# Cascadia Region Earthquake Science Center

## 2023-24 Seed Grant Program
## Final Report

# Evaluating Multi-Hazard Early Warning Systems in Oregon: An Analysis of OR-Alert Notification Patterns

Sharif Coker and Michael R. Brudzinski
Miami University, Department of Geology and Environmental Earth Science, Oxford, OH

Submitted for review to: *Disaster Prevention and Management: An International Journal*

U.S. National Science Foundation

# Evaluating Multi-Hazard Early Warning Systems in Oregon: An Analysis of OR-Alert Notification Patterns

Sharif Coker (1) and Michael R. Brudzinski (1)
*(1) Miami University, Department of Geology and Environmental Earth Science, Oxford, OH*

## Abstract

Purpose: Effective multi-hazard early warning systems (MHEWS) are critical for achieving the United Nations' Sendai Framework target of increasing access to disaster risk information by 2030. This study presents an analysis of Oregon's OR-Alert system to evaluate its capability as a MHEWS.

Methodology: We examined 31,940 alerts and 11.1 million associated messages delivered over a 12 month period in 2024 issued by 35 county groups, 3 tribal groups, and 6 state agencies. We analyzed alert distribution patterns, communication methods, geographic coverage, and temporal variations, with a particular interest to assess system applicability for earthquake early warning (EEW) integration.

Findings: Our results indicate that while OR-Alert demonstrates robust capacity potentially reaching over 2 million reported recipients, challenges remain. Natural hazards comprise 75% of public alerts, delivered primarily through SMS (52%), with distinct seasonal and geographic patterns corresponding to regional hazard profiles. Push notification adoption remains very low at 2%, posing substantial barriers for time-sensitive earthquake warnings. Geographic analysis reveals marked differences in system enrollment, with some counties having high participation while some populous regions show less than 10% participation.

Originality: The evaluation of geographic and temporal alerting patterns provides quantitative information about how MHEWS is functioning across a state with varying hazards both in space and time.  Comparisons with census data provides context for the geographic variations in the alerting data suggesting that infrastructure availability and language use does not significantly influence communication channel selection.

Implications: These findings highlight the need for recruitment efforts to address coverage disparities and for enhanced push notification adoption to enable rapid-onset hazard communication, particularly as the Cascadia region seeks to improve its EEW capabilities.

**Keywords:** multi-hazard, early warning systems, earthquake early warning, emergency alerting, disaster risk reduction, Oregon

## 1. Introduction

The global imperative to enhance disaster risk reduction has gained unprecedented urgency as climate change intensifies hazard frequency and severity (UNDRR, 2023). The Sendai Framework for Disaster Risk Reduction 2015-2030 establishes seven global targets, including substantially increasing "the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to people by 2030" (UNDRR, 2015). This target recognizes that effective early warning systems can significantly reduce disaster mortality and economic losses through timely dissemination of actionable information (Cremen et al., 2022).

Multi-hazard early warning systems represent an evolution from single-hazard approaches, offering economies of scale and operational efficiency by utilizing shared infrastructure across multiple threat types (UNDRR, 2023). As defined by the United Nations Office for Disaster Risk Reduction, MHEWS address "several hazards and/or impacts of similar or different type in contexts where hazardous events may occur alone, simultaneously, cascadingly or cumulatively over time" (UNDRR, 2017). The effectiveness of these systems depends critically on four interrelated elements: risk knowledge, monitoring and warning services, dissemination and communication, and response capability (PrepareCenter, 2024). When alerts are delivered via phone apps, MHEWS strategies have been shown to be retained at higher rates than single hazards apps over several years, improving the likelihood that people will retain other hazard alerting capabilities, especially for low frequency, high impact events like earthquakes or tsunami (Brudzinski et al., 2025)

In the United States, the Integrated Public Alert and Warning System (IPAWS) serves as the national architecture for local alerting, providing authenticated emergency information through multiple pathways including Wireless Emergency Alerts (WEA), the Emergency Alert System (EAS), and NOAA Weather Radio (FEMA, 2024). Since its establishment in 2006 through Presidential Executive Order 13407, IPAWS has expanded to include over 1,800 federal, state, local, tribal, and territorial alerting authorities (FEMA, 2024). However, implementation varies significantly across jurisdictions, with effectiveness dependent on local system configuration, enrollment patterns, and communication strategies (Bean et al., 2015).

The Pacific Northwest faces unique multi-hazard challenges, particularly from the Cascadia Subduction Zone, which poses significant earthquake and tsunami risks (Goldfinger et al., 2012). The ShakeAlert earthquake early warning (EEW) system, now operational in California, Oregon, and Washington, represents a critical advancement in rapid-onset hazard mitigation (Given et al., 2018). ShakeAlert leverages the principle that electronic signals travel faster than seismic waves, providing seconds to minutes of warning before strong shaking arrives (Allen & Melgar, 2019). However, the effectiveness of EEW depends fundamentally on the underlying alert distribution infrastructure and public preparedness to respond appropriately to warnings (Strauss & Allen, 2016).

Oregon's OR-Alert system operates as the state's primary emergency notification platform, utilizing the EverBridge mass notification system to deliver alerts across multiple communication channels. The system serves both internal organizational needs and public warning functions, addressing hazards ranging from severe weather to wildfire to potential seismic events. Considering OR-Alert functions in conjunction with IPAWS that is designed to deliver more critical alerts, OR-Alert can be perceived as a less urgent form of messaging. Understanding the current operational characteristics of OR-Alert is essential for evaluating its readiness to integrate EEW and achieve broader disaster risk reduction goals.

This study presents an analysis of OR-Alert operational data, examining alert patterns, communication methods, geographic coverage, and temporal variations. Our analysis addresses critical questions about system effectiveness, including: (1) How do alert distribution patterns vary geographically and temporally? (2) What communication channels are utilized and how do preferences vary across populations? (3) What gaps exist in current coverage that may impact EEW effectiveness? (4) How can the system be optimized to achieve UN Sendai Framework targets while preparing for Cascadia seismic risks?

## 2. Methods

### 2.1 Data Collection and Sources

We utilized operational data from Oregon's OR-Alert system during 2024, provided through a partnership with Oregon's State Interoperability Executive Council and their industry service provider, EverBridge. Not all counties were represented in the data provided by EverBridge, with Oregon's second most populous county (Washington) not included. Three primary data sources were analyzed, the first two provided by EverBridge and the third collected from the U.S. Census Bureau's website. The first type were monthly "Notifications" documents that contained detailed records of individual alerts, including unique identifiers, notification titles, originating organizations, county information, internal versus public designation, and precise timestamps. This data was available for all 12 months of 2024 capturing seasonal variations in hazard occurrence and alert patterns. The second data source was monthly "Usage" documents that provided aggregate statistics by organization, documenting notification volumes, recipient counts, communication channel utilization, and audience classification. This dataset enabled analysis of system usage patterns and organizational alerting behaviors. The monthly recipient counts were our best window into the number of people that typically receive alerts, so we estimated total recipient numbers by finding the maximum number of this value in any given month. This data was available for 11 months as we were unable to obtain data from August 2024. The third data source was supplementary demographic and infrastructure data that were obtained from the U.S. Census Bureau's 2020 American Community Survey, including county-level population, broadband access rates, and limited English proficiency statistics. Figure 1 illustrates the population density at the county level in Oregon.

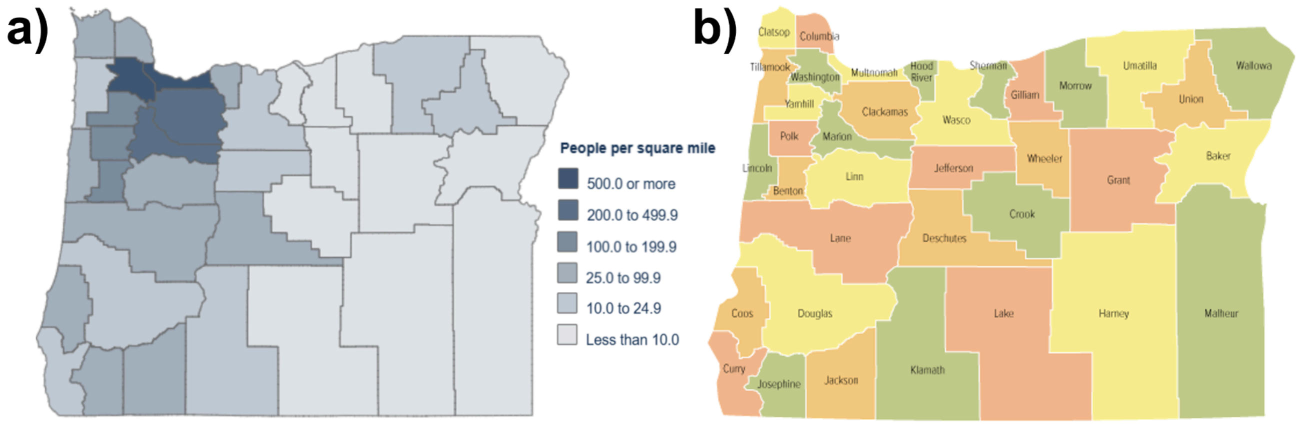


**Figure 1.** Maps of Oregon counties showing a) population density and b) county names.

## 2.2 Alert Classification and Categorization

Individual alerts were initially distinguished based on whether they were listed as internal organizational communications and public-facing alerts in the Notifications file. Public alerts were further categorized based on the notification description using a hierarchical taxonomy developed through iterative content analysis. The primary categorization was based on natural hazard versus non-natural hazard events. Natural hazard subcategories included weather (keywords: storm, lightning, wind, tornado, freeze, fog, gale, heat, surf, blizzard, hail, cooling, warming, weather), fire (keywords: fire, red flag), flood (keyword: flood), and earthquake (keywords: quake, shake) notifications. Non-natural hazard alerts encompassed utility disruptions, transportation incidents, public safety activities, and public health notifications. There were no actual tsunami warnings during our study time frame, only a few drills.

Communication channels were classified into four primary categories: SMS/text messaging (including NIXELSMS), voice calls, email notifications, and push notifications delivered through mobile applications. TTY and FAX messages were also reported but were much smaller in total numbers (12,192 and 337). Geographic analysis was conducted at the county level, with alerts mapped to 20 Oregon counties based on the agency issuing the alerts and reporting throughout the full time frame. There were 4 cases of multi-county reports (Linn-Benton, Jackson-Josephine, Marion-Polk, Frontier Region) which could not be separated and were excluded from county-based analysis. The 6 statewide agencies (State Police, Military Department, State Lottery, Health Authority, Judicial Department, and State of Oregon) and 3 tribal groups (Siletz, Klamath, and CTCLUSI) alerts were only considered in the overall analysis.

## 2.3 Analytical Approach

Descriptive statistical analysis characterized alert volumes, distribution patterns, and communication preferences across temporal and geographic dimensions. Enrollment in OR-Alert for each county was estimated based on the maximum monthly recipient count reported in the Usage files. Recipient coverage rates were then calculated by dividing the maximum monthly reported recipient counts by the census population estimates. However, we acknowledge there are potential limitations to interpreting these values from multiple registrations per individual and non-resident participants in OR-Alert messaging. Temporal analysis examined monthly patterns in alerting, identifying relationships between hazard seasonality and alert frequency. Geographic analysis was performed by plotting alert distributions and communication preferences based on the county locations, enabling visualization of spatial patterns and identification of potential coverage disparities. Correlation analysis explored relationships between demographic factors (broadband access, language proficiency) and system utilization patterns. These analyses were conducted using R statistical software.

### 2.4 Limitations

Several limitations constrain the interpretation of findings. The 12 month analysis period may not capture full seasonal or annual variations, particularly for low-frequency events. Population-based coverage calculations assume single registrations per individual, potentially overestimating coverage in areas with multiple registrations per individual which is likely if people register multiple devices. Only 20 of Oregon's 36 counties were included in the geographic analysis, which may limit our ability to fully resolve spatial patterns. The classification of alerts relied on title and description fields, which may introduce categorization errors for ambiguously described events. Technical constraints of the current system may influence observed patterns, particularly regarding push notification capabilities. Additionally, while prior case studies have incorporated a wider range communication channels such as radio, television, and social media (Hu et al., 2019; Wogalter et al., 2021), our analysis was constrained to the primary four communication channels provided in the OR-Alert dataset. Hazard specific warnings such as ShakeAlert EEW were also delivered via other means such as the MyShake app (Given et al., 2018), which limits our ability to interpret the overall alerting experience for a given person. Our dataset was also limited in that it did not provide information about the demographics of the alert recipients so we could not evaluate variability in who was receiving alerts and if there were demographic disparities. Future studies should consider surveys and focus groups to collect more information about how the alerts are received and to interpret how individuals responded to the alerts (Morss et al., 2016; Sadiq et al., 2023).

## 3. Results

### 3.1 Alert Volume and Distribution Patterns

Analysis of OR-Alert operational data revealed substantial system activity, with 31,940 alerts issued over the 12 months and 11.1 million associated messages delivered during the 11 months when Usage data was available, which extrapolates to over 12 million messages per year. The distribution between internal and public alerts demonstrated that the majority of alerts are issued internally, with 77% (n=24,643) serving internal communication needs and only 23% (n=7,297) directed to the general public (Figure 2a). However, the situation flips when the total number of messages associated with these alerts are considered, with public messages representing 76% (8.5 million) compared to 24% (2.6 million) for internal messages. Among the public alerts, natural hazards comprised the dominant category at 75% (n=5,523), while non-natural hazard events accounted for 18% (n=1,296), and 7% (n=478) were non-specific emergency alert notifications in other languages (Figure 2b). This distribution aligns with findings from other regions implementing multi-hazard systems, where weather-related events typically dominate alert volumes (Sorensen, 2000). The prominence of natural hazard alerts reflects both Oregon's diverse hazard profile and the established integration of National Weather Service products into local alert systems. Non-natural hazard public alerts encompassed diverse event types, with police activity (770), emergency alert testing (292), public utility outages (98), health and medical alerts (62), and road closures (27) being the most common. This diversity demonstrates the system's evolution beyond traditional emergency management applications to serve broader public information needs, consistent with trends identified in national public warning system assessments (NAS, 2018).

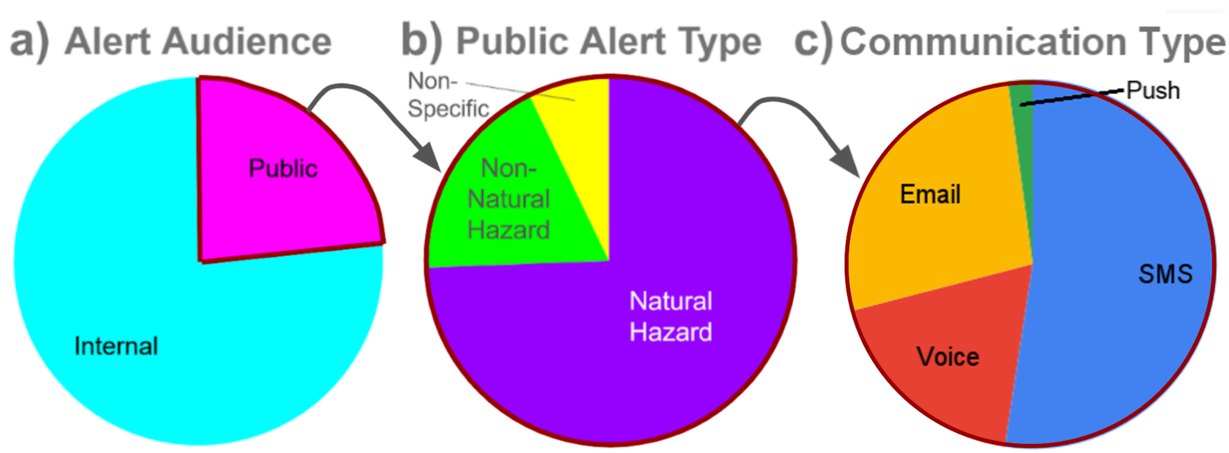


**Figure 2.** Relative distribution of OR-Alert messages based on comparison of a) internal vs. public audience recipient types, b) natural hazard vs. non-natural hazard public message topics, and c) type of communication used to deliver public alert messages. The arrows indicate that b) and c) do not include internal messages.

### 3.2 Communication Channel Utilization

The analysis of communication methods for public messages revealed a substantial reliance on SMS text messaging, which accounted for 52% of all public alert message deliveries (Figure 2c). Email delivery represented 26% of alert messages, followed by voice calls at 20%, while push notifications comprised merely 2% of total alert volume. This distribution pattern raises significant concerns for EEW implementation, where push notifications offer critical advantages including near-instantaneous delivery, rich media capabilities, and ability to override device silent modes (Cauzzi et al., 2016). The minimal utilization of push notifications contrasts sharply with their technical superiority for time-sensitive alerts. Research on EEW systems in Japan and Mexico demonstrates that push notifications can reduce alert latency by 3-5 seconds compared to SMS delivery, potentially doubling available warning time for near-field events (Kohler et al., 2020). The current reliance on SMS introduces vulnerabilities including network congestion during emergencies, character limitations that constrain message content, and inability to include maps or other visual information critical for public response. In addition, nearly 50% of alerts are received via email and voice messaging which potentially have longer latency that would be problematic for expedited alerting across various natural hazards.

We also explored the geographic variation in communication preferences by examining the communication patterns at the county level (Figure 3). Symbol sizes in Figure 3 represent these relative percentages, with push values scaled up for visibility. County-level analysis also showed SMS as the primary delivery method, averaging ~40% overall and exceeding 60% in places like Deschutes and Douglas Counties (Figure 4a). Percentages tended to be slightly higher for SMS in inland counties, with lower percentages in western coastal counties such as Lincoln and Coos issuing ~20-33% of public alerts via SMS. Several inland counties showed lower email utilization (<20%) compared to the statewide average, while the values over 50% in Lincoln County, which also had one of the lowest SMS values. Voice alerts exceeded 35% in some western counties compared to statewide averages near 20%. Push notifications remained minimal and sparse, averaging 4% statewide, with only a few counties reaching 9–11% in Morrow, Coos, and Yarnhill. The most populated county (Multnomah) has a very low push percentage (~0.7%), which is concerning for the lack of adoption of push technologies.

Figure 4 illustrates the relative percentages of alert communication types for each county along with the data from the Census Bureau on the percentage of households with broadband internet and with a language use other than English. Correlation analysis revealed no significant relationship between broadband access rates and email preference ($r(18)=.02$, $p=.93$), suggesting that infrastructure availability does not drive communication channel selection. Similarly, no correlation existed between limited English proficiency populations and communication preferences ($r(18)=.09$, $p=.70$), indicating that language barriers may not significantly influence channel selection within the current system architecture.

### 3.3 Geographic Coverage Disparities

Spatial analysis revealed significant differences in system enrollment across Oregon's counties. Figure 5a shows how coverage rates, calculated as the maximum monthly recipient count relative to census population, ranged from 5-10% in several counties to over 100% in others. Clatsop, Curry, Douglas, and Lincoln demonstrated the highest coverage rates (461%, 282%, 202%, 347%), likely attributable to multiple registrations per person. Conversely, several populous counties showed surprisingly low coverage rates and the low recipient counts despite high alert volumes indicating that many residents in these areas are not receiving important alerts. For example, Multnomah County, containing Portland and representing 19% of Oregon's population, demonstrated only 13% enrollment, with most being due to internal Portland Employees. The low enrollment rates in population centers represent an important vulnerability, as urban areas face compound risks from both natural hazards and cascading infrastructure failures during disasters (Chang et al., 2006).

Figure 5b shows the total number of alert messages issued by county, separated by whether the alert audience was internal or public. The total number of alert messages distributed showed only a weak correlation with population (r(18)=0.34, p=0.09), indicating that the number of alert messages may reflect local population sizes impacted by hazard occurrence and emergency management practices rather than factors related to OR-Alert sign-up rates. Counties with established hazard mitigation programs and recent disaster experiences generally demonstrated higher alert messaging counts and enrollment rates, supporting research indicating that disaster experience enhances risk perception and protective action adoption (Lindell & Perry, 2012).

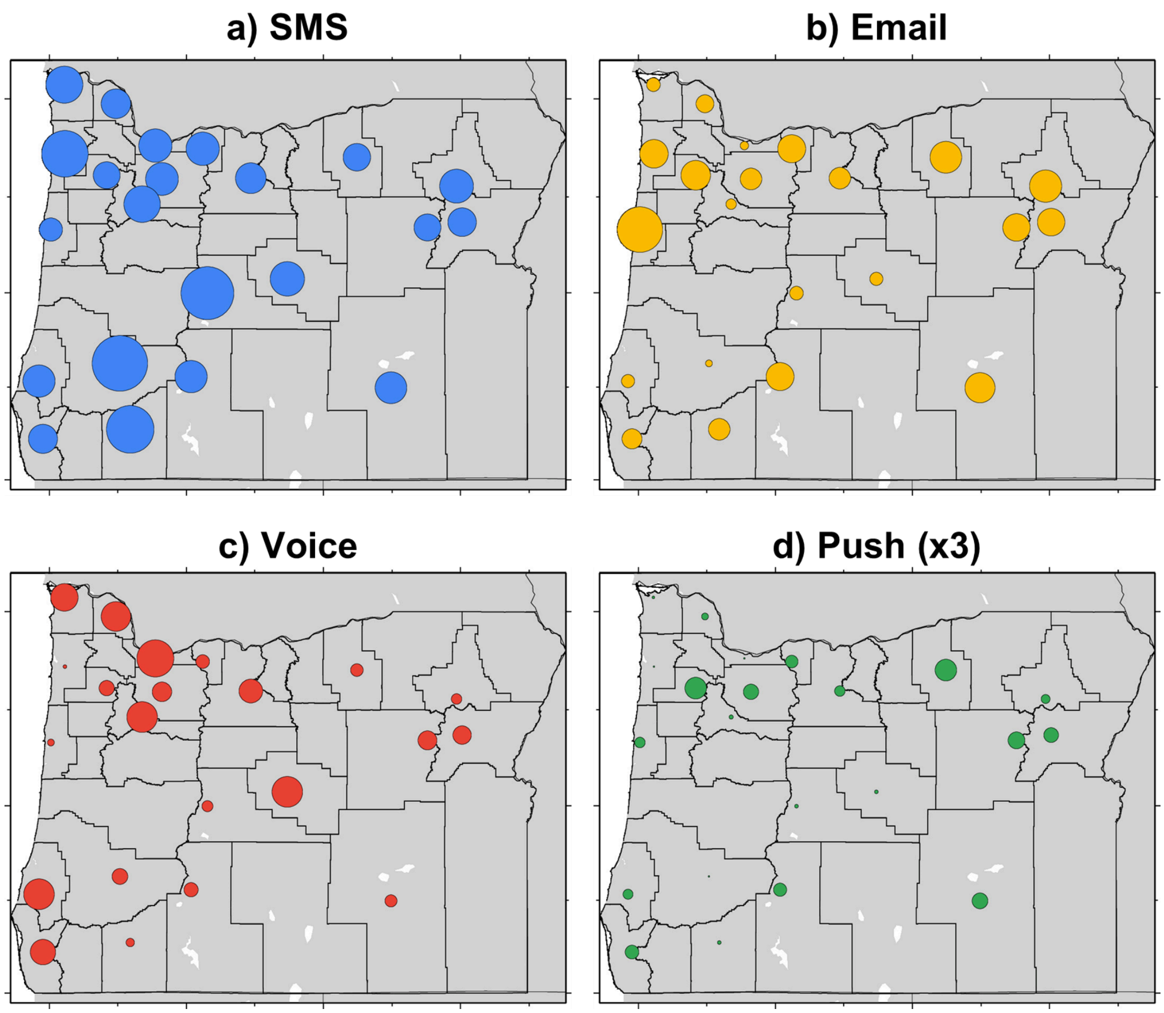


**Figure 3.** Percentage of alert messages received by communication type for each county in Oregon with data available by individual county: a) SMS/text message, b) e-mail message, c) voice/phone message, d) app-based push notification. Size of symbol represents the relative percentage, except this value is tripled for push to enable the symbol relative sizes to be visible.

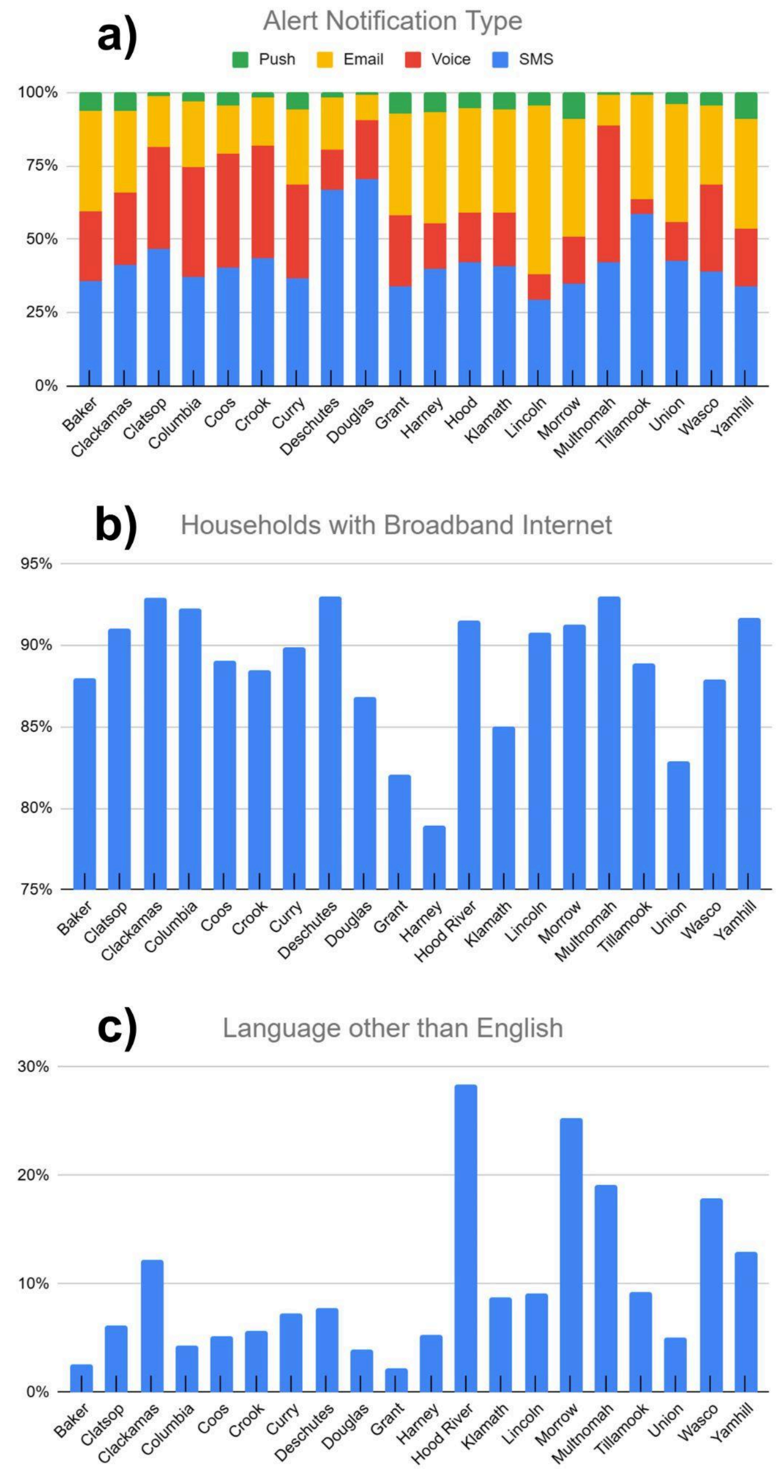


**Figure 4.** Bar graphs to compare a) the relative proportion of alert communication types for each county with data from the Census Bureau on the percentage of households b) with broadband internet and c) with a language use other than English.

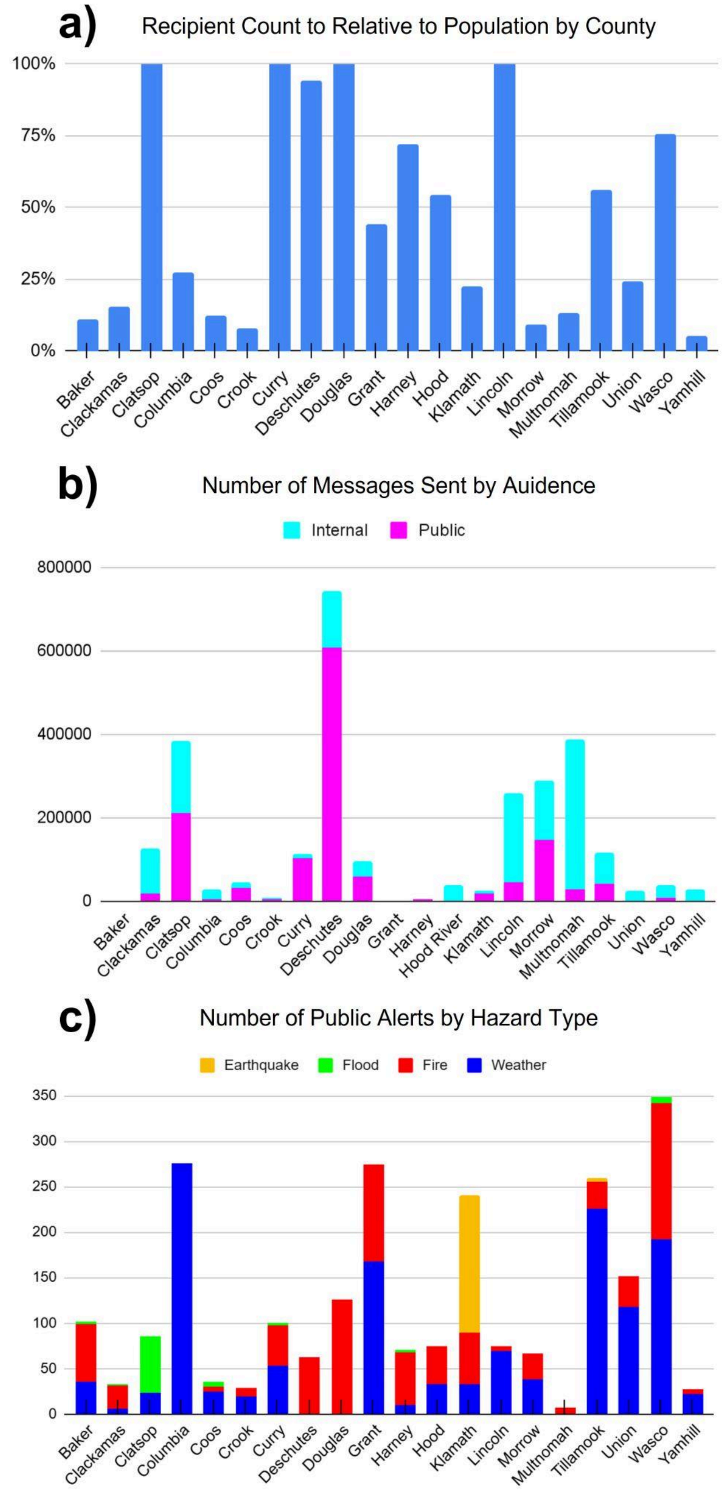


**Figure 5.** Bar graphs to illustrate county based trends including a) the relative proportion of alert recipients to the county population, b) the total number of alert messages issued based on whether it was internal or external, and c) the total number of public alerts issued based on what natural hazard topic was the subject of the message.

## 3.4 Hazard Type Geographic Patterns

Natural hazard public alert distributions demonstrated sharp contrasts in geographic distribution corresponding to regional hazard profiles (Figure 5c and 6). Weather-related alerts were most common (n=3,442, 62% of natural hazard public alerts) and tended to concentrate in northwestern coastal counties, with a few exceptions (e.g., Union and Grant, >100 alerts and >70% of alerts for those counties) (Figure 6a). For example, Tillamook County generated ~400 weather alerts compared to a statewide county average of ~70. This pattern reflects the Pacific Northwest's winter storm exposure, where atmospheric rivers and Pacific cyclones can create persistent severe weather conditions (Ralph et al., 2019).

Fire alerts were the next most common type of alert (n=1,370, 25% of natural hazard public alerts) and tended to show the opposite geographic distribution, concentrating in interior counties in central and southern Oregon that are characterized by more Mediterranean climate patterns and extensive wildland-urban interface (Figure 6b). Interior counties tend to have higher fire alert percentages, with Crook, Deschutes, Douglas, Multnomah each reaching 100% of alerts for those counties. Meanwhile coastal counties including Lincoln (8%) and Tillamook (17%) registered lower percentages for alerts in those counties. This distribution aligns with established wildfire risk assessments for Oregon, where the dry to semiarid regions east of the Cascade Mountains crest and southwestern valleys face elevated fire danger during summer months (Wing and Long, 2015; Short et al., 2016; Schmidt et al., 2022).

Flood alerts were relatively sparse (n=191, 3.5% of natural hazard public alerts) statewide except for a distinct concentration in Clatsop County (74% of county alerts). This reduced the relative amount of weather alerts in this county compared to neighboring northwest counties with high weather alert percentages. We note that this is a region with a major river system (Columbia River).

Earthquake-related alerts were also limited (n=520, 9%), with 46% issued by Klamath County and 54% issued by the State of Oregon during our study time frame. This only considered public alerts, which were almost exclusively due to actual earthquakes, whereas drill notifications like ShakeOut were generally sent to internal audiences. This paucity of earthquake-related messaging suggests limited public familiarity with earthquake alerts, supported by the surveying regarding EEW in the Pacific Northwest (Bostrom et al., 2022). This will potentially compromise response effectiveness to further ShakeAlert integration in OR-Alert.

## 3.5 Temporal Patterns and Seasonality

Temporal analysis revealed pronounced seasonality in alert patterns, with natural hazard notifications demonstrating clear seasonal peaks corresponding to regional hazard calendars (Figure 7a). Winter months showed the most elevated weather alerts, with January recording 584 weather-related notifications compared to a monthly average of 266. However, there was also elevated (>400) weather alerting at other times (e.g., May and September). Fire alerts peaked during late summer, with July generating 512 fire notifications, representing ~30% of annual fire alert volume. This is consistent with the typical fire season due to wet mild winters and warm dry summers in Oregon (Trouet et al., 2009). Although the number of flood alerts was noticeably lower, they appeared to be more common in winter months (Figure 7a). Although the number of earthquake alerts are also low, we would not expect earthquake alerts to have any seasonality.

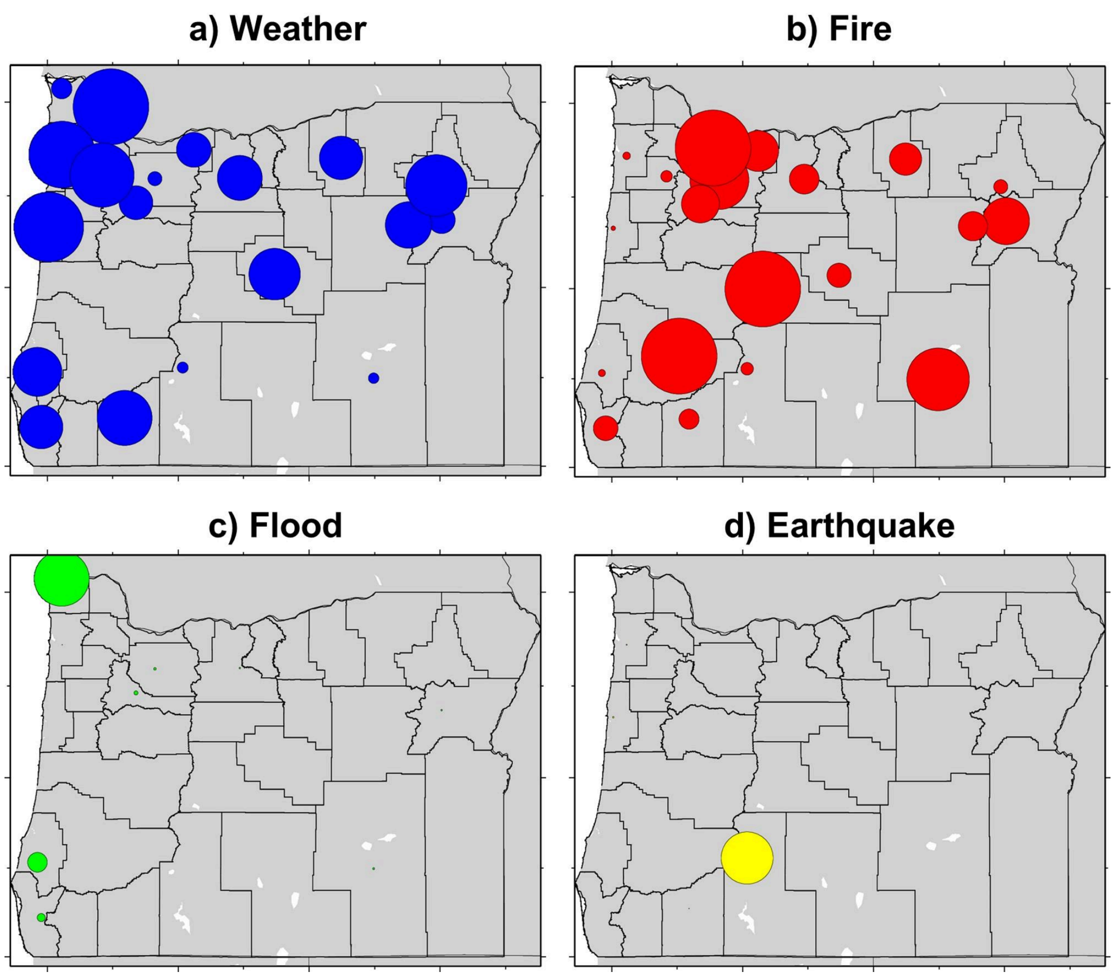


**Figure 6.** Maps illustrating geographic distribution of natural hazard alerting.

The ratio of natural to non-natural hazard alerts varied significantly across months (Figure 7b), ranging from near-parity in March (~1:1) to strong natural hazard dominance in winter and summer months (~3:1). These patterns are generally driven by the seasonal variability of natural hazards as seen in Figure 7a. Non-natural hazard alerts maintained relatively consistent volumes throughout the year (monthly average: 174, standard deviation: 60), suggesting steady baseline system utilization for routine public safety communications. However, we note that the number of non-natural hazard alerts does have a similar overall trend to that of natural hazards (larger in summer and winter months), albeit more muted. This has the potential for system strain during peak hazard seasons, with implications for alert fatigue and public responsiveness. Research on warning effectiveness demonstrates that high alert frequencies can lead to decreased compliance, particularly when false alarm rates are elevated (Trainor et al., 2015).

This would emphasize the importance of taking advantage of opportunities for public education and system familiarity during non-crisis periods, potentially enhancing response effectiveness during actual emergencies.

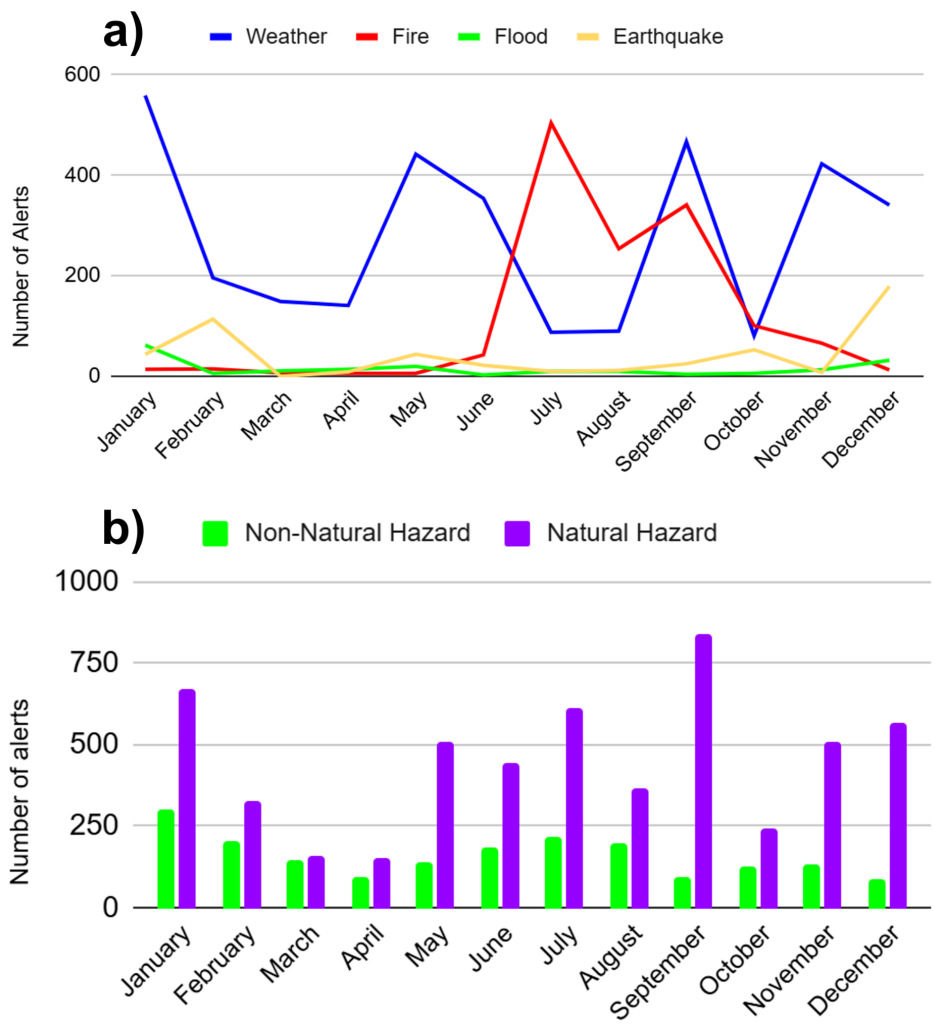


**Figure 7.** Temporal patterns in the number of alerts for a) the specific type of natural hazard and b) natural hazards versus other alert topics.

## 4. Discussion

### 4.1 Alerts from IPAWS

We note that our analysis of OR-Alert means that we have tended to focus on the less urgent forms of alert messaging.  In contrast, IPAWS is often utilized for more urgent alerting as it can engage audiences that did not sign up for alerting. IPAWS operates through the Federal Communications Commission (FCC) to protect property and preserve life, and has been successfully implemented in emergency situations (Leiva, 2014; Sutton & Wood, 2022). Everbridge was able to share the number of IPAWS alerts issued by each county and the state of Oregon in 2024 for comparison with OR-Alert issued alerts.  This data is shown by county in Figure 8 and reveals that no county issued more than 40 alerts, with Grant County having the highest count. The State of Oregon has also utilized IPAWS 19 times, which is the second highest number, suggesting some expected variation in alert frequency and system engagement between local and state authorities.

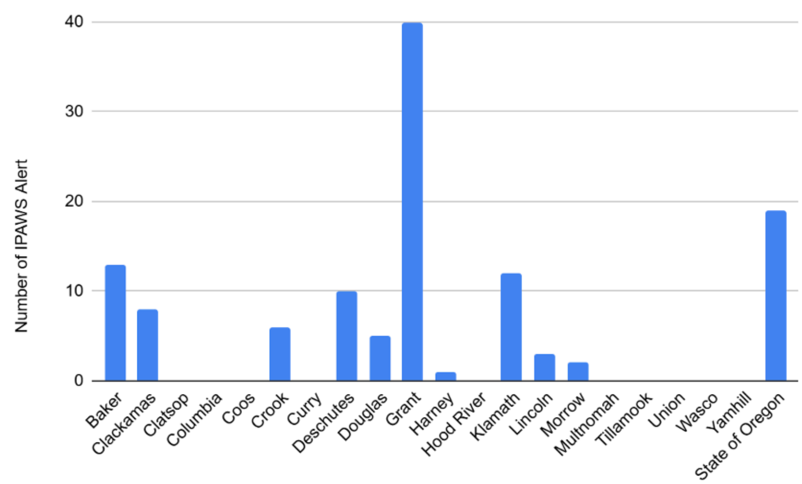


**Figure 8.** Bar graph illustrating number of IPAWS alerts issued in 2024 for each county, along with the alerts issued by the State of Oregon.

Spatially, the comparison reveals that Grant, Baker, and Klamath counties were the most active in IPAWS use, and we note that these were generally rural counties.  There were numerous counties that did not issue any IPAWS alerts in 2024, including both more highly populated counties (Multnomah and Yamhill) and more rural counties (Wasco and Union).  Of the 151 total IPAWS alerts in 2024, 125 were related to natural hazards (83%), 123 of which were fire alerts and 2 tsunami alerts, while 26 were associated with non-natural incidents such as civil or administrative messages (17%).  The fire alerting makes sense given that urgent communication can be needed during such events.  This provides some additional context for the counties with the most IPAWS alerts (Grant, Baker, and Klamath), which also had large numbers of fire alerts in Figure 5c reflecting their higher exposure to wildfire risk.  However, there does not appear to be an overall correlation between the number of IPAWS alerts and the number of public alerts issued by OR-Alert (Figure 8 vs. 5c).

The absence of IPAWS alerts in several counties may reflect administrative or operational differences in alerting practices. We considered that some counties may rely on the state to issue alerts on their behalf, especially in rural areas where staffing and resources are limited. However, we saw no evidence that the IPAWS alerts issued by the state were on behalf of hazards in counties that did not issue alerts themselves, although we could not rule out whether any statewide alerts covered portions of neighboring counties that made local issuance unnecessary.  It seems more likely that county officials may choose to reserve IPAWS for the most critical emergencies to prevent public desensitization or alert fatigue. These differences suggest that population density, local hazard exposure, and resource availability may influence how and when each system is used, rather than any inherent limitation in the alerting platforms themselves.

### 4.2 Implications for Earthquake Early Warning (EEW)

The analysis reveals current issues that would prevent OR-Alert from effectively supporting EEW. The 1% push notification adoption rate represents the most significant barrier, as EEW effectiveness depends fundamentally on minimizing alert latency. Current SMS-dominated delivery would add 5-10 seconds to alert times, potentially eliminating warning capability for near-epicenter populations and substantially reducing protective action opportunities for others (Minson et al., 2018). OR-Alert does not have its own dedicated app, but the EverBridge app can be downloaded to receive OR-Alert messages as push alerts.

It is important to note that MyShake, a dedicated EEW application developed by UC Berkeley, currently provides push notification capabilities for earthquakes in Oregon as part of the ShakeAlert system (Given et al., 2018; Lux et al., 2024). This single-hazard solution effectively addresses the technical requirements for rapid earthquake alerting through push notifications. However, the existence of MyShake as a standalone application highlights a fundamental tension in emergency alerting strategy: while specialized apps may optimize performance for specific hazards, they contribute to application proliferation that can reduce overall public engagement. The UNDRR's vision of integrated multi-hazard early warning systems specifically aims to avoid such fragmentation, recognizing that requiring citizens to download and monitor multiple applications for different hazard types creates barriers to comprehensive preparedness (UNDRR, 2023).

International EEW implementations provide instructive contrasts for integrated approaches. Japan's system achieves near-universal push notification coverage through mandatory installation on all smartphones sold domestically, coupled with extensive public education campaigns (Fujinawa & Noda, 2013). Notably, Japan's J-Alert system integrates earthquake warnings with other hazards in a single platform, avoiding the fragmentation challenge. Mexico City's Sistema de Alerta Sísmica Mexicano combines push notifications with public address sirens, achieving 60-second average warning times for subduction zone events (Cuéllar et al., 2017). Both systems demonstrate that technical capabilities alone are insufficient; success requires comprehensive public engagement and behavioral change initiatives.

The absence of regular earthquake-related alerts in OR-Alert compounds readiness challenges. Research on protective action decision-making emphasizes the importance of message familiarity and behavioral scripts developed through repeated exposure (Wood et al., 2018). Without regular earthquake drills or test alerts, Oregon's population lacks the awareness necessary for rapid interpretation and response to EEW messages. This contrasts with the population's apparent familiarity with weather and fire alerts, where seasonal exposure enables rapid comprehension and appropriate response.

### 4.3 Alert Fatigue, Coverage Disparities, and System Optimization

The high volume of monthly alerts, particularly during peak hazard seasons (~1000 in January), raises concerns about alert fatigue—a phenomenon where excessive warnings lead to decreased attention and response (Bliss et al., 1995; Sutton & Wood, 2025). While natural hazard alerts demonstrate clear seasonal patterns justifying increased communication, the system's use for a wide range of communications may contribute to notification overload. Research in healthcare settings demonstrates that alert effectiveness decreases exponentially with frequency, with response rates dropping below 50% when daily alert volumes exceed 10-15 per user (Cvach, 2012).

Geographic disparities in alert frequency suggest opportunities for system optimization. Counties receiving high volumes of alerts, particularly those with a large number of internal organizational alerts, might benefit from channel segregation, reserving specific communication pathways for public safety warnings. The implementation of hierarchical alerting, where message urgency determines communication channel selection, could preserve push notification effectiveness for critical warnings while utilizing less intrusive channels for routine communications. The Common Alerting Protocol (CAP) provides a framework for such optimization, enabling message prioritization and multi-channel distribution based on event severity (Botterell, 2006). However, implementation requires careful calibration to local conditions and hazard profiles. Research on multi-hazard systems in Europe demonstrates that effective hierarchical alerting requires continuous refinement based on public feedback and response monitoring (Kolen & Helsloot, 2014).

The large variation in enrollment rates across counties likely reflects complex social, technical, and institutional factors that suggests recruitment efforts are warranted. Low enrollment in populous counties may stem from multiple causes including limited awareness, language barriers, trust deficits, or preference for alternative information sources. Survey research in California found that emergency alert enrollment correlates strongly with social capital, disaster experience, and institutional trust (Eisenman et al., 2007). Successful enrollment campaigns in other regions provide models for addressing these disparities. Research on public alert and warning systems emphasizes that building partnerships with trusted community organizations is key to creating equitable enrollment practices and improving safety outcomes (First et al., 2021; Sansom et al., 2021). King County reported that targeted outreach, including door-to-door canvassing and community partner engagement, nearly doubled ALERT King County registrations between 2019 and 2023 (King County OEM, 2019; 2023). Studies have shown that collaborative approaches involving uniformed staff, weather forecasters, and high-credibility organizations can significantly improve public engagement with alert systems (Liu et al., 2019). These collaborative models suggest that targeted outreach through existing community networks may be more effective than standalone enrollment campaigns.

The lack of correlation between limited English proficiency and communication preferences in our study suggests that language barriers operate at the enrollment stage rather than channel selection. This finding emphasizes the need for multilingual enrollment campaigns and translated alert capabilities. Research on warning effectiveness in diverse communities demonstrates that message comprehension improves dramatically when alerts are delivered in recipients' primary languages (Aguirre, 1988). This project had originally intended to offer a survey in Oregon similar to that in San Diego County (Brudzinski et al., 2025) to understand enrollment barriers and communication preferences across diverse populations. However, the efforts in San Diego County identified prominent challenges in getting a large enough number of respondents to draw appropriate conclusions. In that case, NORC was enlisted to aid in increasing participation up to ~1000 respondents, but the additional cost was not budgeted for in this project and thus will be the target of future funding.

### 4.4 Contributions to Disaster Risk Reduction

As climate change intensifies hazard frequency and severity while seismic risks remain ever-present, optimizing multi-hazard early warning systems becomes increasingly critical. The window for action is narrowing; proactive enhancement of alert systems today will determine their life-saving potential when seconds count. This analysis contributes to broader disaster risk reduction efforts by providing empirical evidence of multi-hazard warning system operations in a seismically vulnerable region. The findings align with global assessments indicating that while MHEWS implementation has expanded rapidly, significant gaps remain in reaching vulnerable populations and optimizing for rapid-onset hazards (UNDRR, 2023). Oregon's experience demonstrates both the potential and challenges of leveraging existing alert infrastructure for emerging threats like EEW. Our study's methodology offers a replicable framework for assessing alert system effectiveness in other jurisdictions. By examining multiple operational dimensions—volume, distribution, geography, and temporality—the analysis reveals system characteristics that single-metric evaluations might miss. This approach aligns with recommendations from the Sendai Framework monitoring guidelines, which emphasize holistic assessment of early warning system effectiveness (UNISDR, 2017).

## 5. Conclusions

Oregon's OR-Alert system demonstrates substantial operational capacity, processing nearly 32,000 alerts throughout the state and 12.3 million associated messages per year across diverse hazard types that appear to be reaching millions of recipients. Although 77% of alerts were directed to internal audiences, the 23% of alerts sent to the general public still accounted for 76% of the messages delivered by the OR-Alert system. Delivery patterns show a heavy reliance on SMS messaging (52%), while push notifications were underutilized (2%) by OR-Alert, limiting the timeliness needed for earthquake early warning (EEW). There were some geographic patterns in the communication channel utilized, with email and voice being more common in some counties. However, we saw no correlation between communication type and either broadband internet availability or non-English language prevalence based on county demographics. Enrollment also varied geographically with some rural counties reporting surprisingly high participation rates, while urban areas like Multnomah County showed low participation, leaving large populations more vulnerable. As expected, the types of natural hazard alerting varied with geography, with fire alerts more common inland and weather alerts more common in western and coastal counties. Seasonal hazard patterns are clear, with winter dominated by storms and summer by wildfires, but earthquake alerts are rare, highlighting that most residents have little experience with seismic warnings. Trends highlight both the system's effectiveness and opportunities to enhance alert and warning. The 2% push notification adoption rate, geographic enrollment disparities, and absence of earthquake messaging familiarity represent current barriers to achieving broader disaster risk reduction goals with OR-Alert. Institutional coordination between emergency management, public health, and community organizations can build the engagement and trust necessary for effective warning response.

## Acknowledgments

The authors thank W. Chapman at the Oregon Department of Emergency Management and S. Batmale at EverBridge for providing access to OR-Alert operational data. We thank D. Toomey and the Oregon Hazards Lab for helping us make connections needed to launch this project. We acknowledge the Cascadia Region Earthquake Science Center (CRESCENT) team and participating emergency managers for valuable input throughout the analysis. We thank our colleagues at Miami University for their support and feedback as we developed this project. We acknowledge the use of Anthropic's Claude Opus 4.0 in making suggestions for drafting a project report, which were considered by the authors when writing this manuscript. This research was supported by the CRESCENT Seed Grant Program.

## References

Aguirre, B. E. (1988), "The lack of warnings before the Mount St. Helens eruption", *International Journal of Mass Emergencies and Disasters*, 6(1), 65-88.

Allen, R. M., & Melgar, D. (2019), "Earthquake early warning: Advances, scientific challenges, and societal needs", *Annual Review of Earth and Planetary Sciences*, 47, 361-388.

Bean, H., Sutton, J., Liu, B. F., Madden, S., Wood, M. M., & Mileti, D. S. (2015), "The study of mobile public warning messages: A research review and agenda", *Review of Communication*, 15(1), 60-80.

Bliss, J. P., Gilson, R. D., & Deaton, J. E. (1995), "Human probability matching behaviour in response to alarms of varying reliability", *Ergonomics*, 38(11), 2300-2312.

Bostrom, A., McBride, S. K., Becker, J. S., Goltz, J. D., de Groot, R. M., Peek, L., & Dixon, M. (2022), "Great expectations for earthquake early warnings on the United States West Coast", *International Journal of Disaster Risk Reduction*, 82, 103296.

Botterell, A. (2006, May). "The common alerting protocol: an open standard for alerting, warning and notification", In Proceedings of the 3rd International ISCRAM Conference (pp. 497-503). Newark, NJ (USA), available at http://idl.iscram.org/files/botterell/2006/339_Botterell2006.pdf (accessed 5 December 2025)

Brudzinski, M. R., Sumy, D. F., Jordan, P., Rea, S., Gomez, K., Robles, M., ... & Olds, S. (2025), "Multi-Hazard Improves App Retention: Comparison of Alerting and Attrition for the

Multi-Hazards SD Emergency and the Single-Hazard QuakeAlert", *International Journal of Disaster Risk Reduction*, 130, 105832.

Brudzinski, M. R., Sumy, D., Gomez, K., Briceno, Y., Jordan, P., Robles, M., Rea, S. (2025), "Preliminary Multilingual Survey Results on Earthquake Early Warning and San Diego County's SD Emergency Multi-Hazards App to Improve Equity in Disaster Risk Reduction", Abstract presented at SSA, Baltimore, MD, 14–18 April, available at https://doi.org/10.1785/0220250104 (accessed 5 December 2025).

Cauzzi, C., Behr, Y., Le Guenan, T., Douglas, J., Auclair, S., Woessner, J., ... & Fäh, D. (2016), "Earthquake early warning and operational earthquake forecasting as real-time hazard information to mitigate seismic risk at nuclear facilities", *Bulletin of Earthquake Engineering*, 14(9), 2495-2512.

Chang, S. E., McDaniels, T., Fox, J., Dhariwal, R., & Longstaff, H. (2006), "Toward disaster-resilient cities: Characterizing resilience of infrastructure systems with expert judgments", *Risk Analysis*, 26(3), 523-540.

Cremen, G., Galasso, C., & Zuccolo, E. (2022), "Investigating the potential effectiveness of earthquake early warning across Europe", *Nature Communications*, 13(1), 639.

Cuéllar, A., Suárez, G., & Espinosa-Aranda, J. M. (2017), "Performance evaluation of the earthquake detection and classification algorithm 2(tS–tP) of the Seismic Alert System of Mexico (SASMEX)", *Bulletin of the Seismological Society of America*, 107(3), 1451-1463.

Cvach, M. (2012, "Monitor alarm fatigue: An integrative review", *Biomedical Instrumentation & Technology*, 46(4), 268-277.

Eisenman, D. P., Glik, D., Gonzalez, L., Maranon, R., Zhou, Q., Tseng, C. H., & Asch, S. M. (2007), "Improving Latino disaster preparedness using social networks", *American Journal of Preventive Medicine*, 33(5), 392-397.

FEMA. (2024). "Integrated Public Alert & Warning System. Federal Emergency Management Agency", available at: https://www.fema.gov/emergency-managers/practitioners/integrated-public-alert-warning-system (accessed 1 December 2025)

Fujinawa, Y., & Noda, Y. (2013), "Japan's earthquake early warning system on 11 March 2011: Performance, shortcomings, and changes", *Earthquake Spectra*, 29(S1), S341-S368.

Given, D. D., Allen, R. M., Baltay, A. S., Bodin, P., Cochran, E. S., Creager, K., ... & Vernon, F. (2018), "Implementation plan for the ShakeAlert system—An earthquake early warning system for the West Coast of the United States", *U.S. Geological Survey Open-File Report 2018-1155*.

Goldfinger, C., Nelson, C. H., Morey, A. E., Johnson, J. E., Patton, J. R., Karabanov, E., ... & Vallier, T. (2012), "Turbidite event history—Methods and implications for Holocene paleoseismicity of the Cascadia subduction zone”, *U.S. Geological Survey Professional Paper 1661-F*.

Hu, X., Zhang, X., & Wei, J. (2019), “Public attention to natural hazard warnings on social media in China”, *Weather, Climate, and Society*, 11(1), 183-197.

King County Office of Emergency Management (OEM). (2019). "King County Emergency Management Annual Report 2019." Available at https://cdn.kingcounty.gov/-/media/king-county/depts/executive-services/emergency-management/documents/oem-annual-report-2019.pdf

King County Office of Emergency Management (OEM). (2023). "King County Emergency Management Annual Report 2023." Available at https://cdn.kingcounty.gov/-/media/king-county/depts/executive-services/emergency-management/documents/oem-annual-report-2023.pdf

Kohler, M. D., Smith, D. E., Andrews, J., Chung, A. I., Hartog, R., Henson, I., ... & Cochran, E. S. (2020), “Earthquake early warning ShakeAlert 2.0: Public rollout,” *Seismological Research Letters*, 91(3), 1763-1775.

Kolen, B., & Helsloot, I. (2014), “Decision-making and evacuation planning for flood risk management in the Netherlands”, *Disasters*, 38(3), 610-635.

Leiva, M. (2014), “Leveraging emergency notification alerts”, *Homeland Security Affairs*, 10.

Lindell, M. K., & Perry, R. W. (2012), “The protective action decision model: Theoretical modifications and additional evidence”, *Risk Analysis*, 32(4), 616-632.

Lux, A. I., Smith, D., Böse, M., McGuire, J. J., Saunders, J. K., Huynh, M., ... & Toomey, D. (2024), “Status and performance of the ShakeAlert earthquake early warning system: 2019–2023”, *Bulletin of the Seismological Society of America*, 114(6), 3041-3062.

Minson, S. E., Meier, M. A., Baltay, A. S., Hanks, T. C., & Cochran, E. S. (2018), “The limits of earthquake early warning: Timeliness of ground motion estimates”, *Science Advances*, 4(3), eaaq0504.

Morss, R. E., Mulder, K. J., Lazo, J. K., & Demuth, J. L. (2016), “How do people perceive, understand, and anticipate responding to flash flood risks and warnings? Results from a public survey in Boulder, Colorado, USA”, *Journal of Hydrology*, 541, 649-664.

National Academies of Sciences, Engineering, and Medicine, (2018), *Emergency Alert and Warning Systems: Current Knowledge and Future Research Directions*, NASEM, Washington, DC, available at: https://www.nationalacademies.org/projects/DEPS-CSTB-15-02

NYC Emergency Management. (2021). Notify NYC: A decade of emergency public warning. New York: NYC Emergency Management.

PrepareCenter. (2024), “Early warning systems. International Federation of Red Cross and Red Crescent Societies”, available at https://preparecenter.org/topic/early-warning-systems/

Ralph, F. M., Rutz, J. J., Cordeira, J. M., Dettinger, M., Anderson, M., Reynolds, D., ... & Smallcomb, C. (2019), “A scale to characterize the strength and impacts of atmospheric rivers”, *Bulletin of the American Meteorological Society*, 100(2), 269-289.

Sadiq, A. A., Dougherty, R. B., Tyler, J., & Entress, R. (2023), “Public alert and warning system literature review in the USA: identifying research gaps and lessons for practice”, *Natural Hazards*, 117, 1711-1744.

Schmidt, A., Leavell, D., Punches, J., Rocha Ibarra, M. A., Kagan, J. S., Creutzburg, M., ... & Berger, C. (2022), “A quantitative wildfire risk assessment using a modular approach of geostatistical clustering and regionally distinct valuations of assets—A case study in Oregon”, *Plos One*, 17(3), e0264826.

Short, K. C., Finney, M. A., Scott, J. H., Gilbertson-Day, J. W., & Grenfell, I. C. (2016), “Spatial dataset of probabilistic wildfire risk components for the conterminous United States. 1st Edition. Fort Collins, CO 2016: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2016-0034.

Sorensen, J. H. (2000), “Hazard warning systems: Review of 20 years of progress”, *Natural Hazards Review*, 1(2), 119-125.

Strauss, J. A., & Allen, R. M. (2016), “Benefits and costs of earthquake early warning”, *Seismological Research Letters*, 87(3), 765-772.

Sutton, J., & Wood, M. M. (2022), "Emergency alerts and warnings." McGee, T. K., Penning-Rowsell, E. C. (Ed.) *Routledge Handbook of Environmental Hazards and Society*, Routledge, London, United Kingdom, pp. 319-333.

Sutton, J., & Wood, M. M. (2025), “Opting Out: Over‐Alerting and Warning Fatigue in the Era of Wireless Emergency Alerts”, *Journal of Contingencies and Crisis Management*, 33(3), e70076.

Trainor, J. E., Nagele, D., Philips, B., & Scott, B. (2015), “Tornadoes, social science, and the false alarm effect”, *Weather, Climate, and Society*, 7(4), 333-352.

Trouet, V., Taylor, A. H., Carleton, A. M., & Skinner, C. N. (2009), “Interannual variations in fire weather, fire extent, and synoptic-scale circulation patterns in northern California and Oregon”, *Theoretical and Applied Climatology*, 95, 349-360.

United Nations Office for Disaster Risk Reduction (UNDRR). (2015), *Sendai Framework for Disaster Risk Reduction 2015-2030, United Nations Office for Disaster Risk Reduction*, UNDRR, Geneva, Switzerland, available at: https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030. (accessed 1 December 2025)

United Nations Office for Disaster Risk Reduction (UNDRR). (2017), *Terminology: Early warning system. United Nations Office for Disaster Risk Reduction*, UNDRR, Geneva, Switzerland, available at: https://www.undrr.org/terminology/early-warning-system. (accessed 1 December 2025)

United Nations Office for Disaster Risk Reduction (UNDRR). (2023), *Global status of multi-hazard early warning systems: Target G. United Nations Office for Disaster Risk Reduction*, UNDRR, Geneva, Switzerland, available at: https://www.undrr.org/reports/global-status-mhews-2023. (accessed 1 December 2025)

United Nations Office for Disaster Risk Reduction (UNDRR). (2017), *Technical guidance for monitoring and reporting on progress in achieving the global targets of the Sendai Framework for Disaster Risk Reduction*, UNDRR, Geneva, Switzerland, available at: https://www.undrr.org/quick/11641. (accessed 1 December 2025)

Wing, M. G., & Long, J. (2015), "A 25-year history of spatial and temporal trends in wildfire activity in Oregon and Washington, USA", *Modern Applied Science*, 9(3), 117-132.

Wogalter, M.S., Mayhorn, C.B. and Laughery, K.R., Sr. (2021), "Warnings and Hazard Communications."  Salvendy, G., and Karwowski, W. (Ed.) *Handbook of Human Factors and Ergonomics*. Wiley Online Books, pp. 644-667.

Wood, M. M., Mileti, D. S., Bean, H., Liu, B. F., Sutton, J., & Madden, S. (2018), "Milling and public warnings", *Environment and Behavior*, 50(5), 535-566.