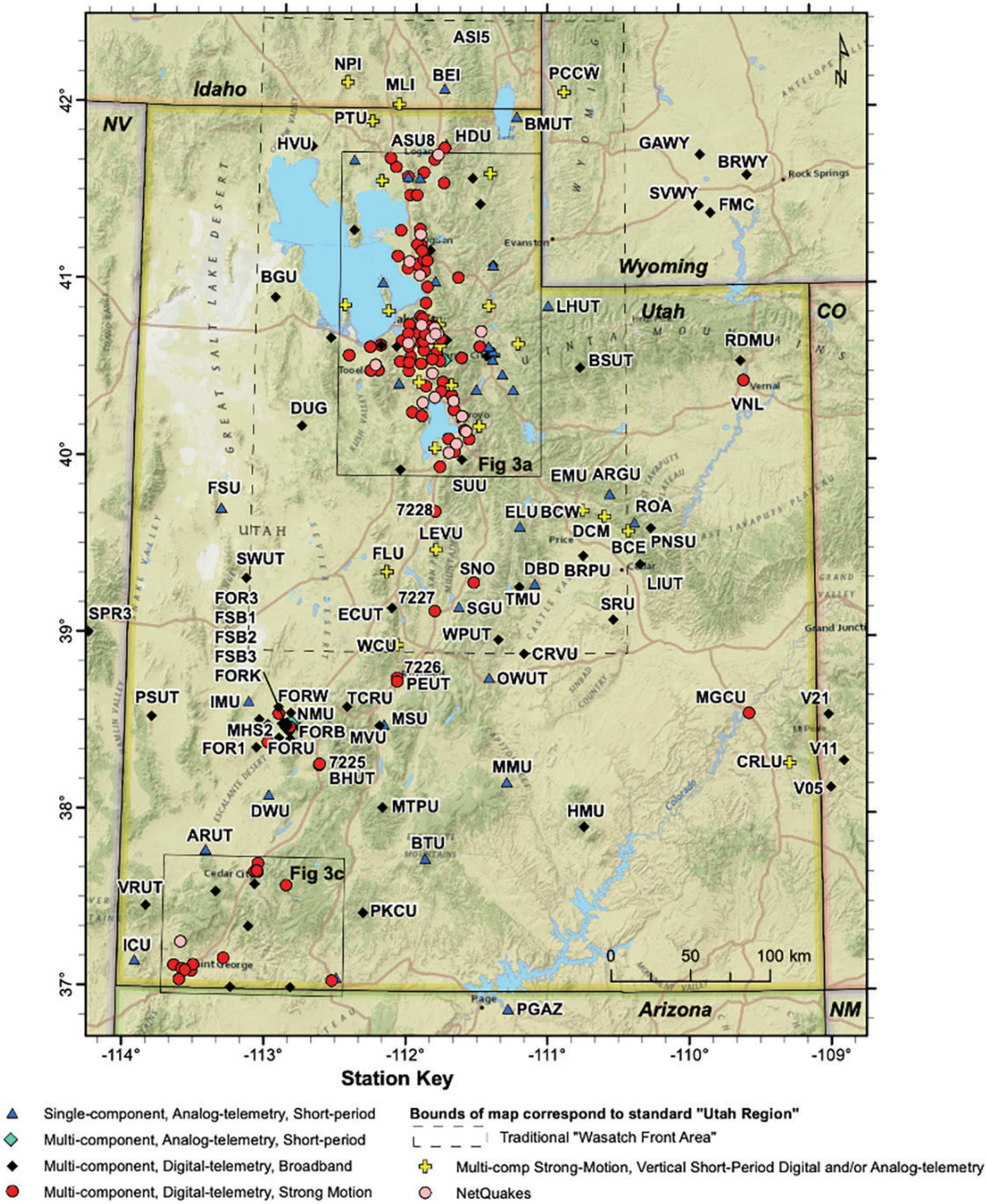


Figure 4.1. *Locations of UUSS seismograph stations in the Utah region as of 23 March 2023. Stations that meet the requirements for use in EEW systems include broadband (black diamonds) and strong motion (red circles and yellow plus symbols).*

for the Advancement of Geoscience (formerly IRIS) Mustang tool set (*Casey and others*, 2018) over a 2-week period, (2) the presence of data spikes and high background noise using the University of Washington SQUAC tool (*Ulberg and others*, 2023) over a 2-week period, (3) current data latency over 30-minute periods, and (4) earthquake phase pick quality over a 1-year period.

Table 4.1 shows the ShakeAlert station acceptance criteria and the corresponding pass- rate for existing UUSS broadband and strong motion stations. Most of the broadband and strong motion sites pass the data availability and quality tests. Of all the compatible sensors, 95% meet the data availability standards, meaning they are not regularly suffering from data gaps and drop- outs, which could delay earthquake detection.

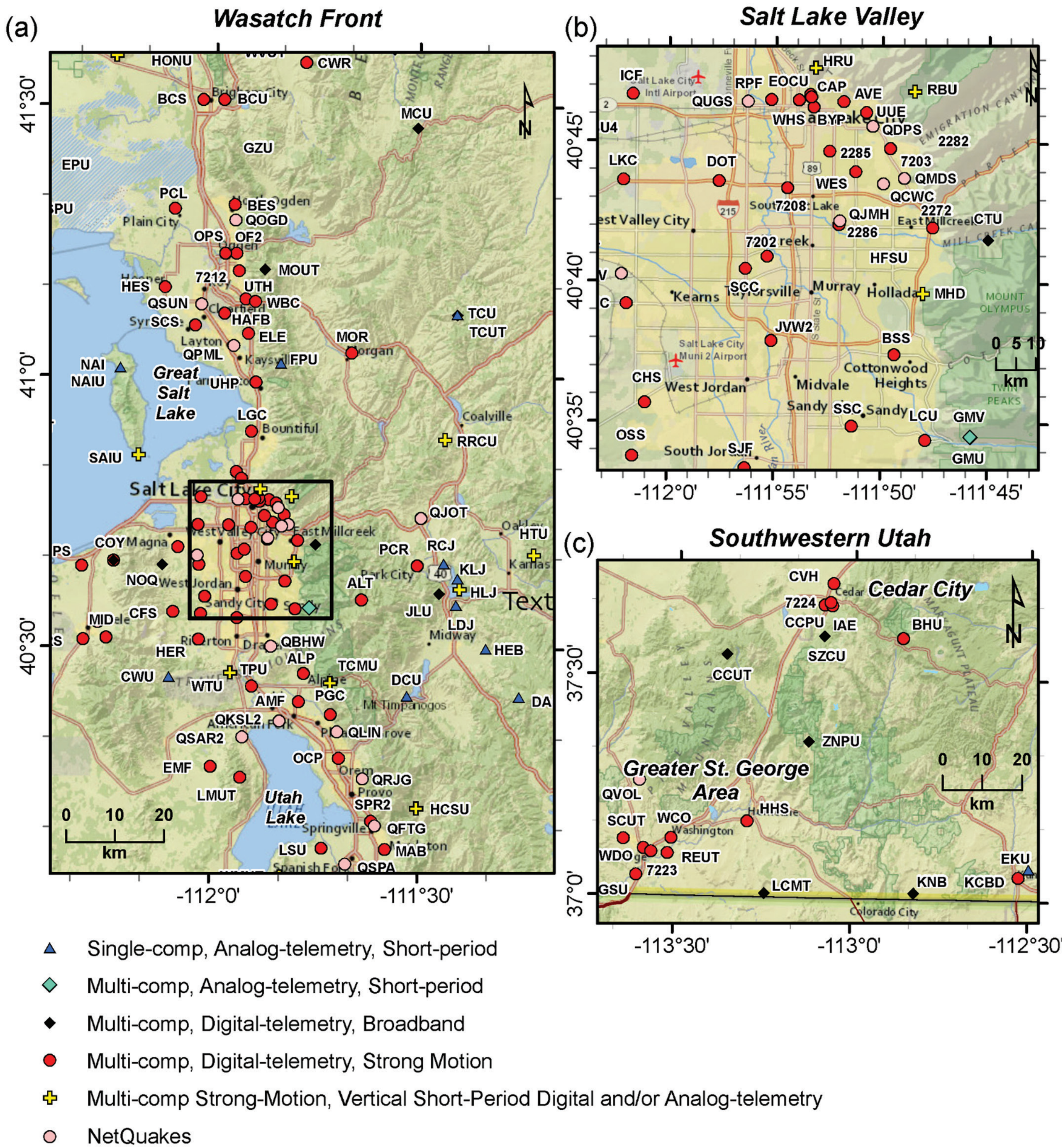


Figure 4.2. *Zoomed in views of UUSS seismograph station locations in Utah.*

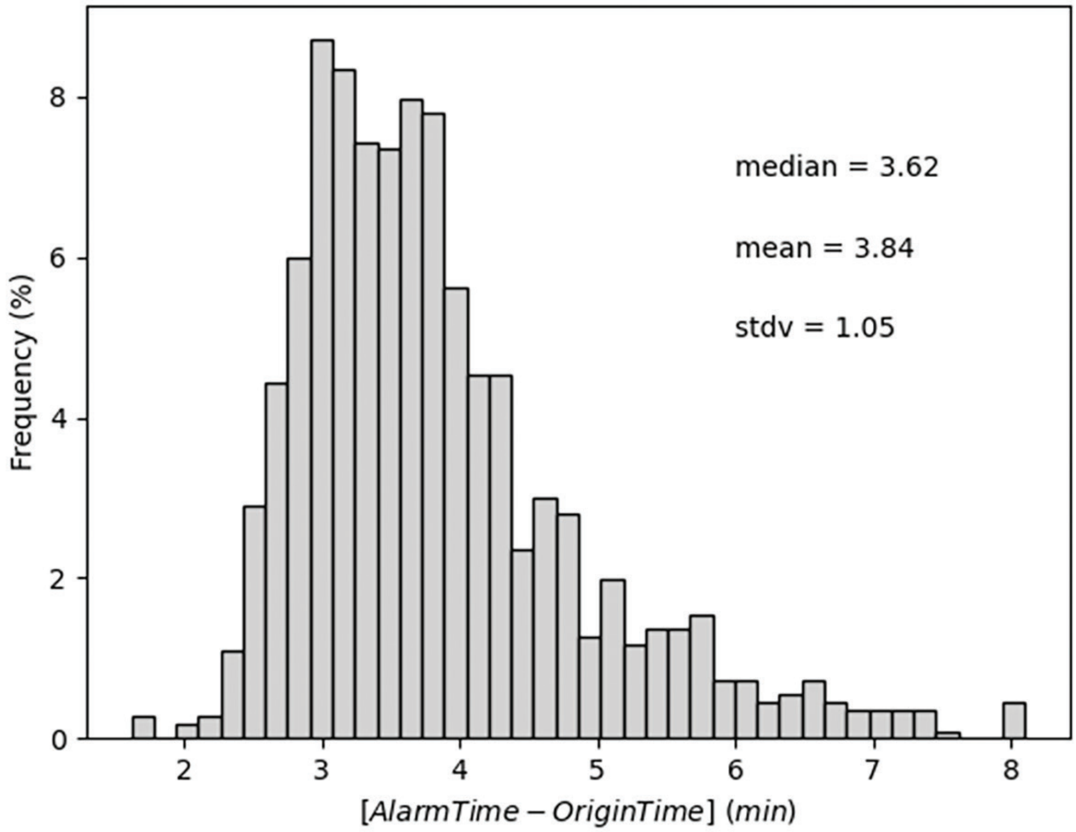


Figure 4.3. *Alert latencies for Utah earthquakes that were significant enough to generate an alert under the current UUSS non-EEW earthquake monitoring system (AQMS). There were 1,102 alerts generated for M2.5+ earthquakes during 2012–2022. In this case, alerts are synonymous with notifications.*

Table 4.1. *Table of ShakeAlert performance requirements and corresponding pass-rate of UUSS early warning-ready seismograph stations. Data completeness and DC bias were determined from a 2-week period using the IRIS Mustang tool; spike and background noise were determined from a 2-week period (if available) using the University of Washington SQUAC tool; data latency was measured on the UUSS data import computers over 30-minute periods; phase residuals were examined from automatic earthquake locations in the UUSS database over a 1-year period. Here, BB stands for broadband stations and SM stands for strong motion stations.*

	90% Data Completeness/ Availability	Data Latency <3.5s 90% of the Time	<20 Spikes/ Glitches per Hour	<1 minute per Hour of High Background Noise	DC Bias Within 10% of Sensor Range	Phase Residuals Within 0.5s of Nearby Stations
Pass Rate	95% of BB and/or SM sensors	0%	99% of available sensors	99% of available sensors	100% of available sensors	P-wave phase arrivals: 87% of applicable seismic sites

Even better, 99% of sensors providing data during these tests were within the minimum allotted data spikes and high background noise limits, minimizing the probability of false detections and false alerts, and missed detections, respectively. All the available EEW-compatible sensors are within the required DC bias range, indicating that their recordings are not substantially offset. Automatic earthquake P-wave arrival flags are acceptable for 87% of sensors, which indicates that initial automatic locations would be fairly accurate for EEW alerting. The only metric in which the UUSS seismic network performs poorly is Data Latency (gray zone in Fig. 2.3). The current UUSS network is designed for monitoring and rapid reporting on the order of minutes. EEW systems require < 3.5 s of Data Latency, and none of the existing UUSS seismograph stations meet this criterion. Many stations exhibit Data Latencies of tens of seconds or more. Potential solutions to this problem are described below.

4.2. Telemetry Upgrades for Existing Stations

Before exploring the EEW benefits of adding new seismograph stations, we consider the effect of telemetry upgrades to the existing UUSS network of broadband and strong motion sensors. Telemetry involves sending data from individual seismograph stations to the UUSS EIC. Telemetry upgrades are cheaper, faster, and simpler than installing new stations because the capital costs are lower, and no new site scouting, environmental assessments, or site licenses are needed.

The primary question we ask is, "Given the current UUSS network configuration, how long would the Alert Latencies be if all the stations met the ShakeAlert Data Latency requirements?". We expect that minimum Alert Latencies will be somewhat longer than the 8 s assumed in Section 3 because the existing network does not have the 6–12 miles (10–20 km) station spacing required for ShakeAlert; however, the existing station density along the Wasatch front is nearly that high and Alert Latencies might not be significantly longer for most of the region.

Assuming an earthquake depth of 7 miles (12 km), consistent with local Utah seismicity, and constant earthquake P- and S-wave velocities, we can calculate the seismic wave travel time (purple zone in Fig. 2.3) for every potential earthquake location along the Wasatch Front Region. Seismograph station configuration directly affects the amount of Warning Time a location receives (red zone of Fig. 2.3) through the amount of time for the earthquake P wave to be recorded on four stations. The travel time contribution to the overall Alert Latency will vary according to the location and depth of the potential earthquake and how far away it is from nearby stations.

Figure 4.4 shows the theoretical earthquake P wave travel times (purple zone in Fig. 2.3) to four stations with the current UUSS network configuration. The lower the travel time, the more Warning Time can be provided. Due to the denser seismograph station coverage, the shortest travel times are within the ISB, especially within the Wasatch Front. In the Wasatch Front, seismograph stations are clustered close to the surface traces of the Wasatch fault system (Fig. 4.2), so the shortest travel times follow this trace (Fig 4.4, right). If we add the 5 s assumed for Data Latency, Processing, and Alert Delivery as described in Section 3, earthquakes in this north-south corridor would yield Alert Latencies of ~7–8 s. Earthquakes originating outside of this narrow zone, however, have increasing Alert Latencies due to the decrease in station density. For earthquakes occurring near Tooele and westward, the Alert Latencies increase from 9 s to ~15 s or more. South of Spanish Fork to Nephi, earthquakes would have Alert Latencies of 9–12 s. Similarly, eastward of Park City and north of Logan, earthquake Alert Latencies increase to 13 s. Thus, if an EEW system was developed with the existing UUSS network, without adding new stations, the Utah EEW system would alert in ~8 s for earthquakes along the Wasatch fault system. However, earthquakes on faults outside this narrow zone could take up to twice as long to send alerts because of decreased seismograph station coverage.

Though there are pockets of similarly short travel times in the southern ISB (corresponding to Washington, Cedar City, and the FORGE experiment NW of Beaver), the station coverage is generally less dense than in the Wasatch Front (Fig. 4.1) and travel times are longer, up to ~10 s for events in the ISB (Fig 4.4, left). For earthquakes in the ISB between Nephi and Beaver, Alert Latencies could be ~12–15 s in an area where there are known faults and as discussed in Section 3, the location of one of the largest historical earthquakes in the state (1901 M6.6 Richfield). In the southwest corner of Utah, earthquakes on the Hurricane Fault and Sevier Fault would have Alert Latencies of ~10–15 s. For an EEW system to be implemented in the central and southern ISB, additional stations would be needed to maximize the Warning Time. Outside of the ISB, travel times are very large because there are few to no seismograph stations (Fig. 4.1), but there are also much fewer earthquakes, and seismic hazard is lower (Figs. 1.1 and 1.3).

For the UUSS network to realize the Alert Latencies discussed above, the current telemetry would need to be upgraded to meet the Data Latency requirements of an effective EEW system. The telemetry upgrades needed to address the Data Latency issues (gray zone in Fig. 2.3) and convert the existing UUSS seismic network along the Wasatch front into an EEW- capable system consist of:

- Adjusting station configurations to send data in smaller time-packets and deliver non- compressed, low-latency data streams,
- Upgrading existing radios to decrease transmission time and radio interference,
- Adding cellular modems and/or commercial internet connections to many existing stations for telemetry redundancy,

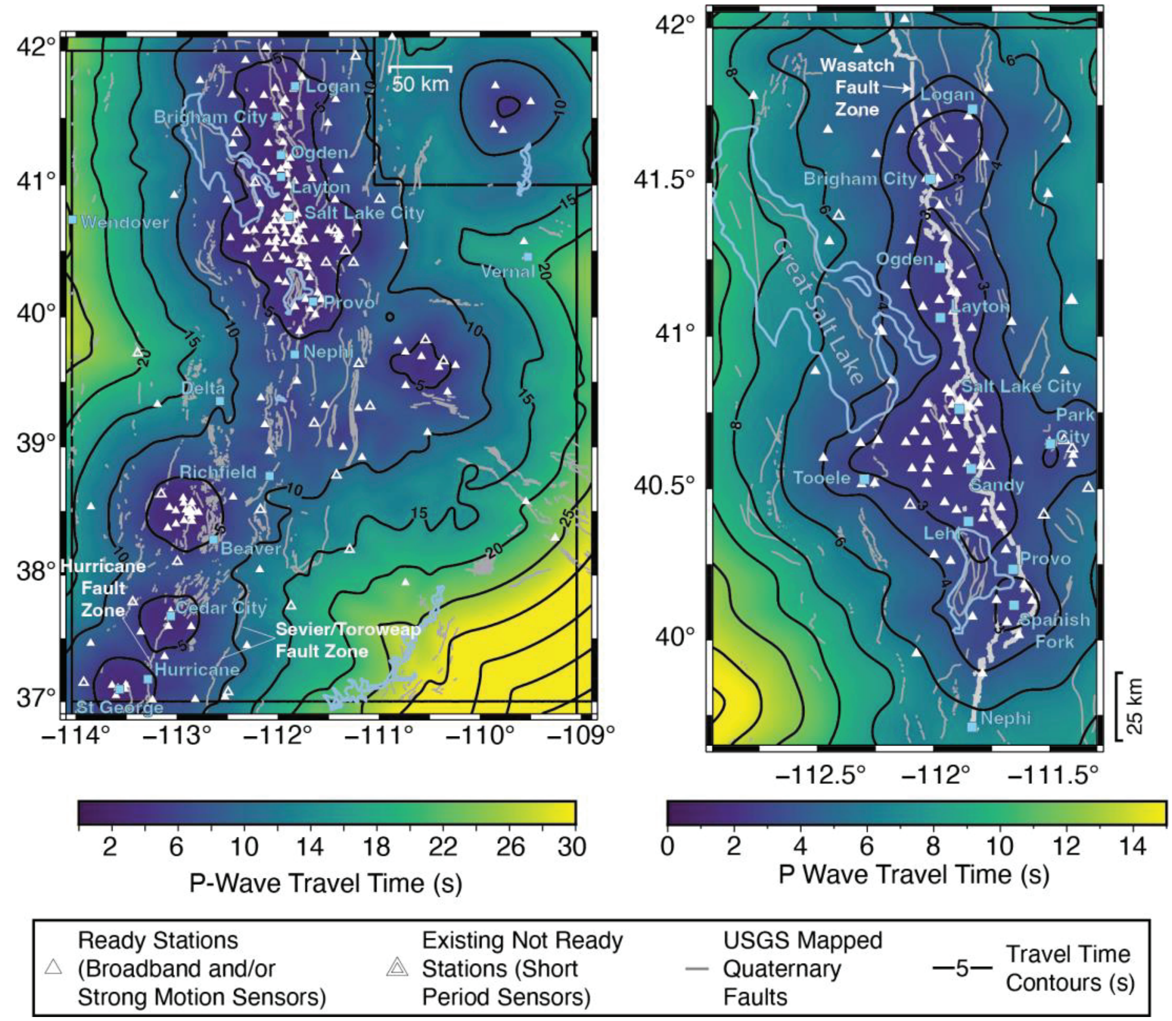


Figure 4.4. *Theoretical P wave travel times (purple zone in Fig. 2.3) for earthquakes originating at a depth of 7.5 miles (12 km) to the existing UUSS network of EEW-ready seismograph stations (has a broadband and/or strong motion sensor) for earthquakes throughout the state **(left)** and within the Wasatch Front **(right)**. Colors represent the travel time to four stations for an earthquake at that location, assuming a P-wave velocity of 3.6 mi/s (5.9 km/s). The grid of potential earthquake source locations is spaced at 0.1° in both longitude and latitude. Alert Latency for a given earthquake with the current network configuration can be estimated by adding 5 s (4 s for Data Latency and Processing Time + 1 s for Alert Delivery Latency, assumed in Section 3) to the P-wave travel times.*

- Upgrading cellular data plans to accommodate increased data needs,
- Adding additional equipment to enable non-compressed data transmission, and
- Upgrading and augmenting power systems (batteries and solar panels) to accommodate newer radios and additional telemetry paths.

4.3. Adding New Seismograph Stations

Previous EEW studies determined that a station spacing of 6–12 miles (10–20 km) is optimal for performance (*Kuyuk and Allen,* 2013); however, it would take a lot of resources and many years to implement this type of spacing everywhere in Utah, and potentially not be cost- effective in areas with large recurrence intervals between significant earthquakes and reduced population and infrastructure. Therefore, we test how a 12 mile (20 km) spaced seismic network would benefit an EEW system in Utah, if pursued. We compare the P-wave travel times for the current UUSS network of EEW-ready stations with a hypothetical, denser network: we assume all short-period seismic sites (“Not ready” sites) can be upgraded to broadband and/or strong motion sensors, and 610 new stations can be added throughout the state (80 in the Wasatch Front Region, an additional 118 in the rest of the ISB) to achieve the 12 mile (20 km) station spacing. EEW-ready stations are those that currently have either a broadband or strong motion sensor. This exercise is simplified and does not consider the ease of station installation in these locations, such as whether the new sites would be underwater or otherwise unreachable. Assuming Data Latencies, Processing Times, and Alert Delivery Latencies remain constant between the current and denser networks, the differences in seismic wave travel times translate to differences in Warning Times. Figure 4.5 shows the decrease in time for the seismic waves to reach the required number of stations for detection with the denser network, and the resulting increase in Warning Time.

Along the mapped Wasatch fault zone (gray lines in Fig. 4.5) and approximately from Logan to Spanish Fork, the denser network decreases the alert latency by less than 1 s (Fig. 4.5, right). The denser network would also yield less than 2 s of reduced alert latency for earthquake sources along the Oquirrh-Great Salt Lake fault zone from approximately 41°N to south of Tooele. This indicates that the current UUSS network coverage is sufficient for detection of earthquake sources on or near the surface expression of the Wasatch fault zone. The additional stations would provide the most benefit for earthquake sources outside of

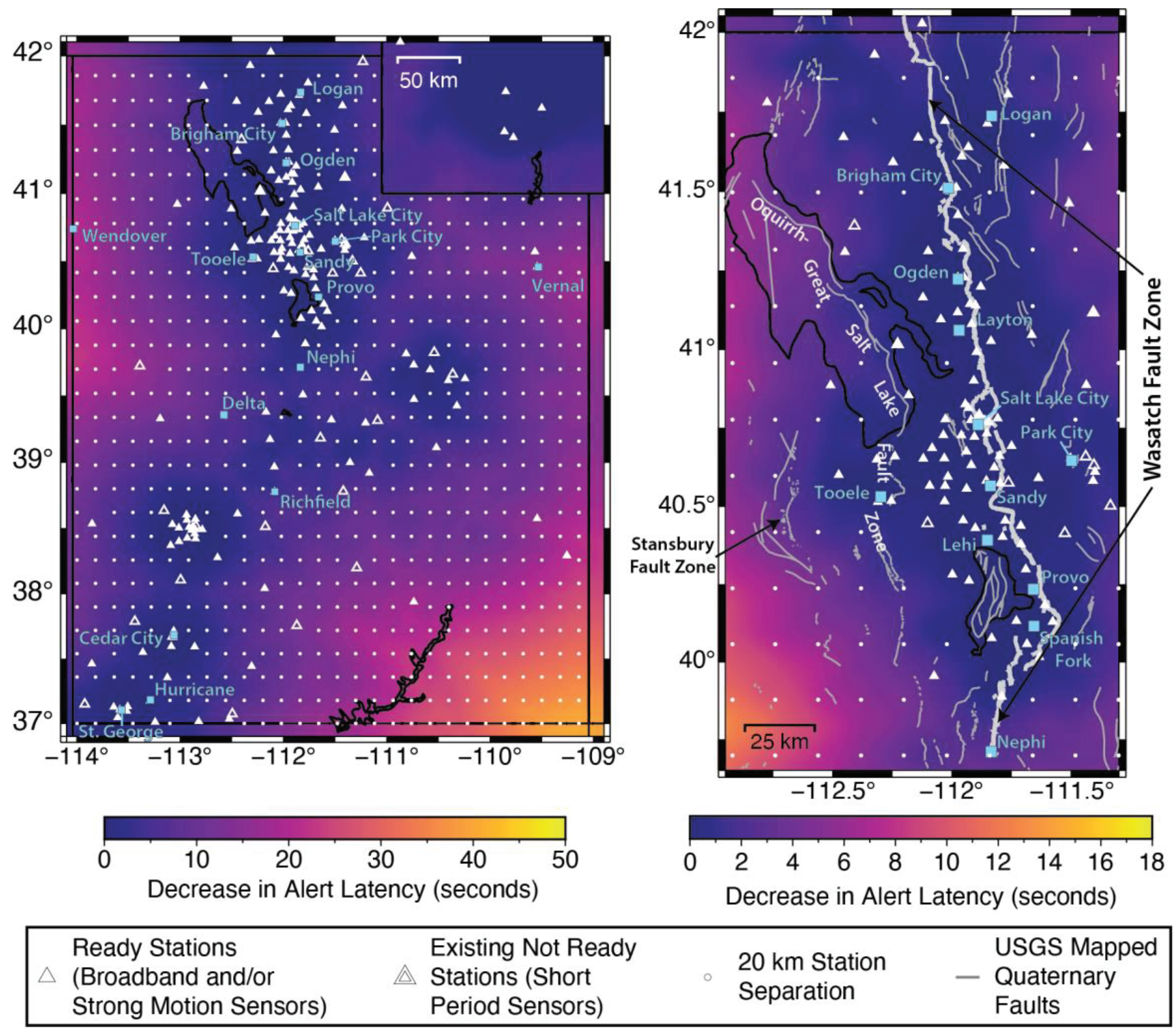


Figure 4.5. *Travel time decreases (Purple zone in Fig. 2.3) from increasing seismograph station density to a 12 mi (20 km) station spacing in the state* ***(left)*** *and within the Wasatch Front* ***(right)****. Maps show the increase in Warning Time gained for every potential earthquake source at 7 mi (12 km) depth with the idealized network, where all the "Not Ready" stations (open triangles) are upgraded to be EEW- compatible, and new stations are added to achieve a 12 mile (20 km) station spacing throughout the state (white dots) in comparison with the current network of EEW-compatible seismic sites ("Ready" stations; solid triangles). Colors represent how much faster an earthquake at that location will be detected with the denser network, and subsequently how much more warning time would be provided. Orange and yellow colors indicate the greatest increase in Warning Time for an earthquake at that location with the denser network.*

the main Wasatch fault zone, particularly southwest of Tooele, west of Tooele on the Stansbury fault zone, beneath the northern Great Salt Lake on the northernmost Oquirrh-Great Salt Lake fault zone, and near the 1934 Hansel Valley earthquake. These improvements would be beneficial, but they also reinforce the point made in the previous section: by upgrading the telemetry at all stations, the existing UUSS stations configuration would constitute an adequate EEW system within much of the Wasatch Front, particularly along the surface expression of the Wasatch fault system. Four new stations west of the Wasatch fault zone could increase Warning Times for earthquakes on other nearby faults, but many more stations would be needed to increase the Warning Times for earthquakes outside of the Wasatch fault system.

As an EEW system potentially rolls out to the rest of the state, additional seismograph stations are needed to fill instrumentation gaps along the ISB and the surrounding areas in the state (Fig 4.5, left). The alert latency could be reduced by up to five additional seconds for earthquakes within the ISB by upgrading 14 short-period stations and adding 118 new stations. Similarly, along the edges of the ISB, the Alert Latencies could be reduced by 15–20 s. Since 1850, 21 M5+ earthquakes have occurred within the ISB outside the Wasatch Front (Fig. 1.1), including an M6.6 near Richfield. In the West Desert, earthquakes with magnitudes between 4 and 5 have occurred historically (Fig. 1.1), and the denser network could decrease the detection time by more than 30 s for earthquakes along the northwestern state border, translating to time gained for additional warning (Fig 4.5). East of the ISB, earthquakes are sparse and historically have magnitudes below 4.5. The denser network could provide more than 40 s of gained time by decreasing the detection time in the southeast, but in this region, the seismic hazards are low, so upgrades are not an immediate need.

When adding new seismograph stations to improve EEW performance, some locations will have more of a positive impact than other locations. We use the upgrade score method (*Hotovec-Ellis and others,* 2017) to evaluate the impact of a new seismic site and assign it a score. The higher the score, the more benefit a seismic site at that location would provide to the EEW system. This method evaluates the improvement in detection times and earthquake location accuracy for each potential new station, weighted by the probabilistic seismic hazard (Fig. 4.6; *Petersen and others*, 2019; *Rukstales and Peterson*, 2019). These changes are then integrated and summed to a single value for each potential new site and weighted by the distance to existing stations. Thus, areas with sparse station coverage and higher seismic hazard are weighted higher. We determine scores for potential new seismograph station locations across the state within 0.1° × 0.1° grid cells. Due to the very sparse station coverage

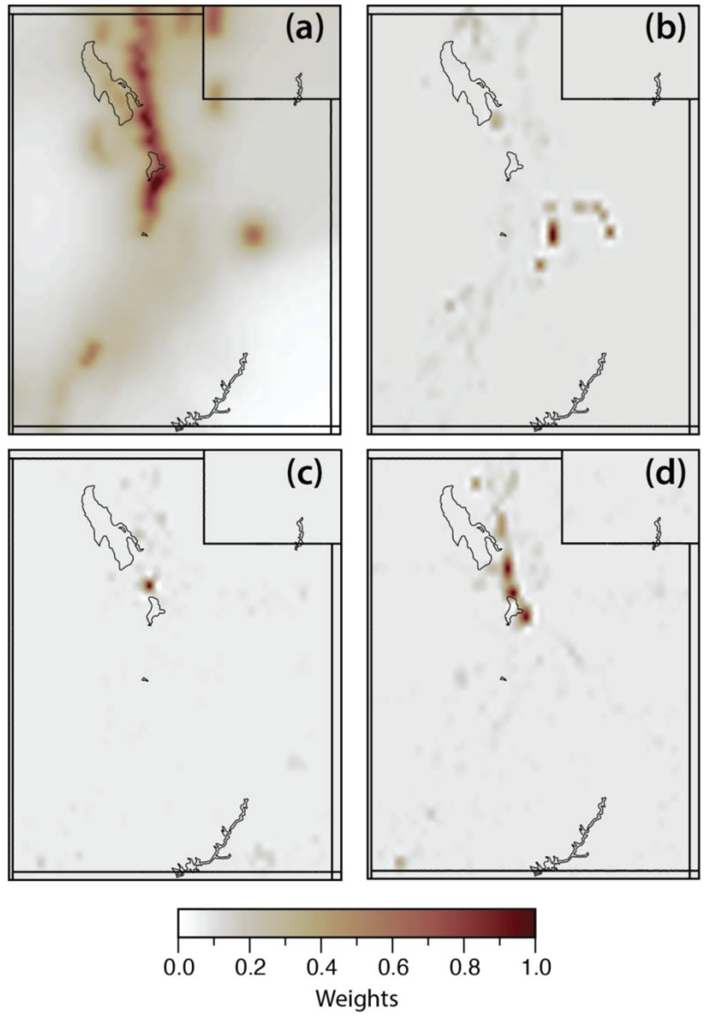


Figure 4.6. *Weighting masks used in determining upgrade scores.* ***(a)*** *Hazard weights calculated from the USGS National Seismic Hazard Mapping Project peak ground acceleration estimates of 2% probability of exceedance in 50 years, used in the initial score method (*Hotovec-Ellis and others*, 2017).* ***(b)–(d)*** *are used to calculate the new, weighted version of the upgrade scores.* ***(b)*** *Normalized earthquake density for earthquakes 1850–2022,* ***(c)*** *Normalized 2020 population, by census blocks,* ***(d)*** *Normalized density of critical facilities (Table 4.2)*

outside of the ISB (Fig. 4.1), we found that the upgrade scores were being heavily weighted by the travel time decreases in the northwest and southeastern portions of the state, even though earthquake rates, seismic hazard, and population in these regions are much lower. To remove the strong effects from the sparser network in these areas, we further weighted the scores by the sum of weights of earthquake density 1850–2022, population estimates from the 2020 census, and the presence of critical facilities (Fig. 4.6). The critical facility types included are listed in Table 4.2.

Table 4.2. *Facility types included in an additional weighting to the computed upgrade scores. Facility presence was counted over the state in 0.1° × 0.1° grid cells and normalized by the cell with the largest facility density. Facility datasets were accessed via the Homeland Infrastructure Foundation-Level Data Geoplatform (https://hifld-geoplatform.opendata.arcgis.com/) and the Utah Geospatial Resource Center (https://opendata.gis.utah.gov/).*

Critical Facilities	
• Canals	• Schools K-12
• Communication towers	• Pharmacies
• Fire stations	• Dialysis Centers
• Police stations	• Nursing homes and retirement communities
• Hospitals and urgent care facilities	• Grocery stores
• Bridges	• Shelters
• Gas pipelines	• Community Centers
• High-risk dams	• Town Halls
• Electrical transmission lines	• Places of Worship
• Wastewater treatment plants	• Embassies
• Public airports	• Natural gas processing plants
• Railroads	• Oil refineries
• Childcare centers	• Power plants
• Colleges and Universities	• Active mines

Figure 4.7 shows the upgrade scores and weighted scores in the Wasatch Front. The patterns of where a seismograph station would have the most positive impact are like those of the Travel Time improvement with a denser station configuration (Fig. 4.5). In the Wasatch Front, it would be most beneficial to add new stations outside of the Wasatch fault zone: west-southwest of Tooele, within the northern Great Salt Lake, and along the eastern edge in the Wasatch range. With the additional weighting from earthquake density, population, and facilities, more distinct areas are highlighted (Fig. 4.7, right). The locations with the highest scores are a zone at the north end of the Promontory Fault and Hansel Mountain Fault, north of the 1934 M6.6 epicenter, and in the southeast corner, east of Nephi. Additional areas that would most benefit from new station installations are located near a small fault northeast of Ogden, near Nephi, and along the northwest bank of the Great Salt Lake. Other potential new station locations west of Tooele and northeast of Logan would be useful for EEW systems targeting earthquakes on or near those faults. The current short-period ("Not Ready") stations that could be upgraded in this region have relatively low upgrade scores. Upgrading the East Promontory (EPU) short-period seismograph station (41.39°N, 112.41°W, circled purple in Fig. 4.7) could be beneficial based on Figures 4.5 and 4.7; however, these maps suggest the most benefit would come from new seismograph installations west of the Wasatch fault zone.

We suggest adding at least four new seismograph stations at (1) the Hansel Valley/Promontory faults, (2) northeast of Ogden, (3) the northwestern bank of the Great Salt Lake, and (4) near Nephi (circled dark orange in Fig. 4.7, right). Secondary target zones would be northeast of Logan, west of Tooele, and east of Nephi (circled light orange in Fig. 4.7).

The areas of the state surrounding the ISB have the largest impact for potential seismic station installations, particularly the southeastern corner of the state and the northern half of the western state border (Fig. 4.8, left). As discussed above, this is because of the limited number of seismograph stations in these areas (Fig. 4.1). Improved earthquake detection times and location quality will be most improved when adding a new station in a sparsely instrumented area. In general, there are more high-quality seismic stations in areas of higher hazard, so adding new stations in these regions will not significantly change network performance. With the additional weighting to remove the effects of a sparse network in areas with lower hazard and seismicity, we can better assess where new or upgraded stations are needed in the ISB (Fig. 4.8, right). The highest potential is still in the southeast corner of the state, due to the relatively higher population and presence of critical facilities. Though this region contains the highest upgrade score, we recommend prioritizing the ISB before any other areas in the state. Many of the higher weighted scores overlap or are near existing short-period stations that could be upgraded to be EEW-compatible

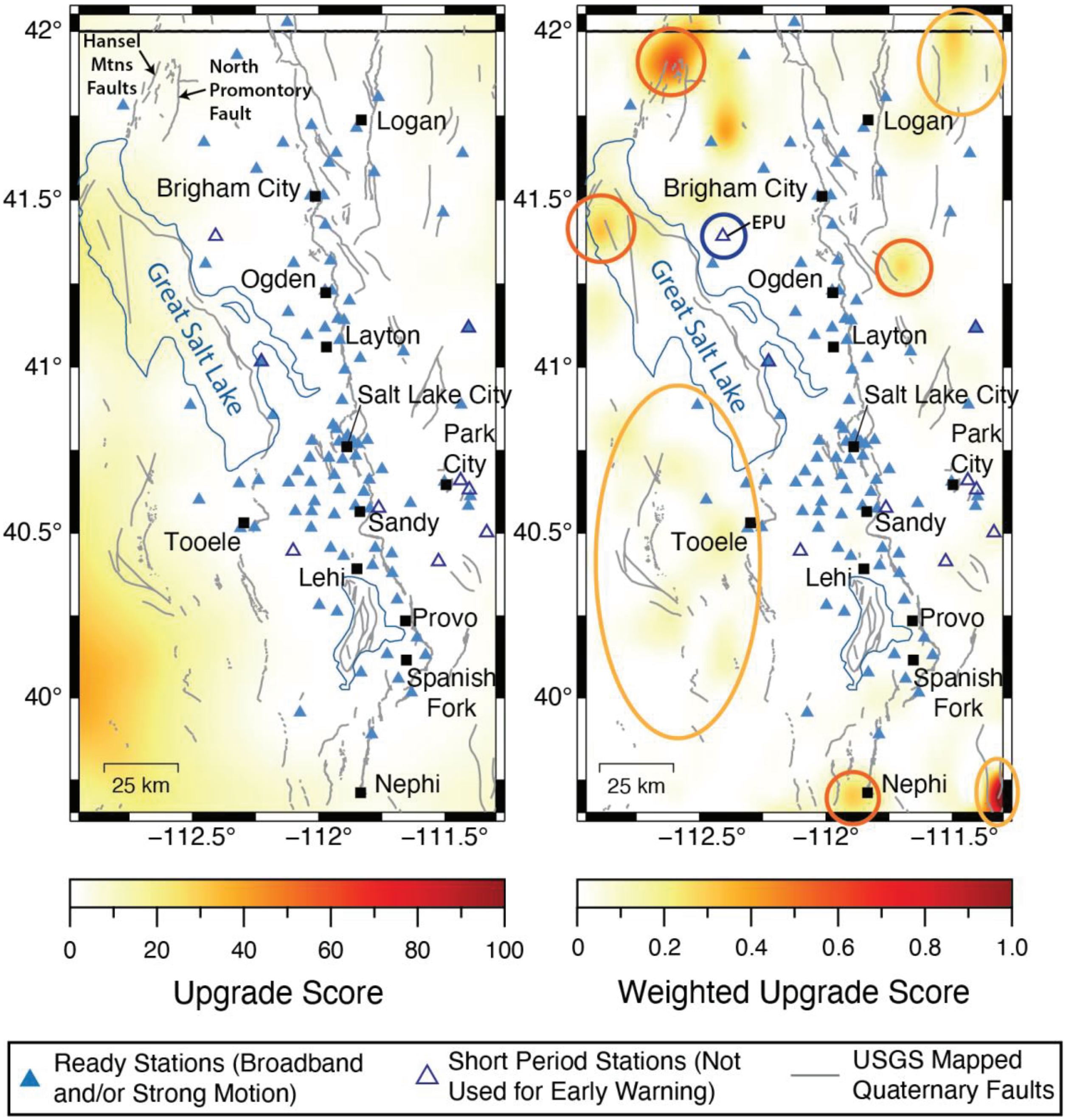


Figure 4.7. *Upgrade scores* ***(left)*** *and weighted upgrade scores* ***(right)*** *for the Wasatch Front, indicating the most impactful areas to add or upgrade seismograph stations. Scores shown in the left panel are determined using the method of* Hotovec-Ellis and others *(2017). Scores in the right panel are determined using a modified version of this method, with additional weighting by earthquake density, population, and critical facilities density, as described in the text. "Ready" stations are those where the seismic sensors are compatible with EEW. Short period sites are currently operating within the UUSS network but cannot be used in an EEW system, though they can be upgraded to be EEW-compatible. Higher upgrade scores (red colors) indicate that an EEW-compatible station at that location adds the most benefit to the network. Low scores (white-to-yellow) indicate that adding a station at that location will provide little to no benefit to the network. Purple circle highlights an existing "Not Ready" station that should be prioritized for upgrade to EEW-compatible sensors. Orange ovals highlight areas to prioritize for new station installations (dark orange for primary targets, light orange for secondary targets).*

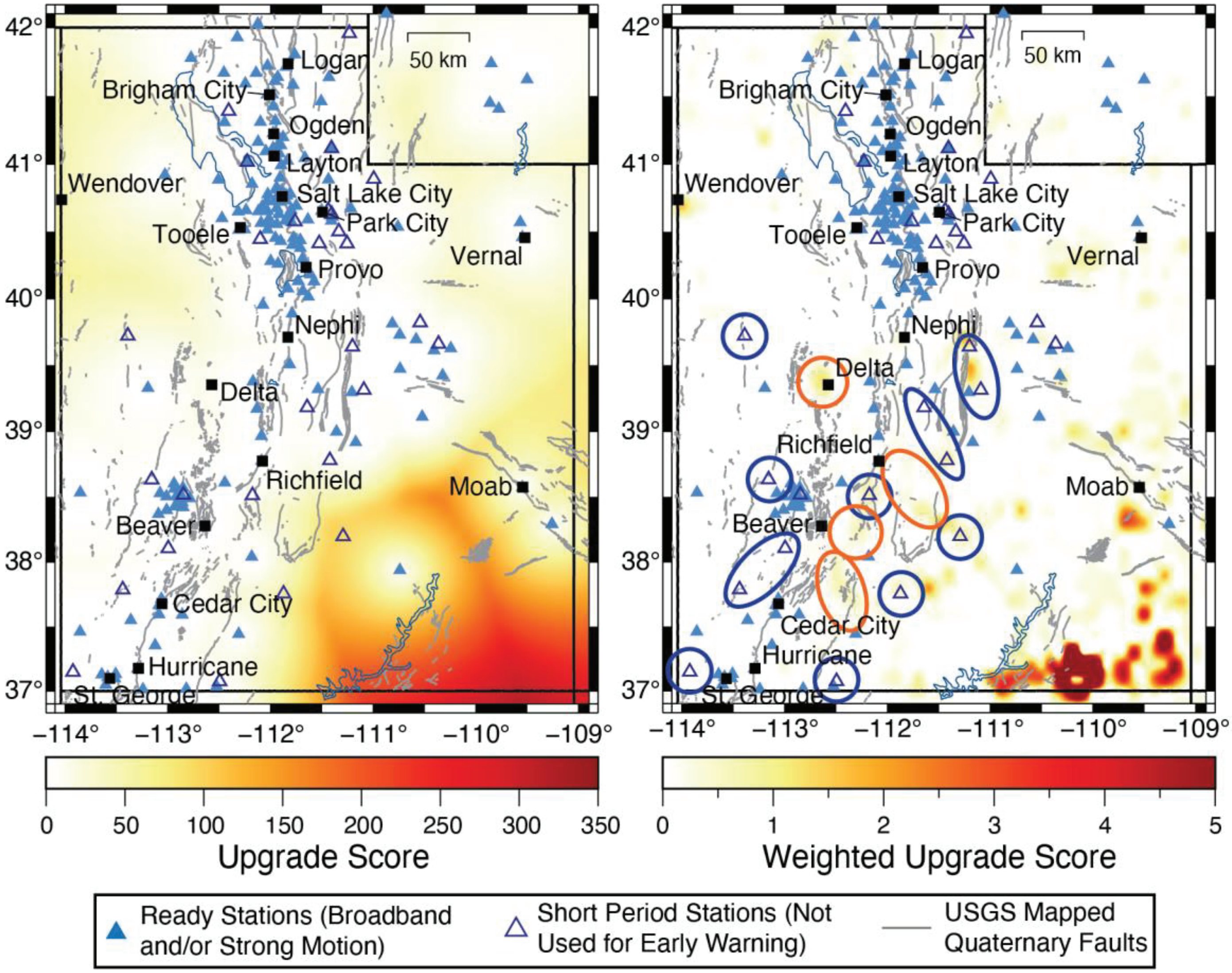


Figure 4.8. *Upgrade scores (**left**) and weighted upgrade scores (**right**) for Utah, indicating the most impactful areas to add or upgrade seismograph stations. Scores shown in the left panel are determined using the method of* Hotovec-Ellis and others *(2017). Scores in the right panel are determined using a modified version of this method, with additional weighting by earthquake density, population, and critical facilities density, as described in the text. "Ready" stations are those where the seismic sensors are compatible with EEW. Short period sites are currently operating within the UUSS network but cannot be used in an EEW system, though they can be upgraded to be EEW-compatible. Higher upgrade scores (red colors) indicate that an EEW-compatible station at that location adds the most benefit to the network.*

Low scores (white-to-yellow) indicate that adding a station at that location will provide little to no benefit to the network. Purple circles highlight existing "Not Ready" stations that should be prioritized for upgrade to EEW-compatible sensors. Orange ovals highlight areas to prioritize for new station installations.

(circled purple in Fig. 4.8, right). New station installations in the ISB would be most beneficial near Delta, and in the areas between Nephi and Cedar City (circled orange in Fig. 4.8). We suggest prioritizing the upgrade of short-period seismograph stations along the outer edges of the ISB (circled purple in Fig. 4.8). Four of these stations are planned for upgrade in summer 2024, as part of ongoing deferred maintenance funding from the USGS Advanced National Seismic System.

4.4. Cost Estimates

Costs associated with implementing an EEW system in Utah can be divided into two categories: capitalization costs related to buying and installing new equipment, and operational costs associated with running and maintaining the EEW system. The needed equipment includes seismic sensors, GPS antennae, power and communication cables, construction materials, computer servers, and the telemetry related items detailed in Section 4.2. Operating an EEW system will incur costs related to software licenses, digital communications, and data storage, among other expenses. The personnel needed for both cost categories include project managers, business managers, field engineers, network engineers, seismologists, software developers, and siting specialists. For planning purposes, we assume a flat rate of $150,000 per year per full-time employee (FTE), including benefits, with the understanding that actual compensation levels will vary according to position.

An important element to consider when designing an EEW system is the cost of adding a new seismograph station. Using supplemental funding from the USGS, the UUSS is currently planning to upgrade four short-period analog seismograph stations to EEW-capable systems with broadband and strong-motion sensors. The USGS is providing all the necessary seismic equipment, including Trillium 120 broadband seismometers, Titan accelerometers, 6-channel Centaur data loggers, GPS antennae, and related communication and power cables, with an estimated cost of $30,500 per station. Travel and ancillary supplies related to building out and hardening the new sites is estimated at an additional $7,000. Personnel expenses sum to about 0.5 FTE for the four stations. The effort includes a mix of engineer, seismologist, and project manager time. These expenses total about $58,000 per new station, which we adopt for the purposes of planning a Utah EEW system. All the costs listed below are in addition to existing funding levels for earthquake monitoring in Utah.

4.4.1. Cost Estimate for a Prototype EEW System Along the Wasatch Front Region

In this scenario, we estimate costs for a prototype EEW system that would provide coverage for earthquakes occurring within the majority of the Wasatch Front Region. This scenario would entail telemetry upgrades for all existing EEW-capable seismograph stations in the Wasatch Front Region, the addition of four new seismograph stations, new computing infrastructure, and related personnel costs. One time capitalization costs are $607,000, with annual operation and maintenance costs of $480,000, inclusive of 2.5 new FTEs.

4.4.2. Cost Estimate for a Fully Functioning EEW System Along the Wasatch Front Region

In this scenario, we estimate costs for a fully functioning EEW system that would provide coverage for earthquakes occurring throughout the Wasatch Front Region. This scenario would entail telemetry upgrades for all existing EEW-capable seismograph stations in the Wasatch Front Region, the addition of 80 new seismograph stations, new computing infrastructure, and related personnel costs. One time capitalization costs are $5,040,000, with annual operation and maintenance costs of $1,110,000, inclusive of 6.0 new FTEs.

4.4.3. Cost Estimate for a Fully Functioning EEW System Along the Intermountain Seismic Belt

In this scenario, we estimate costs for a fully functioning EEW system that would provide coverage for earthquakes occurring throughout the Utah portion of the Intermountain Seismic Belt. This scenario would entail telemetry upgrades for all existing EEW-capable seismograph stations in the Wasatch Front Region and the central and southwestern ISB segments, the addition of 198 new seismograph stations, new computing infrastructure, and related personnel costs. One time capitalization costs are $11,984,000, with annual operation and maintenance costs of $2,270,000, inclusive of 11.0 new FTEs.

5. SURVEY OF EARTHQUAKE EARLY WARNING INTEREST IN UTAH

We developed, distributed, and compiled results from an online survey focused on EEW and general earthquake awareness. The survey aimed to gauge stakeholder interest in an EEW system in Utah, to better understand their earthquake-related needs, and to compile a list of potential concerns. We cast a wide net, distributing the survey to ~2,800 stakeholders, including government agencies, health care workers, emergency managers, school districts, critical facility managers, and representatives of the private sector throughout the state of Utah. Survey participants had the option to watch a short video explaining EEW (*Caltech Science Exchange,* 2023) prior to taking the survey. Our survey used the Google Survey platform and was designed to take ~15 minutes to complete. The survey had 28 questions in various formats, including short answer, long answer, multiple choice, checkboxes, and a linear scale (Appendix A). The survey was accessible for 44 days (February 16, 2023, through April 1, 2023) and received 166 responses, corresponding to a response rate of 6%. Responders did not always answer all questions.

Results from the binary yes/no questions (Fig. 5.1) showed that most organizations do not have threshold criteria in place that would trigger an earthquake response protocol (82%), nor do they have an earthquake monitoring system in place (73%). Out of 157 respondents, 95% reported that they, as an individual, know what to do if they feel strong shaking from an earthquake. And of 150 responses, 91 people said that they would be willing to participate in a focus group to explore EEW system options for the state of Utah. The email addresses of these 91 people were collected and saved via the survey platform.

Select results for multiple choice questions are presented in Fig. 5.2. In terms of preparedness and readiness, most organizations were somewhat prepared (40% selected 3

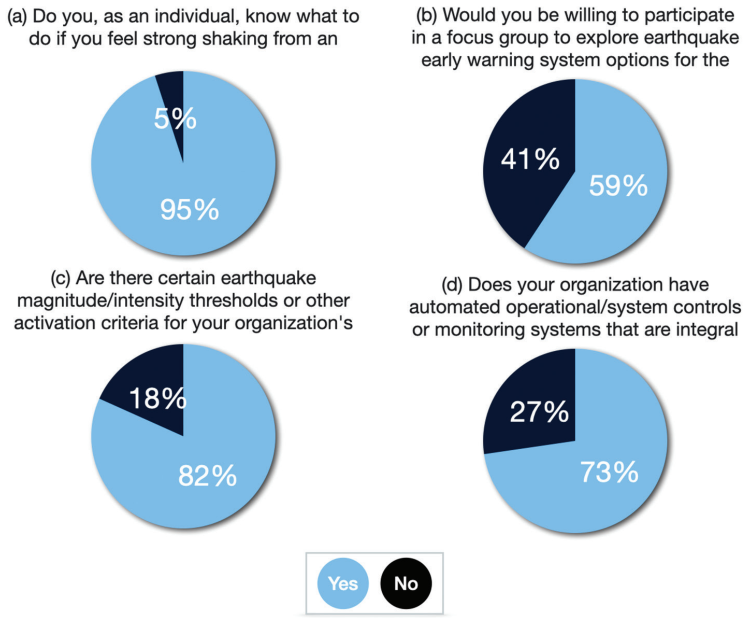


Figure 5.1. *Survey results for yes/no questions. Although 95% of those surveyed know how to respond individually to strong shaking from an earthquake (**subplot a**), most organizations do not have earthquake response plans (**panels c & d**). However, there is strong interest (60%) in participating in focus groups to explore the concept of EEW in Utah (**subplot b**).*

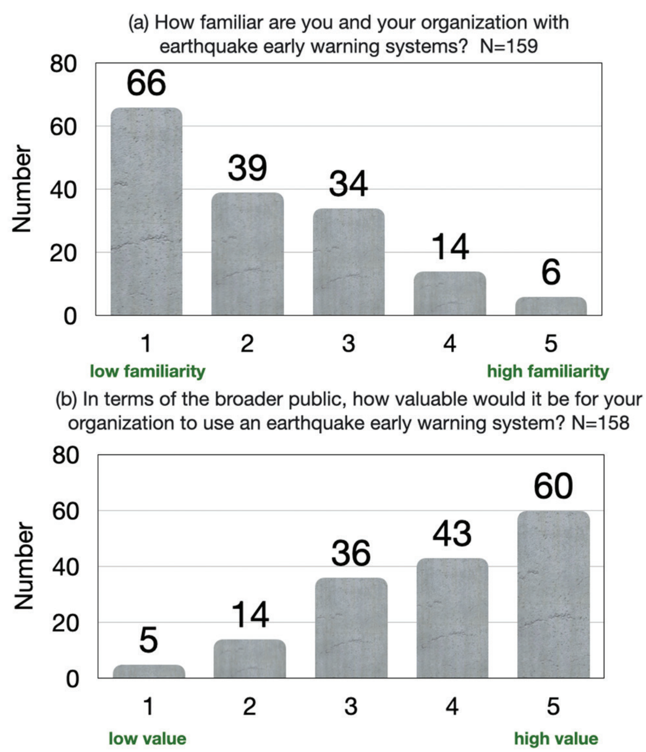


Figure 5.2. *Utah Division of Emergency Management survey results from multiple choice questions, which tended to have a response consensus. Lower and higher numbers correspond to low familiarity or value to high familiarity or value, respectively. The number of survey participants who answered a given question is listed as N=number. **(a)** Most survey participants were not familiar with EEW systems, and **(b)** thought an EEW system in Utah could be valuable.*

on the 1–5 scale). Most organizations were not familiar with EEW: 41% selected 1 on the 1–5 scale, which indicated the least familiarity, and an additional 24% selected 2, with only 4% selecting 5. Most respondents (69%) reported that "training people to know what to do" was the biggest anticipated hurdle in terms of incorporating EEW within their organization. In terms of intention/commitment to incorporate EEW within their organization, most responses fell within the 3–5 range indicating average to strong commitment. The most critical reported aspects of a hypothetical EEW system for business and industry were user training and education (91%), followed by system performance standards, reliability, and notification/alert protocols (83%). Many (38%) reported that an EEW system would be valuable to their organization. A full list of responses to survey questions #15 and #28 can be found in Appendices B and C, respectively, regarding earthquake preparedness and general respondent feedback. Most responses indicated that the biggest risks in implementing an EEW in Utah would be cost and false alarm rates, and the biggest benefits would be potentially saving lives and mitigating key infrastructure hazards.

There was no consistent response to a question about how likely the organization would be engaged in developing and implementing an EEW system in Utah. We expect the wide span of responses to result from the many uncertainties of not knowing what is required, to what extent training about how to respond to an alert would be successful, and reluctance caused by the relatively long interval between large earthquakes in Utah that would hamper practicing what to do during a real earthquake. Regarding earthquake hazards, survey results showed that over 95% of respondents listed employee safety as a primary concern, with less importance (28%) placed on business income/loss protection. Interestingly, training those within organizations on what to do if they were to receive an earthquake alert was of higher priority than potential costs by ~9%.

For the written responses, most respondents favored exploring the costs and benefits of an EEW system in Utah. Tara Thue, President of AT&T Utah, wrote,

> *"The Utah Department of Public Safety has a longstanding history of spearheading efforts to help protect and prepare our communities, and we are excited to share how cellular technology and wireless emergency alerts can support citizen safety initiatives and explore those capabilities with the Early Earthquake Warning System project for the state."*

6. FINDINGS AND RECOMMENDATIONS

6.1. Findings

Finding 1: EEW systems have become feasible because of improvements in the speed and reliability of transmitting digital seismic data and advances in the algorithms used to process seismic data. Fully functional EEW systems can detect potentially dangerous earthquakes and transmit alerts to vulnerable areas as quickly as 8 s after the beginning of an earthquake. The alerts can arrive seconds to tens of seconds before strong ground shaking begins. These time windows are long enough for trains to be slowed, safety controls at critical facilities to be activated, students to take cover under their desks, elevators to stop at the nearest floor, and so on, potentially saving lives and reducing economic damages.

Finding 2: Although we do not know when or where the next large earthquake will strike, we can make probabilistic estimates based on past seismicity and other geophysical data. These earthquake forecasts indicate high seismic hazard along the Wasatch Front. Regardless of where the next earthquake strikes, there will always be a No-Alert Zone within ~19 miles (25 km) of the earthquake epicenter, where issuing alerts prior to large ground shaking will be, at best, difficult and likely impossible.

Finding 3: Network-based EEW systems are more popular than on-site systems. Network-based systems provide robust warnings across broad, seismically active regions. On-site systems are more prone to false alarms and missed detections but may complement network systems especially in the region nearest the earthquake. Massive networks of low-cost "seismometers" (such as smartphones or repurposed optical fiber) are a promising future direction for EEW but are still in the research and development phase.

Finding 4: EEW is an increasingly popular solution for mitigating earthquake risk. EEW systems are operational in Mexico, Romania, Turkey, India, Japan, South Korea, and Taiwan, with real time testing in Canada, Nicaragua, El Salvador, Costa Rica, Chile, Switzerland, Italy, Israel, and China. The USGS-backed ShakeAlert framework is the most successful EEW system in the U.S. and is currently operational in California, Oregon, and Washington. There are discussions about extending ShakeAlert into Hawaii, Nevada, and Alaska. Expanding ShakeAlert into Utah would be a logical next step, but there are no formal plans at this time.

Finding 5: EEW in Utah is most needed along the Wasatch Front, which has the state's highest seismic hazard and risk and the largest population. The existing network of nearly 90 seismograph stations in this region could serve as a prototype EEW system for much of the Wasatch Front if the telemetry system was upgraded with new radios, cellular modems, power supplies, and related equipment. Creating a fully functional EEW system across the entire Wasatch Front would require the installation of approximately 80 new seismograph stations and telemetry upgrades for existing stations. Expansion of EEW in Utah to the south and west along the Intermountain Seismic Belt (generally along the Interstate 15 corridor) would be beneficial after an EEW system is established along the Wasatch Front.

Finding 6: Investment in an EEW system along the Wasatch front would likely be paid back after the next large (M6.75+) earthquake. The moderate-sized 2020 M5.7 Magna earthquake caused no serious injuries yet created $70–$150 million of damage. An M6.75+ earthquake along the Wasatch Front would cause billions to tens of billions in damages. If made a priority, a fully functional EEW system in the Wasatch Front could be operational by 2030, constructed for about $5 million, and operated for about $1 million per year. Assuming a ShakeAlert partnership can be established with the USGS, the costs could be shared with the federal government.

Finding 7: A fully functional EEW system along the Wasatch Front could provide up to 15–30 seconds of Warning Time before noticeable shaking, and up to 5–15 seconds before strong, damaging shaking. We would expect an EEW system that is allowed to warn for light shaking levels to issue an alert every two to three years on average, although the alerts would likely be clustered in time, and dry spells (periods of no alerts) of 5–10 years could arise.

Finding 8: Our online survey of Utah stakeholders showed strong interest in EEW but low levels of familiarity with EEW. Significant outreach and education would be needed in Utah during the installation and roll out of an EEW system. The outreach and education effort would require sociologists, urban planners, and emergency responders, in addition to geologists, seismologists, computer scientists, and engineers.

6.2 Recommendations

Recommendation 1: The State of Utah should pursue a partnership with the federal U.S. Geological Survey to bring the ShakeAlert EEW system to the Wasatch Front, leveraging their existing and developed algorithms and systems, as well as social science experience and expertise regarding EEW.

Recommendation 2: Telemetry upgrades to the existing network of seismograph stations along the Wasatch Front should be implemented in preparation for a future EEW system.

Recommendation 3: EEW should be expanded to central and southwestern Utah after it has been established along the Wasatch Front.

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8. ACRONYMS AND ABBREVIATIONS

ANSS	Advanced National Seismic System
AQMS	ANSS Quake Monitoring System
DC	An Offset or Static Bias in a Seismogram
DYFI	Did You Feel It?
EEW	Earthquake Early Warning
EIC	Earthquake Information Center
EPIC	Earthquake Point-source Integrated Code
FEMA	Federal Emergency Management Agency
FinDer	Finite-Fault Rupture Detector
FORGE	Frontier Observatory for Research in Geothermal Energy
FTE	Full-time Equivalent Employee
IPAWS	Integrated Public Alert and Warning System
IRIS	Incorporated Research Institutions for Seismology
ISB	Intermountain Seismic Belt
M	Earthquake Magnitude
MEMS	Micro-Electromechanical Systems
MMI	Modified Mercalli Intensity
OT	Origin Time
PLUM	Propagation of Local Undamped Motion
SQUAC	Station Quality Assessment Console
UDEM	Utah Division of Emergency Management
UGS	Utah Geological Survey
URM	Unreinforced Masonry Structure
USGS	United States Geological Survey
UUSS	University of Utah Seismograph Stations
USSC	Utah Seismic Safety Commission
WEA	Wireless Emergency Alert

9. APPENDIX A

Stakeholder Survey Questions

Earthquake Early Warning System Survey for the State of Utah

Please complete this survey. It will take approximately 15 minutes or less. It will help us to determine an earthquake early warning system would be beneficial for the state of Utah.

1. Email ______________________________

   Watch this 1-minute video to see how earthquake early warning works.

   https://www.youtube.com/watch?v=%7CSw4ERz36MO

2. What is the name of your institution? ______________________________

3. Where does the responsibility for earthquake response planning reside within your organization?

   ____

4. Describe your organization's earthquake/disaster response plans and procedures.

   ____

5. How is your organization currently preparing for an earthquake? ______________________________

6. What are some of the key earthquake response objectives of your organization's response plans and procedures? (Select all that apply)

   ☐ Public safety
   ☐ Employee safety
   ☐ Property/asset protection
   ☐ Equipment/operations protection
   ☐ Business resumption/continuity
   ☐ Business income/loss protection
   ☐ Other: ______________________________

7. What are some of your organization's top concerns about the effects that an earthquake can have on your operations? (Select all that apply)

   ☐ Impacts to employees/public
   ☐ Impact on your organization's overall mission
   ☐ Key functions or vulnerability points
   ☐ Interdependencies within your system
   ☐ Other: ______________________________

8. Who (what organizational entity(ies) is involved in earthquake preparedness decisions/processes at your organization?

   ____

9. Does your organization have automated operational/system controls or monitoring systems that are integral to your response plans and procedures?
   (Check only one)

   ☐ Yes
   ☐ No

10. What technologies or software do you use for your operational/system controls or monitoring systems?

____

11. Does your organization incorporate any of the following into your earthquake response procedures (Select all that apply)?

- ☐ USGS Earthquake Notification Service (http://earthquake.usgs.gov/)
- ☐ USGS ShakeMap and real-time data feeds (http://earthquake.usgs.gov/data/shakemap/)
- ☐ ShakeAlert earthquake early warning beta system (https://www.shakealert.org/)
- ☐ Other earthquake early warning systems (proprietary commercial, or government)

12. Are there certain earthquake magnitude/intensity thresholds or other activation criteria for your organization's response plans and procedures?
(Check only one)

- ☐ Yes
- ☐ No

13. If yes, what are some of the key activation and time thresholds?

____

14. How widespread is the culture of earthquake preparedness and readiness in your organization?
(Check only one)

	1	2	3	4	5	
Low	○	○	○	○	○	High

15. What, if anything, needs more or better handling for earthquake preparedness?

____

16. How familiar are you and your organization with earthquake early warning systems?
(Check only one)

	1	2	3	4	5	
Low	○	○	○	○	○	High

17. What kinds of organizational challenges would you anticipate in trying to use an Earthquake Early Warning System? (Select all that apply)

- ☐ Sources of resistance/friction
- ☐ Implementation difficulties
- ☐ Cost factors
- ☐ Training people to know what to do if they receive an earthquake alert of feel strong shaking

18. What is the level of intention or commitment of your organization to use an earthquake early warning system if it becomes available? (Check only one)

	1	2	3	4	5	
Low	○	○	○	○	○	High

19. In terms of the broader public, how valuable would it be for your organization to use an earthquake early warning system? (Check only one)

	1	2	3	4	5	
Low	○	○	○	○	○	High

20. Identify what you think would be potential benefit(s) of a statewide earthquake early warning system and their importance? ____________________

21. Identify what you think would be any potential risk(s) or negative consideration(s) of a statewide earthquake early warning system and their importance? ____________________

22. What elements do you think are crucial for a statewide earthquake early warning system to be viable for business and industry use? (Select all that apply)

    - ☐ System development, timeframe, and implementation plans
    - ☐ System Governance and management structure
    - ☐ System performance standards, reliability, and notification/alert protocols
    - ☐ System deployment and rollout plan
    - ☐ System funding for capital costs and annual maintenance
    - ☐ User training and education
    - ☐ User personel/management
    - ☐ User operation/implementation issues
    - ☐ User financial/costs factors
    - ☐ User legal/policy issues
    - ☐ Other: ____________________

23. Does your organization have any suggestions for magnifying the benefit of a statewide earthquake early warning system? ____________________

24. How likely would your organization be engaged in the development and implementation of a statewide earthquake early warning system? (Check only one)

	1	2	3	4	5	6	7	8	9	10	
Not	○	○	○	○	○	○	○	○	○	○	Extremely Likely

25. Do you, as an individual, know what to do if you feel strong shaking from an earthquake? (Check only one)

    - ☐ Yes
    - ☐ No

26. Would you be willing to participate in a focus group to explore earthquake early warning system options for the state of Utah? (Check only one)

    - ☐ Yes
    - ☐ No

27. If you answered "yes" to the question above, please provide your email address below.

    ____

28. What questions, comments, or suggestions do you have about the Earthquake Early Warning System?

    ____

Thank you for taking the time to share your feedback!

10. APPENDIX B

Answers to Survey Question About Earthquake Preparedness

Answers to question number 15 of the survey, that asks *"What, if anything, needs more or better handling for earthquake preparedness"*.

A safe control location located outside the building.
Across the board we need more resiliency in our infrastructure and social support systems.
Additional training
Alert system
An early alert system would be a bonus
An early warning system would be great.
Annual meeting to review earthquake preparedness in person with attendance roll taken.
Basic knowledge
Better detection equipment around our structures and better communication with other local and state emergency agencies.
Better education, system integration.
Better training and access to subject matter experts as resources.
Better utilization of current technology and resources.
Better warning systems, better communication of emergency
Building Inspector Training and Certification
City Alerts of possible earthquakes.
Communications
Constant reminders and training
Continue practicing and taking advantage of opportunities to keep the topic in front of people.
Continued retrofit or replacement of old buildings. Perhaps more seismically resistant design of new buildings as well in order to prevent serious damage and enable immediate post-earthquake use.
Continued training and awareness
Creating a plan and providing that information to the employees.
Detailed list of procedures and who to call and who will call you when it's safe to report to work.
Dissemination of Information, Drills, Reminders
Early warning
Early warning system and monitoring options.
Earthquake exercises performed regularly
Emergency plan that considers our current hybrid work environment.
Employee response plan, system redundancy, temporary power systems, post-earthquake building safety evaluation process
Employees don't understand the importance/reality of what may be coming.
Evacuation drills
Everything! Literally!
For sake of coordination, possible alternatives for communication & transportation
Generators in place at city hall and more inspectors for ATC-20 rapid assessment
We have high turnover, so once year drills can leave some newer employees without knowledge of the plan. We want to make some videos of evacuation routes and meeting places to be sent during onboarding.

I believe the state has done what it can and doesn't need additional precautions at this time
I don't know.
I feel that earthquake preparedness is something that should be implemented in our weekly division meeting at least once monthly. I feel the more earthquake preparedness is talked about and practiced the more prepared you can be in this type of a situation.
I would think more training of key personnel would be a great idea.
If the [organization building] became unavailable due to a quake, our immediate response is to work from home full time, but individual homes will have varied resilience to strong quakes, so it is difficult to predict how many home offices of various staff members will be online and functional.
Improved immediate response and evacuation training. Personal preparedness.
Incorporate early warning sources; conduct more frequent plan reviews and supplies check
Incorporating new technology.
Individual preparedness
Individual preparedness
Individual Preparedness for residents
Information dissemination
Knowledge and drill practices
Logistic support and mass casualty response
Mass communication to employees via paging. Statewide 2way radio system.
More awareness and information
More exercises
More simulations and/or supplies on hand
More streamlined practical guidance across all levels and capacity to train staff on this guidance and their roles/responsibilities.
More training
More training
More training.
Need to develop an earthquake plan.
Need to restart emergency tabletop exercises
Needing some suggested guidelines for small businesses
No one takes it seriously until we have an incident
Nothing
Nothing at this point we have 35 employees, and our training has been going on for over 11 years.
Notification
Notification and Coordination
Notification System
Ongoing training with employees - tools to facility commutations in case of emergency
Operations personnel
Personal preparedness to include family considerations; How will our local shed interface with their stakeholders and partners in the community?
Planning, monitoring, training
Planning. Mitigation of biggest liabilities. Continuity of Government.
Post-event rescue and recovery
Preparation of critical facilities
Probably a plan our employees are aware of.
Process development, Training (muscle memory), communications (radio, ham).
Public Broadcast over Cell Phones similar to Amber Alerts / Warning Sirens etc.
Reasonable, secure, secondary location sites for CCC residents and inmates.

Recognize the threat
Reeducating staff of plans and policies, encouraging personal planning and responsiveness
Regular drills, communication trees
Reinforcement of buildings
Resource availability
Response plan to an earthquake. We have some supplies on hand, however, if everyone could not return home, we are under prepared.
Response plans practiced and reviewed
Resumption of business operations
Review
Since we moved to a new building, we don’t know where to evacuate to or even how to get there. Last I knew the stairs weren’t being used.
Spend time and money on more formal planning and on emergency food supply.
Standardized notification system (ENS) throughout all municipalities within SLC.
State needs an EOC independent of the Capitol or TSOB built to withstand a major seismic event with communications and power redundancies so that in a major seismic event DEM can continue to function and run Utah’s short and long-term response without interruption.
Technologies such as an alert system.
The agency disseminating and discussing current earthquake procedures and plans
The main thing is the discovery of tools and the implementation of those tools that are designed to alert us sooner
The use of a decentralized communications platform as a backup.
Training and integration of ESFs and DEM at state and county levels. More intensive and focused training on the administrative components of EQ response. Notional training does not create a readiness mindset and is not able to exercise crucial elements of response.
Training drills and general education
Understanding step-by-step safety procedures, what to do if in a hybrid workplace environment, how to better communicate and educate on preparedness with vulnerable communities.
Unknown
Unsure at this time
Upgrade of infrastructure
Warning systems.
We are at a low risk for an earthquake
We are continually working on emergency preparedness for our agency.
We at least need to update our policy to include earthquake preparedness.
We did monthly emergency training prior new administration & Covid. It should be reimplemented.
We have an emergency calling tree and emergency contact numbers, but we need a better post- earthquake plan since our office is right by a major fault line.
We have received no information about earthquake preparedness yet.
We need a plan
We need a plan. We reside in an unreinforced masonry building.
We need an actual plan.
We need more drills with the individual regions and sheds.
We still rely on a verbal communication component, we could be more robust to use other employee notification systems/methods which we are starting to do.
We train extensively to respond to requests for assistance. That will do little good if we’re all victims inside our old buildings.
What occurs with our families if we are at work when it hits. Lots of focus on resuming business but when the big one hits, most people will want to take care of family first. That needs to be talked about.

What we discovered with the last Earthquake, is that no matter how many drills you perform, it does not prepare you for the fear. Many people forgot the drills and just ran out of the building instead of getting under something. Having a warning would help allow people to think about what they need to do instead of just panicking.
Whole team training, due to new staff.
With teleworking, they don't talk about it anymore.
With the chance of losing online services, I have not heard any mention of how to operate and provide service to our customers manually - basically without access to data. It would be great to have perhaps some paper forms available to record information that can be entered back into the system when access is available once again.

11 APPENDIX C

Answers to Survey Question Requesting Feedback

Answers to question number 28 of the survey, which asks "*What questions, comments, or suggestions do you have about the Earthquake Early Warning System*?".

A taxpayer black hole
Accuracy and timeliness
An early warning system would be beneficial to saving lives and would enhance our current emergency notification system.
As it may apply to one or more responses provided above, final policy decisions, other action items would likely need to be determined by individuals in authority to do so on behalf of the agency. Questions, comments, suggestions to be prompted by discussion of the topic.
As mentioned above, I think the state does an excellent job (emergency management) talking about earthquake safety and prevention, however, I feel that this topic should be talked about on a regular basis so it's always on the mind of each person. I think there's a point where you can possibly talk about earthquake preparedness to often and then people may ignore it. I don't know what the happy medium is, but I feel this it's more often than one month a year focus.
Early Warning Systems should be regional, with the State of Utah backing up the regional systems and training people on maintaining and operating the early warning systems.
How do we learn more details about how effective it could be. Are others using it and how is cost implementation.
How does this work for people without access to smartphones? How would we ensure that lower-income and rural areas have access to this technology? Who is this system for?
How is it being used in California? How successful is it? How is the public educated about it? What is the public opinion about the early warning system in California? How much does it cost?
How much warning can the system provide and how accurate is the information provided?
I can't get over the feeling you are trying sell me on your service. I am extremely weary of the reason for this survey. I feel like I have been talking to a used car salesman.
I don't know enough to give any constructive feedback.
I have questions. How effective are they, how much advanced notice can they provide and what is the cost?
I have serious doubts about the ability to create such a system.
I have very limited knowledge
I retire soon, but I am confident someone from [organization] will participate in a focus group.
I think it is a good idea. But we also need a system of communication that is effective.
I think it needs to be financed and maintained at a statewide level for it to work.
I think it's a great idea and should move forward (but hope it's not too expensive).
I would be happy to see it implemented, but I simply have the time to participate in the early work at this point.

I would like to see evidence that it has saved lives or protected property.
I'd like to know what the early warning systems are?
I'd like to better understand how early the early notification would be.
If there is any cost.
In my opinion it is important to look into for class 1 railroads.
It sounds good, and with the technology we have, it is due.
It sounds like a good idea; I would like to know where it has been implemented and what the results were.
It sounds very interesting and important. I work remotely, so my participation isn't directly associated with my office building. I would appreciate training for off-site protection.
It would save lives and make response and recovery easier (and cheaper) if less people are injured because they had extra seconds to prepare for it, like getting off an elevator or other dangerous location before it hits.
Let's do it and help ourselves be safe in the event of an earthquake.
Mainly how the federal response could assist with airlift to save lives and distribute goods
Make it centralized and administered by one state agency.
N/A
None
None
None
None
None
None
None
None
None at this time
None at this time
None at this time
None at this time.
None at this time.
None.
Obviously, this is leading up to some program. Need more information on what you are proposing to do.
Overall emergency preparedness should override this system. Earthquakes are only one of the possible devastating events Utah foresees.
Please contact at email above
See above
Someone should really evaluate the ROI.

Sounds great. An early warning system would give us more time to respond appropriately.
The alerts need to be multi-dimensional. Think about the people who don't have a phone for example.
The placement of accelerometers and a dependable signal for warning apparatus
The sooner the better! Development/implementation will require a substantial investment in public education---based on credible, human behavior research findings on the subject of disaster preparedness.
This questionnaire is either badly written or else it should not have been sent to me. It seems to assume that I am an emergency manager for some organization and can speak for this organization. Neither one is true. As one example, take the question "How familiar are you and your organization with earthquake early warning systems"? That's really two questions rolled into one, because my familiarity and my organization's familiarity are two different things. (I answered the question about my own familiarity). I had to skip many other questions because I didn't know the answer. My answers to the questions about my organization's earthquake response objectives and top earthquake concerns are simply my opinion. I really can't say if the [organization] has the same opinions.
This seems like a no-brainer
Training
Understanding the timeframe of warning prior to peak magnitude of event.
We have a small office (about 10 employees) in downtown Salt Lake City with several employees working remotely at least part time. We don't have members of the public coming to our office on a regular basis. How would an early warning system be implemented for an office like ours?
We shouldn't waste precious resources on such a system; other things need our attention
We're very keen to see this effort progress. Thank you!
Web based, access restrictions, what does this give us beyond any earthquake app on smart phones?
What is the cost, maintenance, which State org will be responsible for it long-term, has research on what other states and countries have tried been done so we make sure Utah is getting the best technology for our area and needs. Can we utilize technology similar to an Amber Alert so everyone with a cell phone in an affected area gets the notice, not just individuals who have downloaded an early warning app? If funded, the public information campaign to educate the public about this system is vital to how it will be received, I hope Utah works with a great advertising company to make sure this is done well. I hope this project happens, I think it would be valuable for Utah.
What is the potential timeframe for implementation and costs?
What resources would be available to rural Utah?
Where else is it being used? Are there any comments or concerns from those entities who are using the early warning system? How much time before the quake happens are we alerted? Would technology improve and how would we stay in compliance with any updated systematic improvements?
Who would operate and manage the system?
With most of Utah living right on the fault line and the epicenter is directly below us, how much warning would we actually get, a second or two? I have strong reservations as to how much warning could actually be given. I know we have down hole seismic monitoring at the spaghetti bowl and electricity moves faster than the p-waves but I seriously don't think we would get enough of a warning. Also, how many down hole monitoring stations do we have? If there aren't many of them, then the system wouldn't function well enough. How do you only send the warning to the group that may be affected by the earthquake? If the system were able to keep running after the initial EQ and then give us warnings of aftershocks it might be more valuable. I wonder if it could cause more worry and concern if it kept going off for small aftershocks. Interesting idea and a lot needs to be figured out before it can be implemented.
Would be interested in studies and examples of its use, benefits, and downfalls

UTAH DNR GEOLOGICAL SURVEY

DEPARTMENT of PUBLIC SAFETY UTAH DIVISION of EMERGENCY MANAGEMENT

UNIVERSITY OF UTAH SEISMOGRAPH STATIONS