International Journal of Environment and Geoinformatics
2025, 12 (1): 61–71

https://doi.org/10.26650/ijegeo.1639063
Submitted: 01.02.2025
Revision Requested: 27.02.2025
Last Revision Received: 03.03.2025
Accepted: 05.03.2025

International Journal of Environment and Geoinformatics

Research Article

Open Access

Development of Earthquake Early Warning Systems in Marmara Region: A Hybrid Model Utilizing Mosque Loudspeakers

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Abstract The anticipated major earthquake in the Sea of Marmara presents significant risks due to the dense population and important infrastructure systems living in the region. Earthquake Early Warning (EEW) Systems can play an important role in reducing these risks. In this study, in addition to the existing EEW systems serving the infrastructure, a hybrid early warning model integrated with mosque loudspeakers that have the potential to warn residents is proposed. The system is based on the principle of announcing from mosque loudspeakers within the district borders through the mufti offices by evaluating the seismic data provided by the AFAD infrastructure. Simulations indicate that the proposed system is particularly effective in residential areas beyond 45 km and that a gain of 4.9 to 42.8 seconds can be achieved in warning time. However, it was observed that warnings given to people in areas closer than 45 km would be ineffective due to the rapid arrival of P waves. The novelty of this study is that it increases the effectiveness of early warning in areas where access to traditional infrastructure is limited by integrating the widely used and extensively used mosque loudspeakers into the EEW system. Thus, the model used has the potential to reduce deaths, thanks to the wide geographical spread of mosques. The success of the system is directly affected by factors such as power outages, public awareness, and communication infrastructure. Therefore, the effectiveness of the system can be increased if it is supported by hybrid models that include mobile apps, SMS, and TV broadcasts. In addition, the reliability and applicability of the system should be tested in a selected pilot area. In conclusion, a hybrid EEW system, where the main instrument of the announcement channel is the mosque loudspeakers, offers a powerful alternative to provide early warning to the people of the region surrounding the Marmara Sea.

Keywords EEW · Marmara Earthquake · Hybrid EEW · Mosque Speaker System · Seismic Warning

Citation: Eren, M. (2025). Development of earthquake early warning systems in marmara region: A hybrid model utilizing mosque loudspeakers. *International Journal of Environment and Geoinformatics*, *12*(1), 61-71. https://doi.org/10.26650/ijegeo.1639063

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Introduction

It is not possible to predict with any certainty the timing and location of seismic activity. Nevertheless, earthquake early warning (EEW) systems constitute a significant instrument in the reduction of seismic risk and the mitigation of loss of life. These systems are designed to detect and analyze the initial waves of an earthquake (typically P waves) and subsequently issue warnings prior to the arrival of the more intense S waves, which pose a greater threat to life and infrastructure (Dallo et al., 2022; Jenkins et al., 2022). The basic working principle of EEWs is to estimate the arrival time of seismic waves to regions where the earthquake has not yet reached, using the propagation speed of the seismic waves, and to send the necessary warning (Allen and Melgar, 2019). For example, the UrEDAS EEW system, which has been in service in Japan since 1988, operates based on this principle (Tajima and Hayashida, 2018; Kodera et al., 2016).

EEW systems have two different architectures in terms of the instruments used: in situ (local) and network (regional). In situ EEWS analyzes the P wave (first wave) of an earthquake with the help of data from a single seismogram. Since it provides warning with the help of a single station, it provides shorter warning time and is especially advantageous to be used in areas close to the epicenter (Hsu et al., 2016; Rudyanto, 2023). The in-situ system developed by the National Center for Earthquake Engineering Research (NCREE) in Taiwan can estimate the intensity of an earthquake using the first 3 seconds of the P wave (Rudyanto, 2023). On the other hand, the network-based system sends warnings over wider areas by using data from multiple seismic stations. However, the effectiveness of this system may be limited in areas with low seismic hazard (Picozzi et al., 2015). Each system has its own advantages and disadvantages. In-situ systems provide time savings for important infrastructures and critical facilities due to their ability to detect P-waves and respond quickly (warning time between 3 and 10 seconds). Thus, these systems can provide an advantage to take precautions to reduce the damage caused by earthquakes (Minson et al., 2018; Minson et al., 2019). However, it should be kept in mind that there may be false or missed alarms (Bali, 2023). Network-based EEW systems have been shown to increase accuracy in determining earthquake parameters by using data from multiple seismographs. These systems determine parameters such as epicenter, magnitude, earthquake onset time, etc. with the help of P waves detected by three or more stations (Tajima and Hayashida, 2018). This approach employs a greater number of stations in the network to provide more accurate warnings to a broader audience and to enhance the precision of the estimated earthquake parameters (Cremen et al., 2022). For instance, networked systems of dense seismograph stations utilized in Japan can expeditiously assess the magnitude and impact of an earthquake (Fujinawa and Noda, 2013). However, a significant disadvantage of these systems is that they cause delays in the warning period, which can vary from 10 to 30 seconds after the earthquake occurs (Minson et al., 2015; Hsu et al., 2018). A hybrid approach, where both approaches are used together, allows the creation of a more effective earthquake early warning system at both local and regional levels. The use of both systems together can increase the reliability of the system. For example, a study conducted in Almaty reported that the application of the hybrid approach positively contributed to the warning period (Stankiewicz et al., 2013). As a result, the architecture of the EEW systems used is critical in earthquake risk reduction by affecting the accuracy of the warnings it provides.

The effectiveness of EEWs is closely related to the system design and the technologies used. A study conducted by Bali 2023 showed that on-site EEW works with 80% accuracy and can provide an alarm for at least 8 seconds before the S-wave arrives. The potential of such systems to reduce earthquake damage is proportional to the length of time it provides early warning. A 10-second early warning period can reduce fatalities by 39% (Small and Melgar, 2021).

Warning channels, which are critical for informing users quickly and effectively, significantly affect the success of EEWs. Zhang et al. 2021 emphasizes the importance of EEWs in informing the public and raising awareness in China. Properly transmitting warnings increases the reliability of the system and strengthens society's preparedness against earthquake risk (Zhou et al., 2017). The most common EEW channel used is mobile phones. In Japan, this is provided through the Emergency Alert Messaging (EAM) system, which sends emergency and evacuation information to users' phones through mobile phone notifications (Takemoto et al., 2019). This system helps users to be informed quickly and take necessary precautions during an earthquake (Kong et al., 2016). In addition, EEWs also send warnings using mass media such as television and radio. For example, the Japan Meteorological Agency (JMA) reaches a wide audience with its public warnings via television and radio channels (Nakayachi et al., 2019; Tan et al., 2022; Kodera et al., 2016). In addition, infrastructure systems help increase transportation safety by sending special warnings for trains and other transportation vehicles (Noda and Iwata, 2023). Finally, it increases individual safety by allowing users to receive earthquake warnings through smartphone applications (Kong et al., 2016). Using these multiple/hybrid warning channels not only increases the effectiveness of EEWS, but also helps society to be better prepared for earthquake risk. The expected earthquake in the Marmara Sea poses a significant threat to large urban centers such as Istanbul, Bursa, Balıkesir, Tekirdağ and Kocaeli. Especially considering that Istanbul is the critical center of the Turkish economy with a population exceeding 15 million, the consequences of such an earthquake will be very severe (Chartier et al., 2021; Ersoy and Koçak, 2015). As the North Anatolian Fault (NAF) passes through this region, the potential for a catastrophic seismic event increase, especially considering the historical context of earthquakes that have caused major damage and loss of life in the past (Bohnhoff et al., 2013 ; Martínez-Garzón et al., 2021). This fault has a long history of producing significant earthquakes, the most recent being the 1999 Gölcük earthquake. Studies have shown that the expected earthquake magnitude in this region could exceed 7.0, which could cause serious structural and infrastructure damage and even large-scale deaths (Chartier et al., 2021).

In this study, there are 10581 mosques (URL 1) scattered around the region that have the potential to make announcements almost throughout the provinces bordering the Sea of Marmara. Eren (2025) suggests integrating these mosque speakers into the EEW system. The EEW system in Japan transmits warnings via radio, TV, and mobile phones. There may be obstacles to transmitting the messages sent by these systems to all the inhabitants of the region. However, the system provides a significant advantage over other systems by transmitting voice messages to all mosques through mufti's offices. In a possible Istanbul earthquake, it is predicted that transmitting the message obtained from the on-site solution, which provides a quick solution, through mosques will minimize possible losses. On the other hand, considering the negative impact of power outages on message transmission, it is anticipated that the hybrid approach, which also uses traditional warning channels, will increase its success.

Solution of Earthquake Parameters

Earthquake propagation speed is a parameter that indicates how fast seismic waves travel on the surface or through different layers underground. This speed varies depending on the characteristics of the underground structure and the type of wave. P waves (compression waves) and S waves (shear waves) are usually used to calculate earthquake propagation speed. P waves travel faster than S waves and therefore their propagation speed is usually higher.

P Wave Speed (V_P) and S Wave Speed (V_S) are calculated with the help of Eq. 1 and Eq. 2.

$$V_P = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}} \tag{1}$$

$$V_S = \sqrt{\frac{\mu}{\rho}} \tag{2}$$

Here; V_P is the speed of the P wave (m/s), V_S is the speed of the S wave (m/s), K is the bulk modulus (Pa), μ is the shear modulus (Pa) and ρ is the density (kg/m³). Earthquake propagation speeds vary depending on the ground type, and the ratio of speeds (V_P/V_S) is between ≈1.73 for dense and hard rocks and ≈1.6–1.8 for normal rocks (Demirsikan et al., 2019).

Earthquake Magnitude Calculation

EEW systems play a critical role in minimizing the effects of earthquakes. For the effectiveness of these systems, some parameters need to be determined and analyzed. These parameters are explained below:

In the field of seismology and geophysics, various mathematical models have been developed to estimate earthquake magnitude. The Richter scale, a system first developed by Charles F. Richter and later widely adopted to determine the magnitude of an earthquake, is the most widely used scale in this field.

$$M_L = \log_{10}^{A} - \log_{10}^{\Delta} \tag{3}$$

where ML is the Richter magnitude, A is the maximum amplitude recorded by the seismograph, and Δ is the epicentral distance.

The Duration-Dependent Magnitude (Md) is a measure of the time over which a seismic vibration is recorded by a seismometer. This magnitude is scaled by distance from the epicenter. Md is a commonly used magnitude for small and medium-sized earthquakes, is more accurate in areas with dense seismic networks, and can be calculated using the empirical equation in the network:

$$M_d = a \log_{10}^{T} + b \tag{4}$$

Here T represents the earthquake duration (the time in seconds from the beginning of the P wave until the seismic signal falls below a certain threshold value), a and b are empirical coefficients depending on the region and the seismic network.

The moment magnitude scale (Mw) is another scale developed by Hiroo Kanamori in 1979. It provides more accurate results for large earthquakes. The moment magnitude is less affected by other scales, such as the Richter scale (Foesel, 2025; Gasperini, 2024). This scale was created to solve the problems experienced by amplitude-based scales (such as the Richter scale) in scaling large earthquakes (el-aal et al., 2020). The moment magnitude scale is the common method used to measure the magnitude of large earthquakes around the world. The formula used to calculate it is:

$$M_W = \frac{2}{3}\left(\log \frac{M_0}{N \cdot n} - 10.7\right) \quad (5)$$

Where M_0 represents the moment, which is calculated from data obtained by recording seismic waves.

Earthquake Magnitude Estimation Parameters

On the other hand, the magnitude of the earthquake is estimated with the dominant period (P_d), which represents the frequency range in which seismic waves carry the most energy. This method, developed by Nakamura (1988), determines the dominant period by analyzing the vertical component of seismic data and estimates the magnitude of the earthquake (Şahin et al., 2018). This parameter is the largest displacement value of the first few seconds of the seismic waves. It is very important in estimating the earthquake magnitude. Studies show that Pd has a strong relationship with the earthquake magnitude (Colombelli et al., 2012; Zollo et al., 2010). The relationship between the dominant period and the earthquake magnitude is generally calculated by the following mathematical expression:

$$P_d = \max(|u|) \quad (6)$$

Here max (|u|) represents the maximum displacement during the first few seconds of the P wave.

The dominant period (τc) represents the characteristic period of the first few seconds of the seismic waves of the earthquake. This parameter is used to determine the frequency content of the shaking. Studies show that using τc provides more reliable estimates for high magnitude earthquakes (Wang et al., 2020). In addition, using $\boldsymbol{\tau_c}$ and $\mathbf{P_d}$ together shows that better results are obtained in estimating the earthquake magnitude (Huang et al., 2015; Colombelli et al., 2012). τc is calculated by Eq.7.

$$\tau_c = \frac{1}{2\pi}\sqrt{\frac{\int u^2 \mathrm{d}t}{\int u^2 \omega^2 \mathrm{d}t}} \quad (7)$$

where, u(t) is the acceleration or speed of ground motion, ω is the Angular frequency (ω=2πf), $\int u^2 \mathrm{d}t$ is the energy of the P wave in a certain time interval, and $\int u^2\omega^2 \mathrm{d}t$ is the frequency-weighted energy.

Ground Motion and Damage Estimation Parameters

On the other hand, ground motion assessment and damage prediction are very important in earthquake engineering and seismology. In this context, peak ground acceleration (PGA) and peak ground velocity (PGV) are parameters used to characterize ground motion during earthquakes and to estimate damage to structures.

Peak Ground Acceleration (PGA) is the maximum acceleration that occurs on the ground surface during an earthquake and is used to evaluate the performance of structures under earthquake loads. Movements with high PGA values create more stress on structures, which increases the risk of potential damage (Işık et al. 2020). Güler and Canbaz (2020) stated that PGA is an important parameter that helps in the preparation of earthquake risk maps. In addition, local ground conditions and seismicity should be considered when calculating PGA (Akyıldız et al., 2021)

$$PGA = \max\left(\frac{\mathrm{d}^2 u}{\mathrm{d}t^2}\right) \quad (8)$$

Here, u represents the displacement in m and t represents the time (s).

Peak Ground Velocity (PGV) is the maximum velocity recorded in the ground. It provides more reliable results than PGA because it captures the deformation demands of the inelastic behavior of structures (Kale, 2018). Uysal and Yıldız (2018) reported that PGV is an important parameter for estimating the damage that structures may experience during an earthquake. It was also emphasized that PGV is a critical parameter in understanding the dynamic characteristics of ground motion (Livaoğlu and Sertçelik, 2021).

$$PGV = \max\left(\frac{\mathrm{d}u}{dt}\right) \quad (9)$$

Implementation

Study Area

The Sea of Marmara, which is in the northwest of Turkey, has important tectonic features. The faults in the region consist of three main branches (North branch, Middle branch, and South branch) within the KAF Zone. It has a complex morphology consisting of slopes, basins and ridges (Gokasan et al. 2003). There are 4 basins separated by 3 ridges in this region with a length of approximately 200 km extending in the E-W direction between the Ganos Mountain system and Izmit Bay (Gazioğlu et al. 2002). This is shaped by active fault systems such as the North Anatolian Fault Zone (NAFZ). The Gölcük Earthquake, which caused great losses at the end of the last century, is located at the eastern end of the fault passing through the Sea of Marmara. It is located on the northern branch and consists of six parts from east to west, namely Gölcük-Karamürsel-Darıca, Adalar, Avcılar, Kumburgaz, Tekirdağ and Ganos segments (Demirsıkan et al., 2022). The dense population of the provinces around the Sea of Marmara constitutes approximately 30% of Turkey (Table 1). A large earthquake (MW>7) in such a densely populated region will cause both economic and life losses.

Table 1. Populations of the provinces surrounding the Sea of Marmara

Province Name	2024 Population
Balıkesir	1.276.096
Bursa	3.238.618
Çanakkale	568.966
Edirne	421.247
İstanbul	15.701.602
Kırklareli	379.031
Kocaeli	2.130.006
Tekirdağ	1.187.162
Yalova	307.882
Total	25.210.610

Table 2. Earthquakes occurring on 5 segments in the the Sea of Marmara after the 1999 Gölcük earthquake.

Date	Longitude	Latitude	Depth	Type	Magnitude
26.09.2019	28.214	40.8818	8.0	Mw	5.8
07.06.2012	27.9043	40.8628	27.0	Ml	5.1
25.07.2011	27.7498	40.8195	7.0	Ml	5.1
20.09.1999	27.4600	40.7400	20.9	Md	5.0

Figure 1. Map showing the simulated earthquake and earthquakes with a magnitude of M>5 that occurred on the Adalar, Avcılar, Kumburgaz, Tekirdağ and Ganos segments since the August 17 earthquake.

Since this region has a dense population, it was chosen as the study area, especially on the northern arm of the Sea of Marmara, which is closer to Istanbul. The attributes of the earthquakes with M>5 on the northern branch of the fault from the August 17 earthquake to the present are given in Table 2. Within the scope of the study, a fictional/simulated earthquake epicenter was selected by taking the averages of the coordinates of these 4 earthquakes (Figure 1). The selected epicenter is located on the NAFZ and west of the Marmara Trough.

EEW System's Working Principle

When an earthquake occurs, the P wave is detected by the sensor(s). Seismic data is processed by the data sent to the Data Processing Center via satellite or the internet, and if the threshold value (Cremen (2022) used a PGA of 0.05 g) is not exceeded, the system returns to its initial state. Otherwise, an alarm is initiated. Damage estimation parameters and regions likely to be damaged are identified, and alerts are sent. First, the blind zone is calculated (45 km in current practice). Mufti offices within this zone, where it is not possible to take action against warning messages, are not sent a warning message for

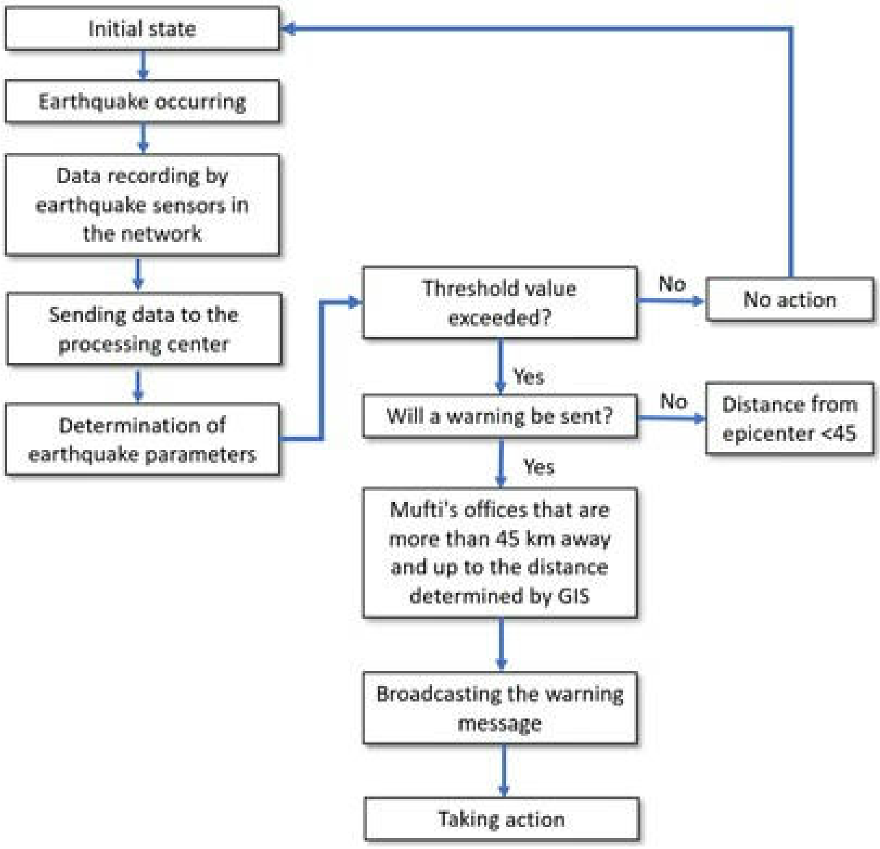

Figure 2. Workflow diagram of the EEW system

residents. More than 45 km away, warning messages are sent for both infrastructure and residents (Figure 2).

Determination of Simulated Earthquake Propagation Velocities

In recent years, research has been conducted to better understand the seismic activity in the Marmara Region, and seismograph data operated by the Turkish Disaster and Emergency Management Presidency (AFAD) are used in particular. These data are of great importance for the development of effective early warning systems, which will enable the population to be informed before the destructive seismic waves reach and have the potential to reduce casualties (Xu, 2023).

In this study, it is aimed to solve the parameters of a simulated earthquake after the arrival of the P wave to the closest stations in the AFAD seismogram network, to send a warning message to the regions where the S wave does not reach about the ongoing earthquake, and to calculate the time required to give an audible warning. In addition, it is aimed at explaining how much time the residents of the region who receive the warning message must take precautions and what precautions they can take in this time gained. After the earthquake, the P-wave capture times were calculated by the accelerometers in the AFAD earthquake station network (Table 3). In calculating the arrival times, the average speeds of the P and S waves arriving at stations up to 200 km away in the Istanbul Earthquake that occurred on September 26, 2019, were used (URL 2). The average speeds of this earthquake: V_P and V_S were calculated as 5471 m/s and 3246 m/s, respectively (from the distance between the station and the earthquake epicenter divided by the time).

Table 3. Location of the nearest seismographs to detect P waves of the simulated earthquake, their distances to the epicenter and arrival times.

Station ID	Longitude	Latitude	Distance (Km)	P wave arrival time (s)
5906	27.93164	40.97338	18.35	3.4
5908	27.54794	40.98205	28.94	5.3
5915	27.45922	40.87996	31.35	5.7
5907	27.77633	41.14180	35.24	6.4

Results

Using the calculated speeds, the arrival times of P and S waves were calculated by considering the distances from the epicenter to the city centers (Table 4). According to the first reception times of P waves at the stations in Table 3 for EEW warning times:

For on-site solution, station 5906 records the first waves 3.4 s after the earthquake. In case of earthquake parameters are calculated using 3 s time window. The system gives alarm decision and sends the message to the mufti offices in the settlements that will be affected by the earthquake according to earthquake damage maps. The time required for the mufti offices to send voice warnings to all mosques within the district borders and to react is calculated as around 12 s.

On the other hand, it takes 5.7 s for 3 stations to obtain wave data for the network solution. Similarly, it is not possible to get a reaction before 15 s, including the 3 s window and the processes in the on-site solution. As the distance from the earthquake epicenter to the stations increases (as you go further into the open sea), this period increases even more. When the periods for both solutions are considered, it is not reasonable to make a warning for a resident at a distance of approximately 45 km from the epicenter. When an earthquake occurs, before the seismic waves reach the warning system, the users in these areas are exposed to the effects of the earthquake, these areas are called “blind zones” (Figure 3). This situation is especially seen in areas close to the source of the earthquake. The warning period increases in proportion to the distance between the epicenter and the sensor. In fact, Lin, while emphasizing the difficulties of existing EEW models for the 2023 major earthquakes, stated the distance of this blind zone as 100 km. It is estimated that there is a time of approximately 9 seconds for operations such as infrastructure services and stopping trains.

When Table 4 is examined, it is not meaningful to give warnings to residents up to Silivri, which is 45 km away from the epicenter. After the earthquake, warnings can be given up to Çorlu to prevent secondary disasters caused by infrastructure services (closing water valves to prevent drowning due to floods and closing gas valves to prevent fires caused by natural gas). From Büyükçekmece onwards, there is time left for many precautions including Drop, Cover, and Hold On, escape to a safe area within the building and evacuation of single-story buildings. Many precautions can be taken for Çanakkale, Gölcük and İzmit, including evacuation of 3-5-story buildings.

Integrating mosques into the EEW system has the potential to significantly increase earthquake preparedness in the community. By leveraging the capabilities of the central system to deliver warning messages, the community can be better able to respond to seismic events. This approach strengthens existing social infrastructure and enables rapid dissemination of warnings to the general population.The success of such an EEW system depends on precise earthquake magnitude estimation.The segments of the NAF under the Sea of Marmara have accumulated significant stress. A major earthquake with a magnitude between 7.1 and 7.4 could occur (Bohnhoff et al., 2013; Martínez-Garzón et al., 2021). The imminent earthquake in the Sea of Marmara demands a proactive approach to disaster preparedness. Utilizing mosques as central communication points for earthquake early warnings, coupled with precise magnitude estimates, is essential for fortifying the resilience of the Istanbul population against impending seismic events.

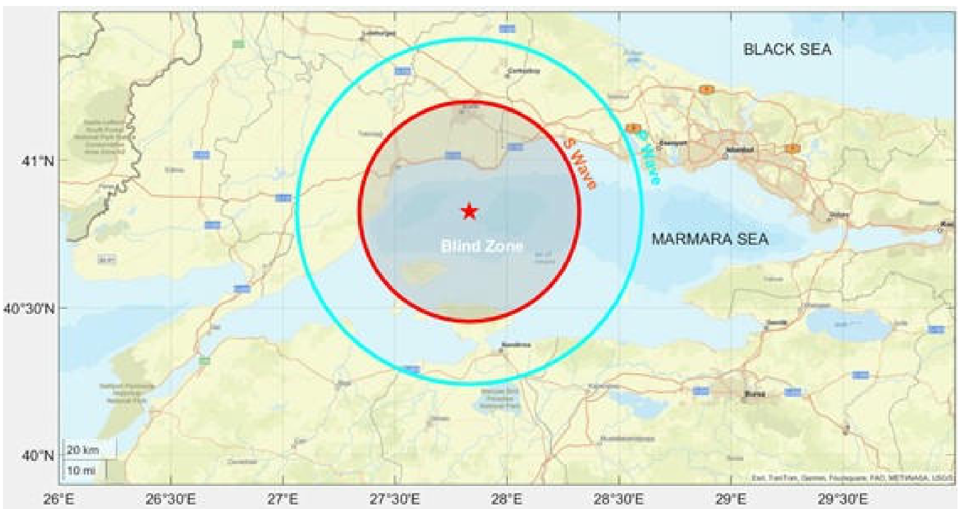

Figure 3. Map showing the propagation of earthquake waves, the area within the red circle called the Blind Zone where no warning can be given.

Table 4. Arrival times of earthquake waves to city centers, time gained for network and on-site solution

City Center Name	Distance (Km)	P Wave Arrival Time (s)	S Wave Arrival Time (s)	Gain On-site (s)	Gain Network (s)	Message status
Tekirdağ	30	5.5	9.2	−2.8	−5.8	Hayır
Çorlu	35	6.4	10.8	−1.2	−4.2	Hayır
Silivri	45	8.2	13.9	1.9	−1.1	Hayır
Bandırma	55	10.1	16.9	4.9	1.9	Evet
Büyükçekmece	63	11.5	19.4	7.4	4.4	Evet
Lüleburgaz	75	13.7	23.1	11.1	8.1	Evet
Avcılar	76	13.9	23.4	11.4	8.4	Evet
Yeşilyurt	85	15.5	26.2	14.2	11.2	Evet
Fatih	95	17.4	29.3	17.3	14.3	Evet
Mustafakemalpaşa	100	18.3	30.8	18.8	15.8	Evet
Kadıköy	102	18.6	31.4	19.4	16.4	Evet
Nilüfer	113	20.7	34.8	22.8	19.8	Evet
Kartal	113	20.7	34.8	22.8	19.8	Evet
Yalova	120	21.9	37.0	25.0	22.0	Evet
Tuzla	120	21.9	37.0	25.0	22.0	Evet
Bursa	123	22.5	37.9	25.9	22.9	Evet
Gebze	137	25.0	42.2	30.2	27.2	Evet
Edirne	140	25.6	43.1	31.1	28.1	Evet
Çanakkale	140	25.6	43.1	31.1	28.1	Evet
Gölcük	167	30.5	51.4	39.4	36.4	Evet
İzmit	178	32.5	54.8	42.8	39.8	Evet

Discussions

EEW Systems aim to send rapid warnings to potentially damaged areas that have not yet experienced an earthquake after the detection of seismic waves. However, there are some obstacles that limit the functionality of these systems. These obstacles include technical, social and cultural difficulties encountered during the transmission process of the message.

One of the main technical difficulties in the transmission of messages by EEW systems is the reliability and speed of the communication infrastructure. In particular, the detection of waves and rapid data processing are vital. However, the inadequacy of the communication infrastructure may prevent the timely transmission of messages in certain regions (Tripti and Jibukumar, 2021). In addition, during disasters, damage to communication lines may prevent the transmission of warning messages (Choo and Nadarajah, 2013).

Studies have shown that people's responses to warning messages are affected by social barriers. The content and delivery style of warning messages can affect people's sensitivity to warning messages. The fact that some individuals ignore or misunderstand warning messages can reduce the effectiveness of these messages. For example, a study conducted in Japan confirms that people's responses to earthquake warnings are affected by cultural and social factors.

Cultural differences can significantly affect individuals' perceptions and reactions to warnings, and some cultural beliefs can affect people's behavior in the face of natural disasters. For example, some individuals who believe that disasters are divine punishment may not respond to warning messages (Ayeb-Karlsson et al., 2019). Individuals with such beliefs may reduce the effectiveness of warning systems and, moreover, endanger people's safety.

Integrating the central system in the Mufti's Offices into the EEW is expected to provide a significant improvement in message transmission capacity.This system offers a more comprehensive solution with its hybrid approach, addressing the limitations of other systems in providing message delivery channels to users. These limitations may include the inability to constantly follow TV and radio broadcasts, not being able to receive phone messages, and not being able to access e-mails in a timely manner. It is more likely that the warnings made from mosques will be heard loudly from the mosque speakers.

There are EEW systems in the world that warn the public. These systems aim to deliver messages to more people by using multiple channels. In Japan, a multi-pronged approach is used, including television and radio broadcasts and mobile phone alerts. The Mexican EEW system uses channels including landline alerts, SMS notifications, radio broadcasts, and public sirens (in high-risk areas) (Prasanna et al., 2022; Cremen et al., 2022). However, these systems have their own disadvantages, including the constant monitoring of radio and television, and the inability to hear SMS alerts. The proposed EEW is similar to the Mexican SASMEX system, which provides siren alerts. However, it is limited by the proposed alert system, as it is not distributed throughout the country.

However, there are deficiencies in the system, including failure to transmit messages due to technical failures such as power outages, foreign nationals not being able to understand the message because the warning is in Turkish, or hearing-impaired citizens not being able to access the message. In order to eliminate these deficiencies, the hybrid warning system, which includes mobile phones, will eliminate the deficiencies caused by technical failures. Another and most important deficiency of the system is the lack of sufficient awareness among the public about earthquakes. The success of the system is directly related to the public's education on this subject. Due to the lack of sufficient knowledge about earthquakes and EEW, injuries and deaths may occur due to jumping from buildings due to the panic caused by the warning received. In order to increase the effectiveness of EEW systems in Japan, various training programs are implemented to provide information about warning systems to employees in both the public and private sectors. The training courses are usually provided by professionals specialized in seismology, emergency management, and public health. The content of the trainings covers topics such as the perception of seismic waves, the transmission of warning messages, and how to respond to these messages (Şentürk and Aktuğ, 2020).

A pilot region should be selected to increase the effectiveness of the system in which warning messages broadcast from mosques are integrated. When determining the pilot region, priority should be given to regions with high earthquake expectations. The public in this region should be trained about earthquakes and EEW, and the demands of the residents should be received. After the first simulations, the public's reactions should be measured with surveys, and any deficiencies in the system should be improved. On the other hand, necessary infrastructure investments should be made to use both solar energy and grid-powered battery systems against power outages.

Conclusions

In this study, a hybrid model based on mosque loudspeakers is proposed by improving the existing Earthquake Early Warning Systems (EEW) in order to reduce the effects of the expected major earthquake in the Sea of Marmara. The simulations showed that the system can be effective especially in areas farther than 45 km. Since the arrival time of P waves is less than 8.2 seconds in settlements 45 km or closer to the epicenter, it is not possible to give individual warnings. However, it is calculated that a warning time gain between 4.9 seconds and 30.2 seconds can be achieved in Bandırma (55 km) and more distant settlements.

One of the most important advantages of the system is that 10,581 mosque loudspeakers are used as part of the system, spread over a wide geographical area. Thanks to this, in densely populated districts such as Büyükçekmece (63 km), Avcılar (76 km) and Kadıköy (102 km), the early warning period varies between 7.4 and 19.4 seconds. These periods allow individuals to Drop, Cover, and Hold On or move to safe areas. However, the success of the system is directly affected by factors such as power outages, communication infrastructure and public awareness. While individual warnings are not meaningful in areas up to Silivri (45 km), critical infrastructure measures can be taken in cities such as Çorlu (35 km) and Tekirdağ (30 km). For example, this hybrid model, which saves time for automatic closing of natural gas valves and stopping transportation systems, can play an important role in increasing infrastructure security.

On the other hand, since the earthquake in the Sea of Marmara is far from the seismic network, processing the data and making the alarm decisions will cause serious loss of time. In addition, since at least three stations are needed in the network solution, the on-site solution will give faster results. In this regard, it is recommended to use on-site EEW systems to shorten the early warning period.

In order to increase the applicability of the system, pilot tests should be carried out in cooperation with AFAD, the accuracy rates of the model should be analyzed under different scenarios and public awareness should be increased. Field tests should be carried out especially in critical cities such as Istanbul and Bursa to evaluate how the public reacts to the warning system and to optimize the model.

As a result, this hybrid EEW system integrated with mosque loudspeakers has the potential to reach almost the entire region against the expected major earthquake in the Sea of Marmara. The system has been proven to be effective with early warning times ranging from 10 to 30 seconds for residents more than 50 km away. With future field tests, the system's effectiveness can be further increased, and it can play a critical role in disaster management.

Peer Review Externally peer reviewed.
Conflict of Interest The author has no conflict of interest to declare.
Financial Disclosure The author declared that this study has received no financial support.

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