ANALYZING THE NECESSARY CONFIGURATIONS OF A LONG-TERM EARTHQUAKE EARLY WARNING SYSTEM

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By

Keerat Singh

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

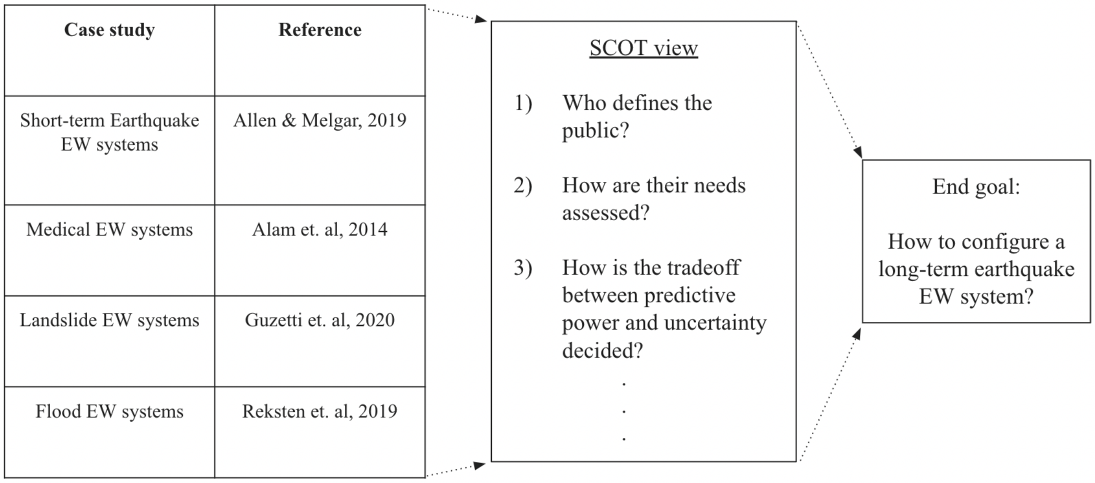
ADVISOR
Catherine D. Baritaud, Department of Engineering and Society

Predicting earthquakes is a significantly challenging problem with a long history of largely unsuccessful attempts. As defined by the United States Geological Survey (USGS), an acceptable earthquake prediction must include its date and time, location, and magnitude (*What is*, n.d.). In addition, earthquake predictions deal with larger-scale time windows on the order of months and years. There has never been an accurate prediction of any major earthquake (*Can*, n.d.). The technical research is focused on predicting earthquakes by feeding large historical datasets of events into machine learning models.

The ability to predict will eventually lead to the deployment of earthquake early warning (EEW) systems in certain regions. Earthquake forecasting models, predicting the characteristics of an earthquake hours in advance, usually upon receiving preceding ground motion, have become more successful over the last few decades . As a result, there are many short-term EEWs, built on these forecasting models, dispersed in high-impact regions of the world. While potentially a powerful tool in any field, early warning (EW) systems must be carefully configured due to the uncertainty in any prediction. Especially if longer-range prediction from the technical project proves to be successful, EEWs built on prediction models need to be standardized before implemented. As the overall power of EEWs will increase, the chance for mispredictions increases with it. The STS research is comparing and contrasting EW systems from many different fields to see how such tradeoffs in predictive power and uncertainty are generally made. The analysis will be guided by the Social Construction Theory of Technology (Pinch & Bijker, 1984). This is tightly coupled with the technical research, as this knowledge ultimately assists in imagining how a larger-window EEW would be best configured and deployed.

QUESTION: COMPARING AND CONTRASTING DIFFERENT DOMAINS OF EARLY WARNING SYSTEMS

The STS research is comparing and contrasting EW systems from other application domains in order to suggest necessary technological and policy configurations for such a novel EEW system. Papers were found for geographical landslide EW systems, patient monitoring EW systems in hospitals, flood detection EW systems, and current short-term EEW systems. Each case study will be analyzed with the SCOT framework. Therefore, relevant questions, such as those presented in Figure 1, will be addressed within each case study.



Case study	Reference
Short-term Earthquake EW systems	Allen & Melgar, 2019
Medical EW systems	Alam et. al, 2014
Landslide EW systems	Guzetti et. al, 2020
Flood EW systems	Reksten et. al, 2019

Figure 1: Outline of the STS study. Organizes the case studies and how SCOT will be applied to each. (Singh, 2022).

EARLY WARNING EARTHQUAKE SYSTEMS

This study aims to compare and contrast the implementations and efficacies of various EEW systems around the globe (Allen & Melgar, 2019). With a heavy focus on regions within Japan and Mexico, this paper was published after major, catastrophic events in both places in 2011 and 2018, respectively. Earthquake early warning systems were directly involved in the outcome of both of those events, so this paper also serves the purpose of analyzing their performance after-the-fact. Their findings are largely aimed to aid EEW system developers, administrators, and policy makers in their decisions in setting the procedure for alerting the public early to earthquakes.

According to Allen and Melgar, most systems around the world use point-source algorithms, which essentially combine P-wave readings from multiple sources to forecast earthquakes and their characteristics like magnitude, time, location (p. 367). P-waves and S-waves both travel from the earthquake fault in the Earth to eventually trigger the surface waves that cause damage. P-waves travel faster than S-waves. If the forecasted event is above a certain magnitude threshold, then an alert will be released. The authors find no common standard in terms of how low or high to set this magnitude threshold (Allen & Melgar, 2019, p. 369). Based on referenced studies, it appears that locals prefer to be alerted more often than not (Allen & Melgar, 2019, p. 364). That is, they prefer false negatives over false positives. Although, the authors admit these are very preliminary studies. As for the question of who to alert, the authors point out that generally they find authorities directly contacting those who appear in the algorithm’s predicted significant impact zone (Allen & Melgar, 2019, p. 363). This has had its downsides, as in the example of the 2011 Tohoku-Oki magnitude 9.1 earthquake in Japan, when the predicted area of impact was much less than the actual and EEW alerts were subsequently underdistributed. This resulted in around 20,000 deaths. How these alerts are distributed also ranges. Mexico City has a network of about 12,000 sirens spread out through the city that ring when an alert is issued (Allen & Melgar, 2019, p. 369). Japan uses the radio and television. Although, many places, including San Francisco, have started notifying cell phones using apps such as MyShake (Allen & Melgar, 2019, p. 371). The authors expect this to become the standard way to alert the public. One of the advantages of this beyond scalability is that infrastructure such as trains, planes, and elevators can all be automatically triggered to pause operations once alerted until the shaking has passed.

EARLY WARNING LANDLSIDE PREDICTION SYSTEMS

Guzetti, Gariano, and the other authors of this paper provided a comprehensive review of 26 landslide early warning (LEW) systemsaround the globe in 2020 (Guzetti et al., 2020). The impact of landslides is vastly underestimated, resulting in several thousand deaths per year annually (Perkins, 2012). They primarily impact areas with high rates of precipitation. These scientists all work at the Institute for Geo-Hydrological Hazards Assessment in Perugia, Italy (Research Gate, 2023). Italy has many operating LEW systems in different regions, many of which the authors mention explicitly as case studies. Their work was published in *Earth-Science Reviews*, a monthly peer-reviewed journal focused on Earth Science. Their review serves to both provide a common point of reference for the global state of LEW systems and raise specific calls for action that the community should take. By outlining current practices, they are able to suggest best practices that can make LEW systems more reliable and effective.

Landslides are mass-movements of land, generally caused by high levels of precipitation (Guzetti et al., 2020). They can often be deadly and damaging to surrounding communities. As a result, LEW systems have been implemented in many communities with the hopes of mitigating landslide-induced death and damage with early preparation. Most early warning systems share a similar set of problems in the inherent difficulties of translating uncertain model predictions into administrative actions that cost resources and affect the livelihoods of the public. Because of the influence of local specifities on model configurations, administrative reactions, and advisory plans, the authors find that most regions end up developing their own local standards. By comparing and contrasting the standards of different regions, the authors are able to put each region's LEW systems into perspective, and ultimately advise certain actions that the whole LEW community should pursue.

The authors found that all 26 LEW systems followed the same general flow of a model producing a warning, internal experts interpreting that warning, administrators creating an advisory based on the input of the internal experts, and finally the public receiving and acting on the advisory (Guzetti et al., 2020). There are challenging questions that must be tackled at each level. At the level of the model, the authors found that, among the 26 LEW systems, many were not validating the performance of their model. This was less an outcome due lack of effort, and more because there was not enough performance data to properly validate. The authors claim that regions need to "collect more accurate information on the time of occurrence of the landslides" (Guzetti et al., 2020, p. 20). This would also help in validating the threshold value for a model's confidence in its prediction, as there is currently "little or no information available on the methods and techniques used to determine the thresholds used in the LEW systems" (Guzetti et al., 2020, p. 21). In Indonesia, the rainfall thresholds were determined by studying past rainfall events with landslides and considering the cumulated rainfall on the day of the landslide and on preceding days (Guzetti et al., 2020, p. 11). The authors claim that more accurate historical data of landslides would help standardize an effective method for determining thresholds.

Given an exceeded threshold, administrators have to decide which areas to alert. Beyond the model's spatial predictions, administrators have to take into account which areas are more or less susceptible to fatalities and damage if hit. There isn't a standard approach for determining this. In addition, they have to translate the probabilistic warning to an advisory level relayed to the public. Inherently, methods for relaying messages define the public. Therefore, the authors found that many of the LEW systems' approach of posting to a website leaves the technologically-deprived in the dark. These are all common problems around how best to transfer messages to the public with no standard, effective approach. Poor practices in Taiwan led to people losing trust in the system, and thus the system becoming useless (Guzetti et al., 2020, p. 11). Best practices to prevent such situations from repeating are necessary.

EARLY WARNING SYSTEMS FOR HOSPITAL PATIENTS

Alam, Hobbelink, and the other authors analyzed the effects of EW systems in patient-outcomes in a hospital setting. They analyzed seven studies performed in different hospitals that compare outcomes before and after the introduction of EW systems (Alam et al., 2014, p. 588).

Specifically, these systems are called Early Warning Scores (EWS). They take in physiological input from a patient and provide a score of how susceptible they are to a serious adverse event (SAE), such as a cardiac arrest, within the next few hours (Alam et al., 2014, p. 588). With this information, nurses can more effectively deliver aid to improve patient outcomes while not wasting hospital resources. This study aimed to assess the effectiveness of EWS on patient-oucomes such as number of SAEs, mortality rates, and length of stay.

The authors had trouble drawing statistically significant results across studies partly because of the lack of standardization and documentation of these EWS systems. Each hospital had their own EWS implementation despite a standard approach being available (Alam et al., 2014, p. 593). Implementations included different threshold values for when to take action on a patient (Alam et al., 2014, p. 591-592). Although, they were somewhat close in value. The authors emphasized a need for greater standardization of EWS (Alam et al., 2014, p. 593). This also included better documentation of what vitals are being inputted to the EWS. A shared use of one standard, well-documented EWS would presumably allow for faster, more wide-ranging iterative progress. The authors also mention the effectiveness of intensive staff education programs (Alam et al., 2014, p. 594). Two studies found that mortality rates significantly reduced after hospital staff completed an educational program on the EWS (Alam et al., 2014, p. 589).

EARLY WARNING FLOOD DETECTION SYSTEMS

Floods are frequent in the jagged, fjordian landscape of Norway (Reksten et al., 2019, p. 349). In order to both detect and monitor ongoing floods, satellite images are commonly used because they can capture the whole of a landscape in single pictures. The analysis of these pictures needs to be automated, as actionable information cannot be gathered in time otherwise. The authors of this paper present a method to automatically detect flooding by using machine learning to compare real-time images to reference flood images.

They explicitly point out the challenge in maintaining predictive power while reducing the number of false positives (Reksten et al., 2019, p. 350). This is a common theme of detection systems. In their case, areas with wet snow or agricultural areas commonly tricked their model into generating a false positive. They accounted for this by essentially extracting more flood-specific features from the images. Then, they handled the challenge of finding the cut-off value of a flood by setting it to the cut-off value that maximized the F2 score (Reksten et al., 2019, p. 354). The F2 score acts a weighted average of precision and recall. They found that this was a generally successful technique for picking the threshold value.

ANSWER: EFFECTIVELY CREATING AND DEPLOYING A LONG-TERM EARTHQUAKE EARLY WARNING SYSTEM

Upon performing their analysis, Allen and Melgar seem to land on a Social Construction Theory of Technology (SCOT) view on EEW systems. The SCOT view will be used to analyze the common features of each of EW systems, as shown in Figure 2.

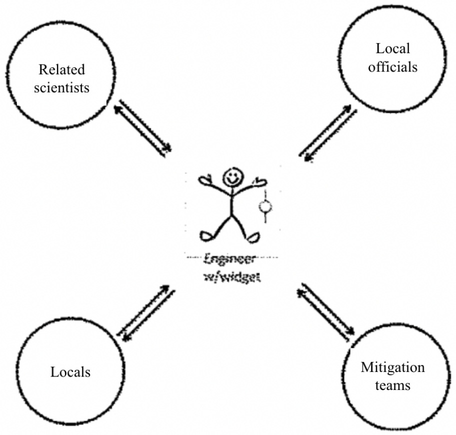


Figure 2. Mapping of SCOT to problem space. Visualizes the relevant social groups that affect the engineers of early warning systems. (Singh, 2022).

They generally find that studies on the public's preferences are used to assist the configuration of the EEW system, an otherwise tricky task. Although, the definition of who is in the public is determined by the EEW system, so there is a potential point of failure. The authors who studied LEW systems suggested that susceptibility models are a better method. Their idea is that given an exceeded threshold from the prediction model, the susceptibility model would separately describe which areas are most at risk, and thus who to alert. Over time, data from the susceptibility model could help us define the public.

As for the public's tolerance of false positives, Allen and Melgar found from a poll in Mexico City that they would generally prefer to be alerted more often even if an event doesn't happen, although I suspect this could be due to the fact that the sample size of significant earthquakes is quite small (p. 364). If the public has not experienced too many events, their opinion or lack thereof is, by definition, immature. Therefore, even in the case of the public preferring to be alerted more liberally, I am not sure whether this would remain if the public had experienced more false negatives, false positives, and successful events. This becomes even more challenging in the case of a long-term EEW system, in which the confidence level for an alert naturally reduces as the prediction window increases. The authors of the LEW study stated that in places like Colombia, they combat false positives and negatives by incorporating a cost of distributing a false alert into the warning system. So before a prediction is made, there is also an associated cost/reward of alerting that the model must weigh (Guzetti et al., 2020, p. 8).

In addition, Allen and Melgar stressed the importance for standardizing EEW systems (p. 378). This was a view also shared by the authors who studied EWS in hospitals. Guzzetti and the authors who studied LEW systems add that not only should the usage of the system be standard, but the evaluation of systems should be standardized (p. 14). Standardization within any early warning system helps in that different communities can most effectively compare and contrast the configuration and performance of their system to others, allowing all parties the chance to improve.

In discussion of future work within short-term earthquake prediction, Allen and Melgar mention the potential in using machine learning algorithms as supplements to current algorithms (p. 382). This is a viewpoint also shared by Guzetti and the authors who studied LEW systems (p. 314). They state that multiple sources of data for prediction should be used to reduce the inherent uncertainty in each one.

In addition, Guzetti and the other authors stated that multiple Italian landslide event models take multiple prediction windows into account, weighting each differently (p. 10). This suggests how best to use a long-term prediction system as created in the technical project. An EEW system would benefit from using the long-term model in conjunction with models based on shorter-term prediction windows, weighting each according to some optimization procedure. The authors suggest that the procedures for determining advisory levels from a prediction be revised about as often as warnings are issued (Guzetti et al., 2020, p. 21). This also directly applies to a proper EEW system, as advisory levels should speak to the severity of the predicted event in a way that is organized and understandable to the public. The authors suggest that advisories issued to the public should concisely contain a trusted source, the type of event, the reason for belief in a threat, and actionable advice (Guzetti et al., 2020, p. 20).

All authors from these case studies stress the importance of a thorough data collection process. Guzzeti and his co-authors mention that for validifying a threshold value, the more examples of events and predictions there are, the more confident one can be. For example, to establish a threshold value for an LEW model in Indonesia, they looked at past landslide events and adjusted the threshold value to best meet all events (p. 20). In addition, they, along with the authors who studied EWS in hospitals, mentioned that the more qualities of data the better for establishing confidence.

Multiple methods were proposed for how to broadcast alerts to the public. In the study of EW systems, they found that places in Mexico City and Japan use large alarms scattered around to signal that an event is eminent (Allen & Melgar, 2019, p. 364). In the case of LEW systems, the authors found that places such as Piedmont and Tuscany, Italy use the Internet to alert the public (Guzetti et al., 2020, p. 9). I believe that both physical and digital alerts have their advantages and disadvantages, and there is no harm in using both.

THE EFFICACY IN DEPLOYING A LONG-TERM EARTHQUAKE EARLY WARNING SYSTEM

Based on the findings of each of the case studies, we can hypothesize that an effective long-term EEW system would need to equitably describe the public, either by using the model itself, a separate susceptibility model, or another holistic approach. The public’s preferences would need to be gauged on topics such as false positive tolerance level and methods for alerting. Alerts should concisely contain a trusted source, the type of event, the reason for belief in a threat, and actionable advice. They should be delivered through multiple mediums such as warning speakers, phone alerts, and website alerts. Engineers, project administrators, and local government officials should all be knowledgeable on how the long-term EEW system works. This can be implemented through a general staff educational program. The implementation of long-term EEW systems should be standardized from the start in terms of thorough datasets, the exact model, and model and threshold validation procedures. They would best support the overall goal of reducing earthquake-induced damage by assisting rather than replacing current short-term models.

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