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Earthquake Early Warning System: A Solution for Life Rescue in Health Facilities and Risks Mitigation for the population of the Virunga Region

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ABSTRACT

The desire for earthquake hazard mitigation has been the focus of many researchers and governments for decades. This is paramount because an earthquake disaster can quickly cause many injuries, fatalities, and damages. The global database of the 21,000 most devastating disasters (earthquakes included) since 1900 indicates that 50% of them with the most significant number of injuries occurred only during the past 20 years. In human history, the Xaanxi earthquake is ranked third among the disasters that claimed more lives. In addition, earthquakes contributed to six of the most deadly disasters of the past two decades and 21% of the economic losses. In the same period, the earthquakes due to the Virunga volcanic activity were responsible for more than 100 deaths and extensive material and infrastructure damage. The referenced information and statistical data about the earthquake occurrence process, adverse effects, economic losses, and the current technological success in reducing its risks through warning systems are the basis for developing this paper. The authors aim to raise awareness and recommend that the Virunga region countries (Democratic Republic of the Congo, Rwanda, and Uganda) be a good place for an Earthquake Early Warning System and Earthquake Management Plan. An Earthquake Early Warning System even caught the attention of the United Nations, where the endorsed Sendai Framework for Disaster Risk Reduction (UNISDR, 2015) specified that early warning must be a priority and has to be substantially evolved by 2030.

Keywords – *Earthquake, early warning, Rwanda, Virunga region, health facilities, Disaster, Seismic activity.*

BACKGROUND

An earthquake is a weak to violent ground shaking produced by the sudden movement of rock materials below the Earth's surface.[1] Over the past 40 years, natural disaster effects have drastically increased in terms of reported number, total deaths, total people affected, and economic loss (Figure 1).[2]

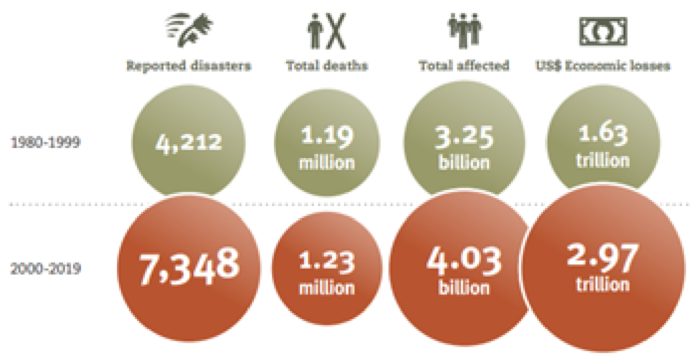


FIGURE 1. Disaster impact 1980-2019, showing that in the last two decades, disasters have significantly increased.

Earthquakes are the most destructive natural hazards throughout human history. Hundreds of thousands of people lost their lives, and the loss of billions of dollars of properties occurred in these disasters.[3] Earthquakes occur naturally (i.e., tectonic and volcanic) or as a result of human activity (i.e., explosion, mine collapse, or reservoir-induced).[4] The Earth is made of different layers classified rheologically or chemically. Rheologically speaking (classification based on the liquid state of rocks under tremendous pressure and temperature), the Earth is divided into five layers: lithosphere, asthenosphere, mesosphere, outer core, and inner core.[5] Chemically speaking, the Earth's geological structure comprises four layers: the crust, the mantle, the outer core, and the inner core, though researchers of the Australian National University have, in 2021, uncovered a fifth layer within the Earth's inner core.[6] The different earth layers and corresponding thicknesses are shown in Figure 2.[7]

An earthquake happens when two blocks (tectonic plates) of the Earth's lithosphere or upper mantle suddenly slip past one another. The surface where they slip is called the fault or fault plane. The location below the Earth's surface where the earthquake starts is called the hypocenter, and the location directly above it on the surface of the Earth is called the epicenter.[8]

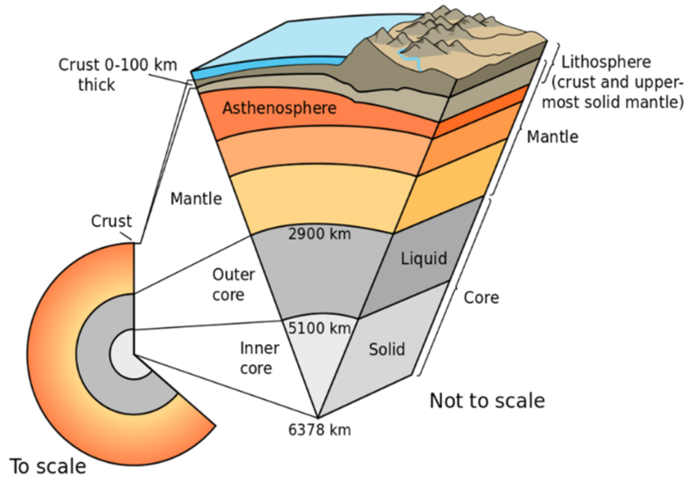


FIGURE 2. A cut-away of the Earth's layers.

Diverging and converging tectonic plates' action in the Earth's crust is responsible for the creation of volcanoes. The volcanic activity is rooted in molten rock called magma, which is squeezed onto the Earth's surface.[9]

A key control on the eruptive processes is the tectonic setting, which determines how magma is generated, the pathways by which it reaches the Earth's surface, and the characteristics of eruptions.[10] A volcano may be active, dormant, or extinct.[9]

The activity of the tectonic plates responsible for the volcanic eruption can have divergent boundaries (when tectonic plates move apart) (Figure 3).[11] Or convergent boundaries (two tectonic plates are moving toward each other, often causing one plate to slide below the other in a process known as subduction) (Figure 4).[12]

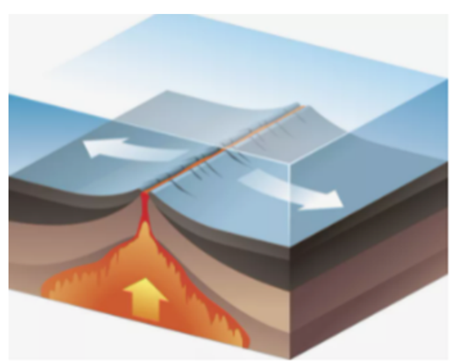


FIGURE 3. Diverging tectonic boundaries.

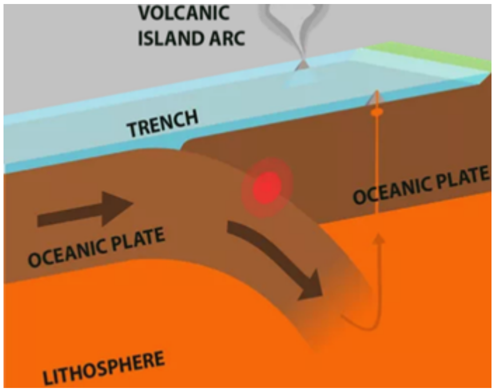


FIGURE 4. Converging tectonic boundaries.

Convergent plate boundaries are often the sites of earthquakes, volcanoes, and other significant geological activity.[12]

The Earth's crust is divided into six continental-size plates (African, American, Antarctic, Australia-Indian, Eurasian, and Pacific) and about 14 of sub-continental size (Caribbean, Philippine, etc.)

As per 2014, about 1,900 volcanoes on Eartare considered active, meaning they show some occasional activity and are likely to erupt again.[9] Earthquakes are measured by their magnitude, energy release, and intensity.

From 1935 to 1970, the Richter scale was the method for measuring earthquake magnitude.

Measurements on the moment magnitude scale are determined using a complex mathematical formula to convert motion recorded with a seismometer into a magnitude number that represents the amount of energy released during an earthquake.[13]

This method suffered from being only used in California and measuring earthquakes within only 370 miles from seismometers. Today, the Moment Magnitude Scale method is used and it works by measuring the movement of the rock along the fault.[14] The classes of earthquake magnitude are presented in Figure 5.[14]

The second way of earthquake measurement is by intensity, whereby measurement is an on-the-ground description.

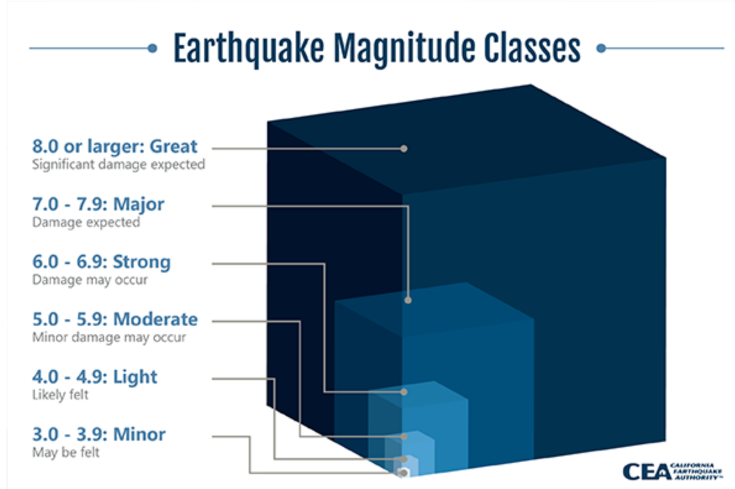


FIGURE 5. Earthquake Magnitude Classes.

Earthquake intensity is very different from earthquake magnitude. Earthquake intensity is a ranking based on the observed effects of an earthquake in each particular place. Therefore, each earthquake produces a range of intensity values, ranging from the highest in the epicenter area to zero at a distance from the epicenter.

Earthquake intensity values follow either the modified Mercalli Intensity Scale (1 to 12) or the Rossi-Forel Scale (1 to 10).[14] However, the Modified Mercalli Intensity (MMI) is now dominantly used worldwide (Figure 6).[13,15]

Worldwide, more than one million earthquakes occur yearly, an average of about two every minute.[16] A database including the 21,000 most devastating disasters worldwide since 1900 indicates that 50% of disasters, including earthquakes, with the most injuries, occurred only during the last 20 years.[17] In 2000-2019, earthquakes affect few people but are responsible for claiming more lives than floods, droughts, and storms (3% and about 59% of total disasters).[2]

Between 1998-2017, according to WHO, earthquakes caused nearly 750 000 deaths globally. The extent of destruction and harm caused by an earthquake depends on the magnitude, intensity, and duration, local geology, time of the day, building design and materials, and the risk management measures put in place.[18] In 2021, the worst magnitutde earthquake (8.2) occurred in Alaska, USA.

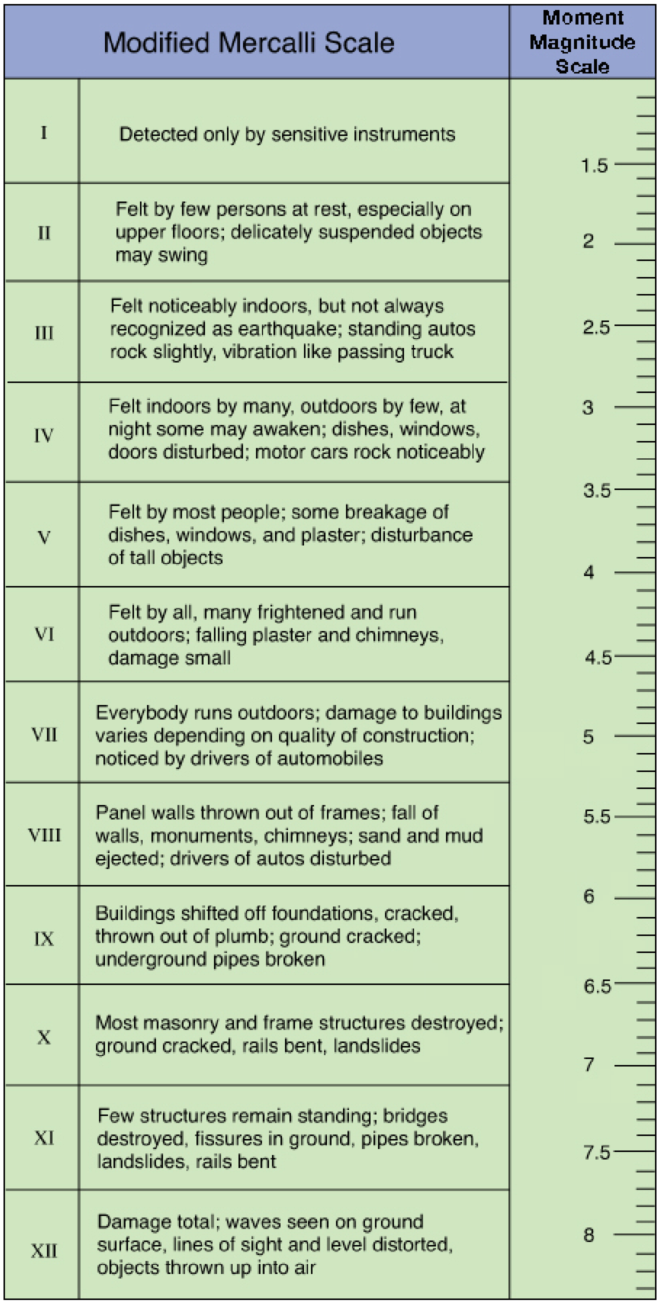


FIGURE 6. Comparison of intensity and magnitude methods of earthquake measurement.

The earthquake prompted a tsunami warning (lifted within 1 hour) and residents in towns and cities took protective cover.[19] This earthquake resulted in minimal damage, and no big wave was recorded.[20] According to USGS data, this quake was the seventh-largest recorded in US history, tied with another Alaskan quake from 1938.[21]

On August 14 2021, a 7.2 magnitude earthquake hit Haiti's southwestern departments of South, Grand' Anse, and Nippes. Over 2,200 people died, 12,700 people were injured, and 137,000 homes were destroyed, putting thousands of people in urgent need of assistance.[22] The countries with the greatest number of earthquakes were Mexico (9572), Indonesia (5484), and New Zealand (3544).[23]

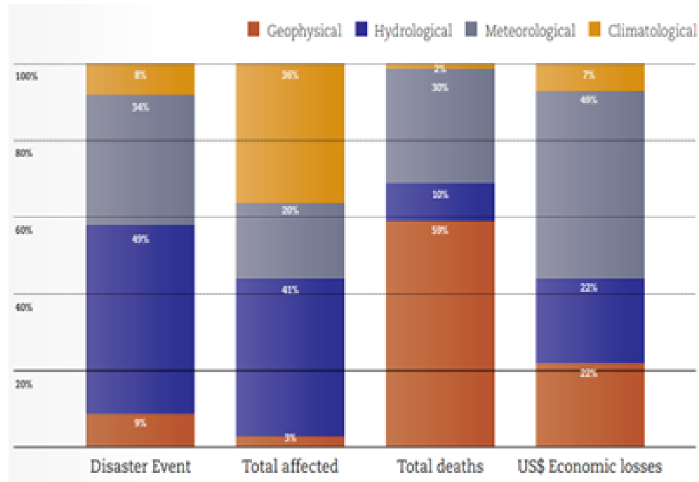


FIGURE 7. The proportion of various types of impacts by disaster sub-group (2000-2019).[2]

The Indian Ocean earthquake and tsunami caused the most casualties of all earthquakes that have taken place in the 21st century thus far. In the same period, top 15 deadliest earthquakes killed 558340 persons.[24]

Earthquakes contributed to six of the top deadliest disasters of the last two decades, contributing 21% of the economic losses.

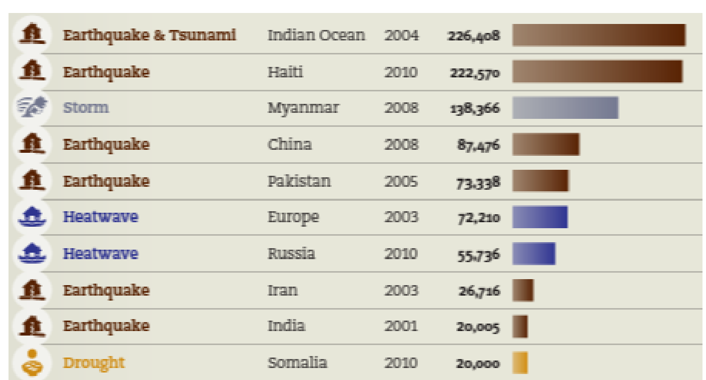


FIGURE 8. Top 10 deadliest disasters (2000-2019).[2]

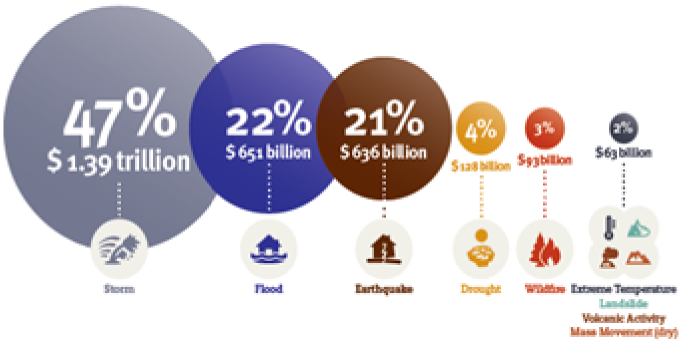


FIGURE 9. Breakdown of recorded economic losses (2000-2019).[2]

Hospital systems play a critical role in treating injuries and preventing additional deaths during earthquakes and other disasters. Hospital systems are at the core of disaster resilience because they must provide timely essential healthcare services to communities during and after an emergency response.[17] However, like other types of infrastructures, hospitals are not invulnerable to an earthquake.

Earthquakes can significantly damage and disrupt a community's interdependent infrastructure, including residential and commercial buildings; utilities (e.g., water and sewage); dams; levees; fires, tsunamis, flash floods, communications technology; healthcare facilities; chemical plants; industrial storage tanks; nuclear power plants and other hazardous materials storage locations; and bridges, tunnels, airports, roads, sea ports, and/or rail lines. In addition, outages may lead to secondary radiological or other hazardous materials incidents, transportation and supply chain disruption (including those used to transport food and medicines); and significant financial losses.[25]

Though natural disasters kill over 100,000 people and affect more than 150 million, the deadliest disaster is reported to be the 1931 Yangtze River floods which claimed over million deaths.[26]

Ranked third globally among other natural disasters to have claimed more lives, the worst humanitarian earthquake disaster in history is recorded in Xaanxi, China. An earthquake of magnitude 8 occurred in 1556 and resulted in 830,000 deaths, and reports indicated that all 97 counties were affected. For some counties, 60% of the population died.[27]

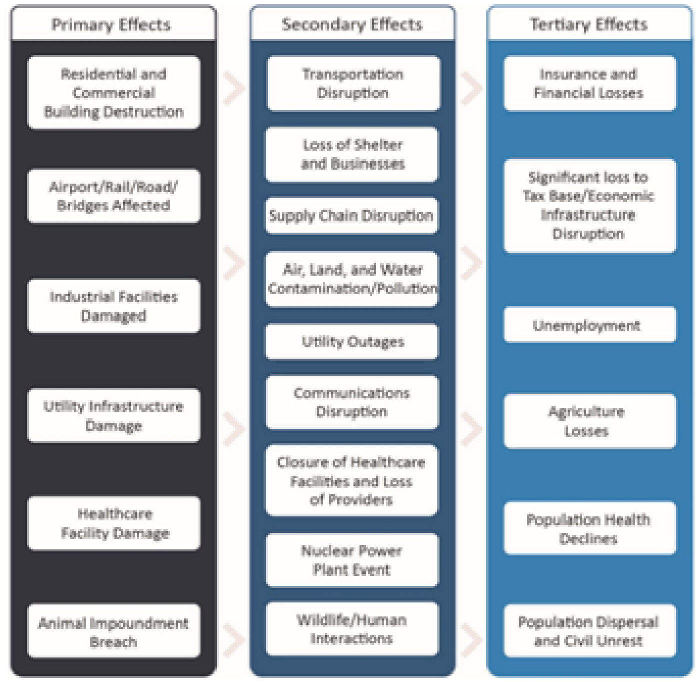


FIGURE 10. Earthquakes and Critical Infrastructure Disruption.[25]

It was seconded by an earthquake in Latin America and the Caribbean, where an earthquake struck Haiti on January 12, 2010. This quake killed an estimated 220,000 people and displaced 1.5 million; damages included but were not limited to housing, agriculture, water and sanitation, education, transport, health, and energy, valued at US$7.8 billion.[28] According to the Haitian government.[27] 316000 people were reported to have lost their lives in the disaster.

Volcanic Activity of the Virunga Mountains

The East African Rift System is one of the most outstanding and significant rift systems on Earth and transects the high-elevation Ethiopian and East African plateau.[39] The African Rift Valley extends over almost one-fifth of the Earth and is one of few active rifts on the Earth's land surface.[40] It is often mentioned as the modern archetype for rifting and continental break-up showing the complex interaction between rift faults, magmatism, and pre-existing structures of the basement.[41] The East African Rift System (EARS) (Figure 11) forms a narrow (50–150 km wide), elongated system of normal faults that stretch some 3,500 km in a sub-meridian direction.[40] EARS results from continental extension and thinning of the crust.[39]

TABLE 1. Examples of Health Facilities Damaged by Earthquakes

Medical facilities destroyed by Earthquake	Country	Year
Olive View Medical Center[29]	USA	1981
Kumamoto Hospital[30]	Japan	2016
Loma Prieta[31]	USA	1989
1059 health facilities destroyed, 401 completely damaged[32]	Nepal	2015
In 2 minutes, 97% of City hospital beds were destroyed in Pisco City earthquake[33]	Peru	2007
50% of health facilities destroyed in Pakistan Earthquake	Pakistan	2005
Bhuj Hospital, 150deads inside hospitals and 20000 overall died[34]	India	2001
10 hospitals destroyed to relacarion, and 50000 persons killed[17]	Turkey	1999
Maternité Solidarité hospital, a 75-bed emergency obstetrics facility damaged,[35] also 22% of hospitals were destroyed[36]	Haiti	2010
Bushenge Hospital, 80% of its structure damaged[37]	Rwanda	2008
Mexico City Earthquake,13 hospitals collapsed, 866 people died and 100 were health personnel[38]	Mexico	1985
Bam Earthquake, 3500 people injured, many health facilities destroyed[38]	Iran	2003
Maule and Bio-Bio Earthquake, 20% of the hospitals in the region suffered, and 484 people died[36]	Chile	2010

Tectonic activity in East Africa is often attributed to mantle upwellings at various scales.[10]

The Virunga Mountains, which make up part of the EARS range North of Lake Kivu in East-Central Africa, extend about 50 miles (80 km) along the borders of the Democratic Republic of the Congo, Rwanda, and Uganda.[42] The volcanic mountain range features eight major volcanoes, namely Nyiragongo (3470 meters), Nyamuragira (3058 meters), Mikeno (4437 meters), Kalisimbi (4507 meters), Gahinga (3473 meters), Sabyinyo (3671meters), Muhabura (4127 meters), Bisoke (3711 meters). Only two (Nyiragongo and Nyamuragira) of these volcanoes are active, while the others are dormant.[43]

The most earthquake-affected areas of the Virunga volcanic regions are the Northern and Western Provinces of Rwanda and the North-Kivu province on the DRC side. The two provinces of Rwanda have a population of 4,206,869 (Data from the websites of both provinces) spread over 9175 km^2 in which 20 hospitals were constructed, while the North Kivu province has a population of 6 000,000 as per the 2015 Census, over a surface area of 59,483 km^2.[44]

The active mountains/volcanoes are responsible for different earthquakes which ravaged the Virunga region (especially DRC and Rwanda). To mention some, two earthquakes of magnitude 6.0 and 5.0 struck the Great Lakes Region on February 3 2008, the first in the DRC and the second in Rwanda. It was reported that 34 died, 434 were wounded, and considerable damage in the two countries.[45]

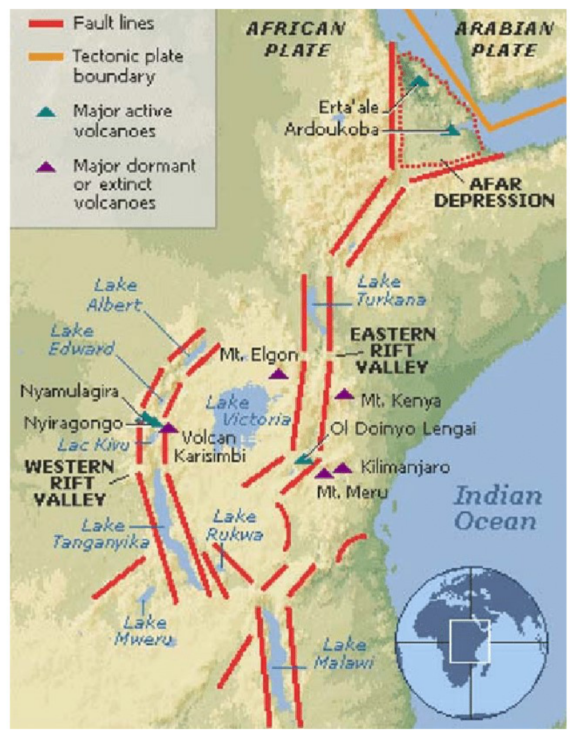


FIGURE 11. Tectonic plate boundaries for East Africa Rift Valley, including the Virunga Mountains.

In 2002, Nyiragongo erupted, and the lava lake drained from fissures on its western flanks. The city center of

Goma town, the capital of the East Virunga province, had been destroyed by voluminous lava flows. Over 200,000 people were left homeless, adding to the pre-existing human disaster caused by frequent civil wars.

From 1882 to 2021, Nyiragongo erupted at least[46] 35 times.[47] Between 2002-2008, 85 people died, and several infrastructure damages were recorded in Rwanda due to earthquakes.[48]

TABLE 2. Natural Methods of an Earthquake Early Warning System[49]

Earthquake Detection method	Explanation
Unusual animal behavior	Some animal (birds, dogs, swans, cats, deers, snakes, insects, worms, fishes, horses, donkeys, geese, fowls, ducks, pigeons etc) are endowed with sensory perception denied to human beings, upon which their change of behavior informs the public about the earthquake occurrence nearby. Before the earthquakes in Haichang (1975), Bahai (1969), Chile (1835), Ryakya (1896), Yogoslavia (1963), San Andreas (1906), Japan (1896), Tango 1927, Kanto 1923, Eddo (1855), India (1892), Uttarkashi (1991), Latur (1993), Jabalpur (1997), Chamoli (1999) and Bhuj (2001), different animals had already shown unusual behavior
Hydrochemical precursors	Concentration levels of dissolved minerals and gaseous components.
Temperature change	There seems to be a relation between temperature and earthquake. For example, a considerable rise of temperature by 10°C and 15°C was reported before earthquakes in Lunglin in China (1976) and Przhevalsk in Russia (1970).
Water level	Drastic changes in water level occurs before major earthquakes. The rise of water level by 3 and 15 cm was reported before Lunglin (China) and Przhevalsk (Russia) earthquakes. Also, the decrease in water level before the Nankai earthquake in Japan (1946). Similarly, water level rose by 3 cm a few hours before the earthquake in Meckering in Australia (1968). In China rise in water level in wells was observed before earthquakes of Haicheng (1975), Tangshan (1976), Liu-quiao and Shanyin (1979).
Radon gas	It is a radioactive gas which is discharged from rock masses prior to earthquake. It is dissolved in the well water and its concentration in the water increases. This happened before earthquakes of Tashkent (1972), Tangshan (1976), Luhuo (1973), and Uttarkashi earthquake (1991)
Oil Wells	Large scale fluctuation rate of oil flow from oil wells are observed before earthquakes. For example, such cases were observed in Israel, China, Northern Caucasus before 1969, 1971 and 1972 earthquakes.
Foreshocks	Foreshocks provide valuable dues to the occurrence of a strong earthquake. Haichang earthquake in China (February 4, 1975), Oaxaca, Mexico earthquake of November 1978Anantnag (1967), Dharmasala (1968), Kashmir (1973), Kinnaur (1975) were forecast by studying the foreshocks
Changes in Seismic Wave Velocity:	The lead time (time difference between primary and shear waves) and a longer period of abnormality in wave velocity presaged a larger quake.

In 2016, the combined effect of disasters in Rwanda were forecast to cost the country a massive Rwf 100 billion, earthquakes contributing Rwf 21.6.[51]

In May 2021, following the eruption of Congo's Mount Nyiragongo volcano, a 5.3 earthquake struck the border of Congo and Rwanda, resulting in the demolition of 17 villages and damaging infrastructure including roads and hospitals. In addition, about 1,000 houses were destroyed, and more than 5,000 people were displaced by the eruption, killing at least 32 people.[52,53] Reports indicate that 21,000 Congo residents cross into Rwanda for refuge.[54] According to UNHCR, the eruption led to the displacement of over 500,000 individuals to the surrounding areas of Goma, Sake, Minova, Kiwanja in Rutshuru, Bukavu, and Rwanda.[55] The total recovery of Rubavu will cost a whopping Rwf 91,430,692,000, according to officials.[54]

TABLE 3. Challenges in Disaster Management, Earthquakes Included[38]

Challenge category	Examples
Lack of preparedness	No previous training of personnel and lack of training programs, Lack of prior planning for disaster situations, Lack of attention to the experiences and lessons of previous disasters
Logistics challenges	Inappropriate places for providing services to the injured, Management of donations, No emergency fund, Security management, Human resources management
Technical challenges	Evacuation of hospitals, Patient security, Admission, Entry and exit management and discharging of injured, Triage and prioritization of patients
Communication and information management	Contact with the media, Communication within the hospital, Out-of-hospital communications, Management of very important people and visitors
Lack of coordination	Coordination problems with volunteers who were referred to help, Lack of coordination among hospital officials, Lack of coordination among the authorities in different hospitals, No Incident Command System, Disobeying the orders of officials by personnel, Intractable performance of tasks by staff, Absence of command unity and single commander, Frequent examinations of some injured, Bewilderment of personnel and officials, Fragmentation and repetition, Inappropriate interventions of unrelated individuals

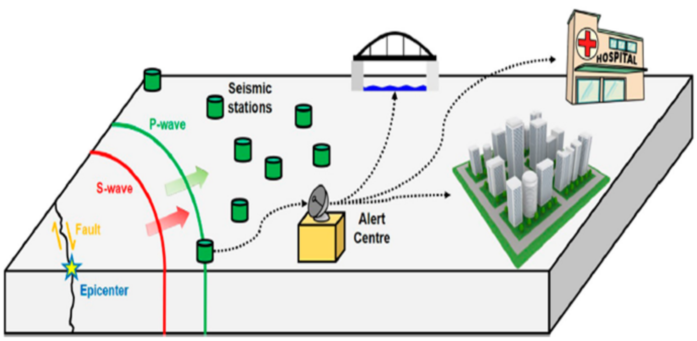


FIGURE 12. The technical principles of an earthquake early warning system.[50]

Weak shaking might have been felt in Ruhengeri, located 28 km from the epicenter, Sake 40 km away, Gitarama 66 km away, and Kigali 83 km away.[56] During the same disaster of Nyiragongo eruption and consequent earthquakes, there were 92 earthquakes and tremors of which only 4 were felt by humans. The rest were only picked up by instruments.[57]

Considering the human and material losses caused by earthquake, an early warning system and management plan would contribute to saving lives. The technological advances have made it practical to design and implement Earthquake Early Warning System Based on Internet of Thing.[58]

Traditionally, before the invention and development of recent advanced technologies for earthquake detection and warning, other methods were used to detect the occurrence of the earthquake in the near future, as presented in Table 2.

EARTHQUAKE EARLY WARNING SYSTEM (EEWS)

The immediate resilience after the earthquake is becoming an important aspect worth being investigated.[59] An Earthquake Early Warning System (EEWS) is both a scientific and a societal challenge. It would be wonderful to see EEW save many lives and reduce societal losses in future earthquakes.[60]

The success of EEWS will be attributed to advances in communications, digital seismology, and automatic processing.[61,62] The first successful EEWS were developed by Japan and proved useful before the 1975 Haicheng, China earthquake. Shortly after receiving the warnings, the government urged the residents to evacuate to a safe place, and on February 4, an M7.3 earthquake struck the region.[63]

Japan invested $600 million in such a system after the 1995 Kobe earthquake killed 6,400 people. Today, Japan's system allows every citizen to receive an advance alert of an earthquake ground shaking from the Japan Meteorological Agency. Thanks to this system, no trains derailed in the magnitude 9.0 2011 Tohoku earthquake, and according to a poll in Japan, 90% of the citizens think the system is worth the investment.[64]

Today, the technology exists to detect earthquakes so quickly that an alert can reach people before strong shaking arrives. EEWS entail detecting initial earthquake shaking and rapid estimation and notification to users before imminent, stronger shaking.[60]

EEWS are beneficial as they allow organizations to take either automated or procedural actions to counter the impacts of the shaking. Examples of organizational actions include slowing trains, halting surgeries, elevators, and traffic, evacuating hospitalized patients, securing sensitive machinery, and turning off dangerous or essential equipment (Figure 13).[65,66]

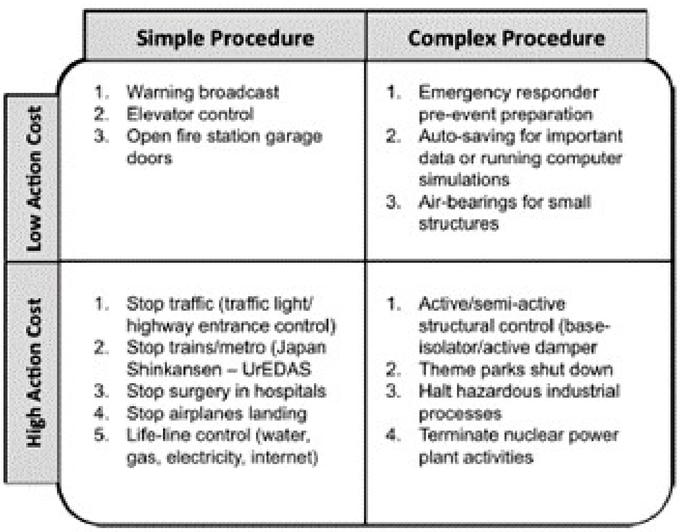


FIGURE 13. Examples of EEWS applications categorized in terms of procedure complexity and potential action cost.[66]

The emerging computing technologies such as mobile computing and Internet-of-Things (IoT) systems are equipped with various MEMS (Micro Electro Mechanical Systems) sensors (e.g., accelerometers, gyroscopes, GPSs), Wi-Fi, Bluetooth, making it possible to build and operationalize earthquakes early warning stations. However, the project is not only expensive but also difficult to realize a countrywide network.[67] The idea of using early warning for earthquakes was first considered by J.D. Cooper in November 1868; he proposed the installation of seismic sensors near Hollister, California, that would send an electric signal via telegraph to San Francisco once an earthquake was detected.[68] However, the first practical EEWS was UrEDAS installed in Japan for Railway Systems in 1988.[66]

Today, EEWS are used to deliver public warnings in Japan, Mexico, South Korea, Romania, Turkey, China, Italy, Switzerland, Canada, India, Taiwan, and along the west coast of the United States of America.[63,66,69,70] For example, following the 2008 Wenchuan earthquake, China's central government encouraged the establishment of a national EEWS. It resulted in a high-quality national seismological network with 15 000 stations, 1928 seismic stations (equipped with collocated broadband seismometers and force-balanced accelerometers), and 3114 strong-motion stations (equipped with force-balanced accelerometers), and 10 349 sensors based on low-cost MEMS.[71] Post-earthquake engineering reconnaissance missions play an important role in learning about the performance of structures and infrastructure under seismic loading, the social impacts of disasters, disaster management processes, and the science of seismic events.[72] The complete scope of the EEW problem can be summarized in four steps (Figure 14).[66]

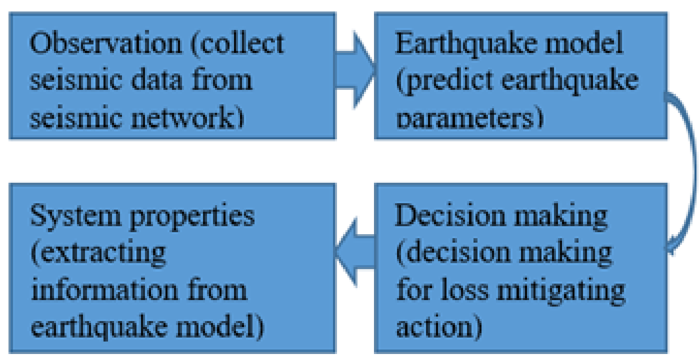


FIGURE 14. Scope of Earthquake Early Warning System problems.

Seismic waves detection and transmission

When an earthquake occurs, energy is released due to tectonic plates moving relative to one another. The energy generated from the collisions propagates through and around the surface of the Earth as seismic waves. Seismic waves are not generated by earthquakes only because explosions, volcanic eruptions, wind, supersonic planes, people's footsteps, vehicles, and bikes can generate them. Seismic waves can be divided into surface waves that travel on Earth's surface and body waves that travel through Earth. There are two types of body seismic waves.[15]

- Primary waves, compression waves, or dilatation waves (P-waves) are waves that reach the Earth's surface first. They can travel through all mediums of liquid, solid, and gases. They possess high velocity (4-8 km/sec) with low destructive power and move radially from the focus of the earthquake.[50]
- Secondary waves (S-waves, also called Shear waves) reach the Earth's surface following primary waves. Such waves travel only through solid media and get aborted in liquid media. They are characterized by lower speed (2-4 km/s) compared to primary waves and scatter in all directions from the earthquake focus point (they displace material at right angles to their path). These waves are more damaging, causing maximum destruction during an earthquake.[50]

The S wave carries the major destructive energy, and the smaller amplitude P wave precedes the S wave by the time equal to 70% of the P-wave travel time to the station.[61]

TABLE 4. Various Minerals and their P and S Wave Velocities

Mineral	P-wave velocity (m/s)	S-wave velocity (m/s)
Soil	300-700	100-300
Dry sand	400-1200	100-500
Limestone	3500-6000	2000-3300
Granite	4500-6000	2500-3300
Basalt	5000-6000	2800-3400

When measuring seismic waves, the time difference between the P- and S-waves tells us the distance the earthquake is from the seismograph. Data from a seismometer, also called a seismogram, shows velocity on the y-axis and time on the x-axis (Table 4).[73]

The fundamental observations used in seismology are seismograms , a record of the ground motion at a specific location. Seismograms come in many forms, on smoked paper, photographic paper, common ink recordings on standard paper, and digital format (on computers, tapes, CD ROMs). The strength of shaking can practically be represented by peak ground acceleration (PGA), peak ground velocity (PGV), and peak ground displacement (PGD).[61]

The ground vibration measurements by seismograms are used for estimation earthquake source parameters (origin of the earthquake and rupture duration, earthquake location including epicenter and depth, sie of the earthquake expressed in magnitude), getting seismic wave travel path information (seismic velocity model, attenuation model).[74]

Different instruments are used to detect and measure the seismic magnitude, and their difference depends on the parameter to measure, types of sensing transducers, bandwidth, and signal intensity. They detect the seismic waves created by subsurface ruptures and convert ground motions into electronic signals suitable for transmission. Generally, seismometers, accelerometers, and gyrophones are standard for measuring earthquake magnitude.

- Geophones: these are electricity-powered devices that have been used for measuring seismic data.[75] They are ingenious devices with active elements hanging over a spring, amplifier, and magnet, as shown in Figure 15.[76]

The magnet moves up and down around the mass when the Earth moves. The magnetic field of this moving magnet produces an electrical voltage in the wire. This voltage can be amplified and recorded by a simple voltmeter.[76]

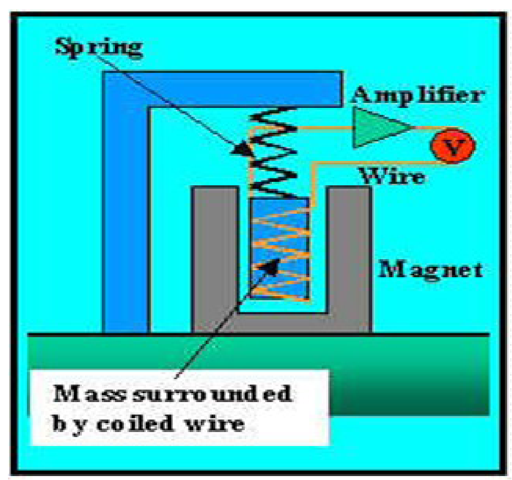


FIGURE 15. Basic principle of a gyrophone.

An important feature of geophones is that they can only monitor frequencies above their natural frequency, up to a specified spurious frequency (10Hz-250Hz).[77]

- Seismometers are instruments used to identify vibrations brought about by the plates' movement. The device measures the velocity of a point on the ground during an earthquake. A seismometer, a clock or time-signal receiver, and a recording system constitute a seismograph. The basic seismometer is presented in Figure16.

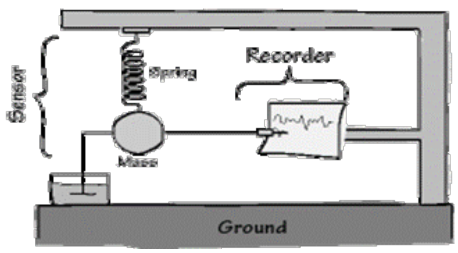


FIGURE 16. Basic seismometer [Image from IRIS Website]

The output of the seismometer is usually measured in volts/rnrn/s. The damping is typically measured as a ratio of critical damping, and is normally set to a value of about 0.7 critical. The natural frequency of the seismometer is measured in hertz and for local earthquakes normally has a value less than 2 Hz, with 1 Hz often used. Each seismometer can measure motion in one direction, either vertical or horizontal.[74] Seismometers are classified into broadband (capable of sensing ground motions over a wide range of frequencies) and short period types (cover the frequency band from 1 Hz to 100 Hz).

Seismometers are classified by type (Tele seismometers, Strong-Motion Seismometer, Strain-Beam Seismometer), range (50 to 750 V/m, 1500 V/m, and 20,000 V/m), and varieties (Short Period, Long Period, and Broadband).[78]

- Accelerometers: Accelerometers give information about forces that a subject experiences during a seismic activity.[79] They measure the acceleration of the shaking ground and are designed to measure the large-amplitude, high-frequency seismic waves typical of large local earthquakes. In addition, the double integration of the accelerometer output gives the distance function, which can detect the distance from the epicenter.

Nowadays, there has been considerable interest in the seismic exploration industry in MEMS microchips as acceleration-measuring sensors.[75] Though accelerometers and geophones are used in seismometry, attention to seismometer and its market up to 2022 was shown to grow in recent applications (Figure 17).[78]

FIGURE 17. Seismometers Market growth from 2016 to 2022.

According to the configuration of the networks/sensors, an EEW system can be conceptually classified as a regional or an onsite system. A regional EEW system is based on a dense sensor network covering a geographical area of high seismicity, and when an earthquake occurs, the relevant source parameters are estimated from the early portion of recorded signals at sensors close to the rupture. Regional EEW systems typically require many stations triggered on the arrival of the P-wave signal to provide stable early estimates of earthquake location.[50,80]

The regional EEWS takes 10-15 secs to detect an earthquake, and by the time the damaging S-waves reach some locations close to the epicenter, a warning is not possible. The areas without warning are termed blind zones and may range around 40–60 km from the epicenter, depending upon how quickly an earthquake is located. The problem of the blind zone can be overcome by the onsite EEW system, under which a single station installed in the target area will immediately sense the earthquake and issue a warning.[80]

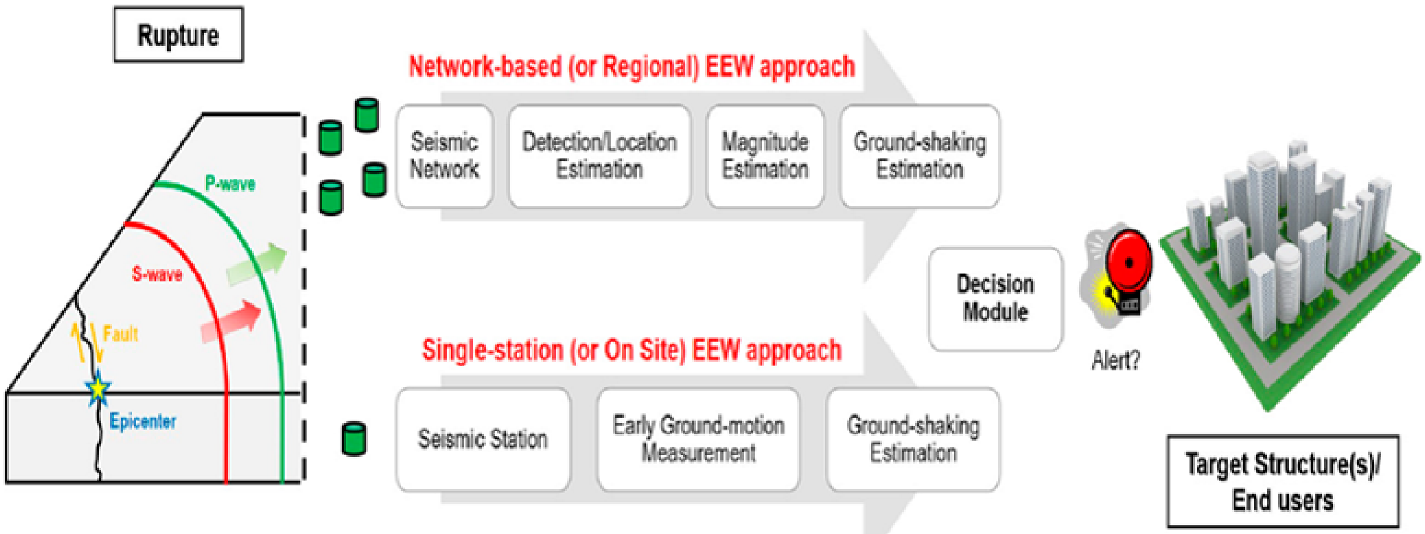


FIGURE 18. The two possible approaches to earthquake early warning.

Site-specific or onsite EEW systems consist of an array of sensors or a single sensor located in the vicinity of a single target site or structure /infrastructure of interest. Site-specific systems provide estimates of peak-ground-motion IMs [e.g., PGA, or PGV] based directly on the amplitude and/or predominant period of the initial recorded P-wave signal (Figure 18).[50] Generally an EEWS consists of:

- Remote Station: The remote station is generally located in the neighborhood of the earthquake source. It contains different sensors for seismic waves detection, the data acquisition and processing system, the power supply, and the data transmission system. The remote station monitors and detects earthquakes based on seismic networks. The station processes can estimate the earthquake location, magnitude, maximum seismic intensity, earliest arrival time, and alert notification decisions.[36]
- Communication Network: the rapid development in communication technologies, especially in satellite communication, has impacted the evolution of the seismic network. Communication technologies used in seismometry help exchange seismic data between stations and warn the target users. Each communication network has five elements for the successful transmission of information. Data, sending, receiving, channel, and communication protocol are elements.[81]

Communication technologies can be wired, wireless, or satellite-based. There are different topologies used in seismic networks, which differ based on the distance at which data are to be transmitted, data rates, efficiency, and robustness (Table 5).[82]

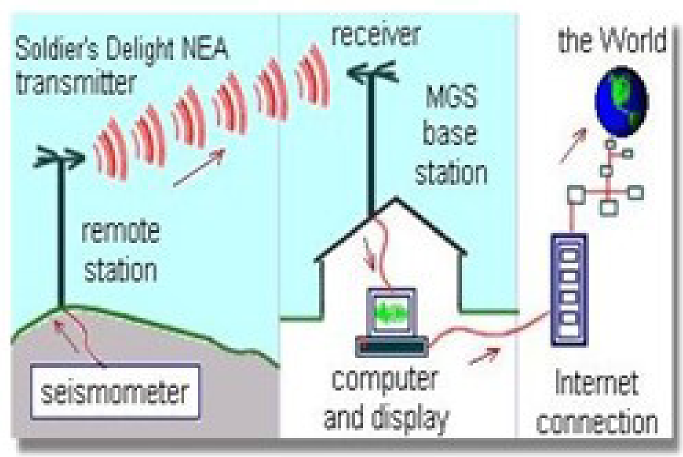


FIGURE 19. Earthquake Communication Network for Maryland Geological Survey.[83]

The communication system is entitled to strong computer algorithms to quickly estimate an earthquake's location, magnitude, and fault rupture length and to map the resulting intensity. It should also be capable of delivering quick and reliable mass notifications, and end-users must be educated on how to use the alerts.[64]

The different earthquake prediction methods include support vector regressor, ElarmS or epic, machine learning algorithm models, deep neural networks, or VS models.[29]

- Base Station: The base station is generally located at the site whose warning is addressed. The base station is composed of Mast/Tower, Sectorial antennas, PDH & SDH Microwave, Waveguide cables, Rectifier, Generator, Radio Base Station, Duplexers, Data Distribution Frame rack, Transceiver Unit (TRU), Trunking, TX cabinet & Shelter a short-haul modem, and a computer for data processing, display, storage and Internet distribution of data.[83,84] The base station is meant to give alarms to the region to be warned.

Currently, there are successful EEWS in the world, but most of them were initiated and installed after the concerned countries were seriously struck by earthquakes. Successful EEWS implementations include UrEDAS for Japan, ShakeAlert for USA, and Sasmex for Mexico.

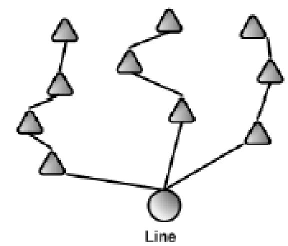
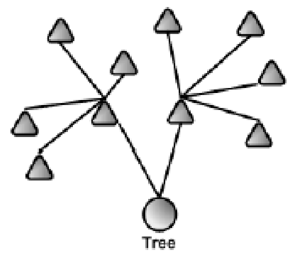
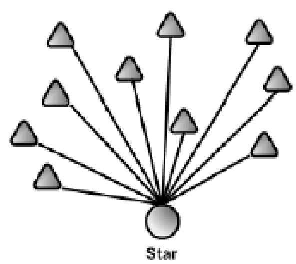
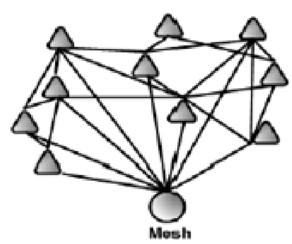
Japan has the most widespread network for earthquake warnings worldwide, and China is currently building a nationwide EEWS which will be completed in June 2023. The seismic network can be broadband, short period, or MEMS-based.[85]

The Global Seismographic Network (GSN) is a permanent, digital network of more than 150 modern stations in over 80 countries. It is composed of a globally distributed, state-of-the-art digital seismic network that provides free, real-time, open-access data through the IRIS DMC.[86]

Since its operation, the GSN has produced high-quality digital data from widely distributed, similarly equipped, and well-calibrated stations.[87]

GSN instrumentation is capable of measuring and recording with high fidelity all of Earth's vibrations, from high-frequency, strong ground motions near an earthquake, to the slowest free oscillations of the Earth. As a result, GSN seismometers have recorded the greatest earthquakes on scale (for example, the 1994 Mw-8.2 Bolivia earthquake at 660 km depth) and the nano-earthquakes (M < 0) near the sea floor at the Hawaii-2 Observatory. In addition, GSN sensors are accurately calibrated, and timing is based on GPS clocks.[88]

TABLE 5. Seismic Network Topologies: Nodes Represent Stations and Lines the Communication Links

Topology	Characteristics
	Short distance, different data on each link, data exchange passes through other nodes, not robust because link outage can affect different nodes
	Short distance, different data rates, data exchange passes through other nodes, not robust because link outage can affect different nodes
	Large distance, same data on links, data exchange travels through central node, Robust because link outage only effects one node
	Large distance, same data on links, rate in links can differ, Robust because link outage only affects one node

The GSN, together with the USGS National Earthquake Information Center (NEIC), are the principal global sources of data and information for earthquake locations, earthquake hazard mitigation, and earthquake emergency response. The real-time seismograms provided by NEIC for different regions update every 30 minutes.

To achieve this telemetry coverage, a wide range of solutions—geosynchronous satellites employing antennas in the 1 to 4 m range, Inmarsat, Iridium, landlines, local

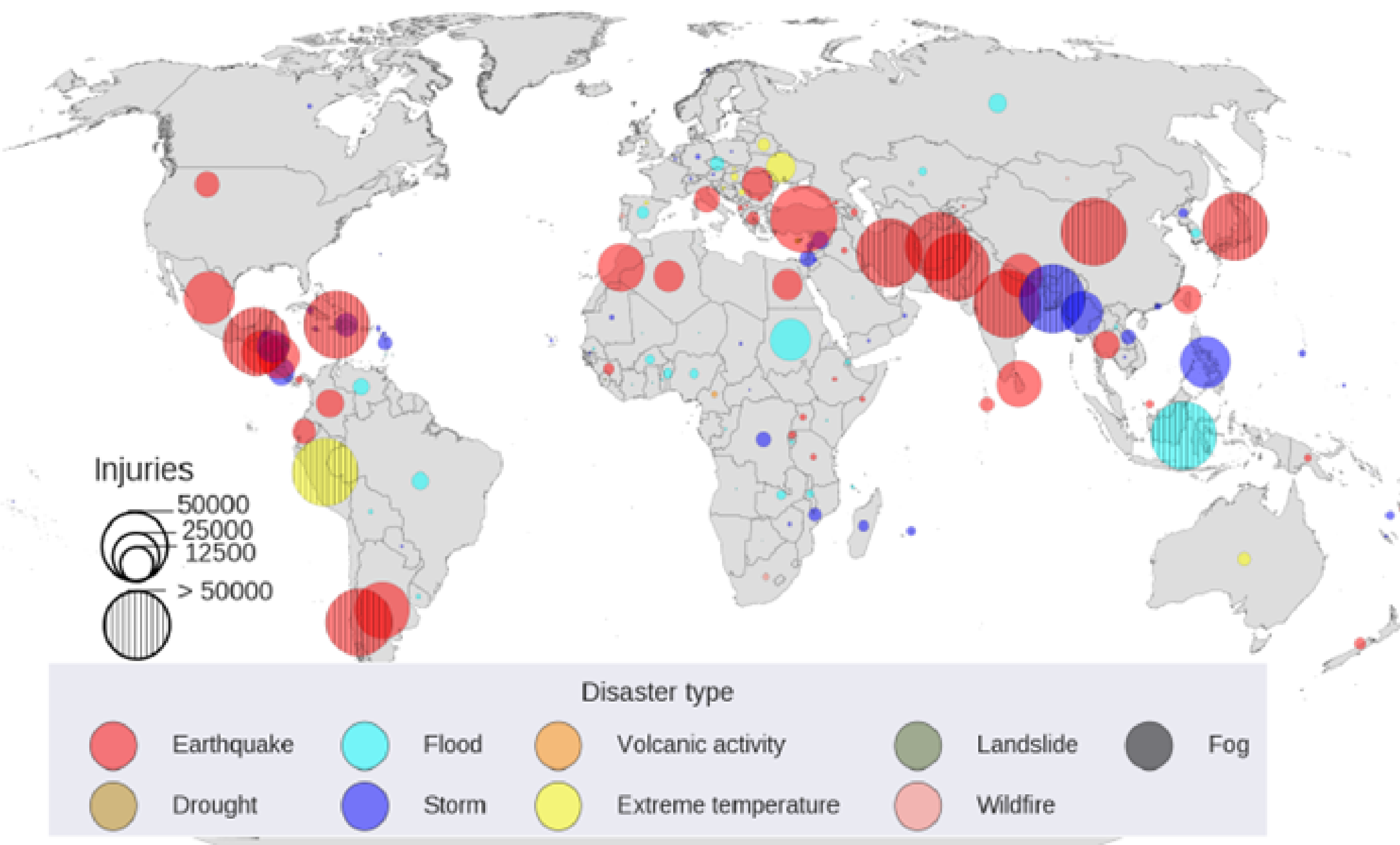


FIGURE 20. Per-country distribution of disasters with the highest number of injuries since 1900.[17] It is observed that earthquakes dominated the disasters which ravaged and shocked mankind.

Internet Service Providers, submarine cable, etc.—has been implemented, in cooperation with NASA/Jet Propulsion laboratory the US National Imaging and Mapping Agency, the US. National Weather Service, Japan's National Research Institute for Earth Science and Disaster Prevention, and the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) (Figure 21 and 22).[88-90]

CONCLUSION

In conclusion, this paper highlighted the natural process behind volcanic activity and the role of EEWS in mitigating earthquake risks. In addition, this paper presented the historical statistics of earthquakes in fatalities, infrastructure damages and economic losses caused, and the stand of earthquakes among other disasters.

The EEWS came to the attention of researchers as a solution to reduce the adversity of earthquake risks. Though the conceptual idea about EEWS started many decades ago, today, technological advancements have transformed the dream into reality.

Across the world, many operational seismic stations and networks are used to monitor and provide real-time information about seismic activity. Even if, in many cases, the public is warned a few seconds before destructive seismic waves, the alert can enable immediate actions that protect people and property. The activities which must be urgently performed include halting delicate medical procedures and moving patients to safe assembly points, pausing airplane landings, students exiting classrooms, turning off household appliances, and safely stopping and exiting vehicles. Also, automated responses must be addressed, such as opening elevator doors, shutting down production lines, securing chemicals, stopping trains, and protecting power stations and grid facilities.

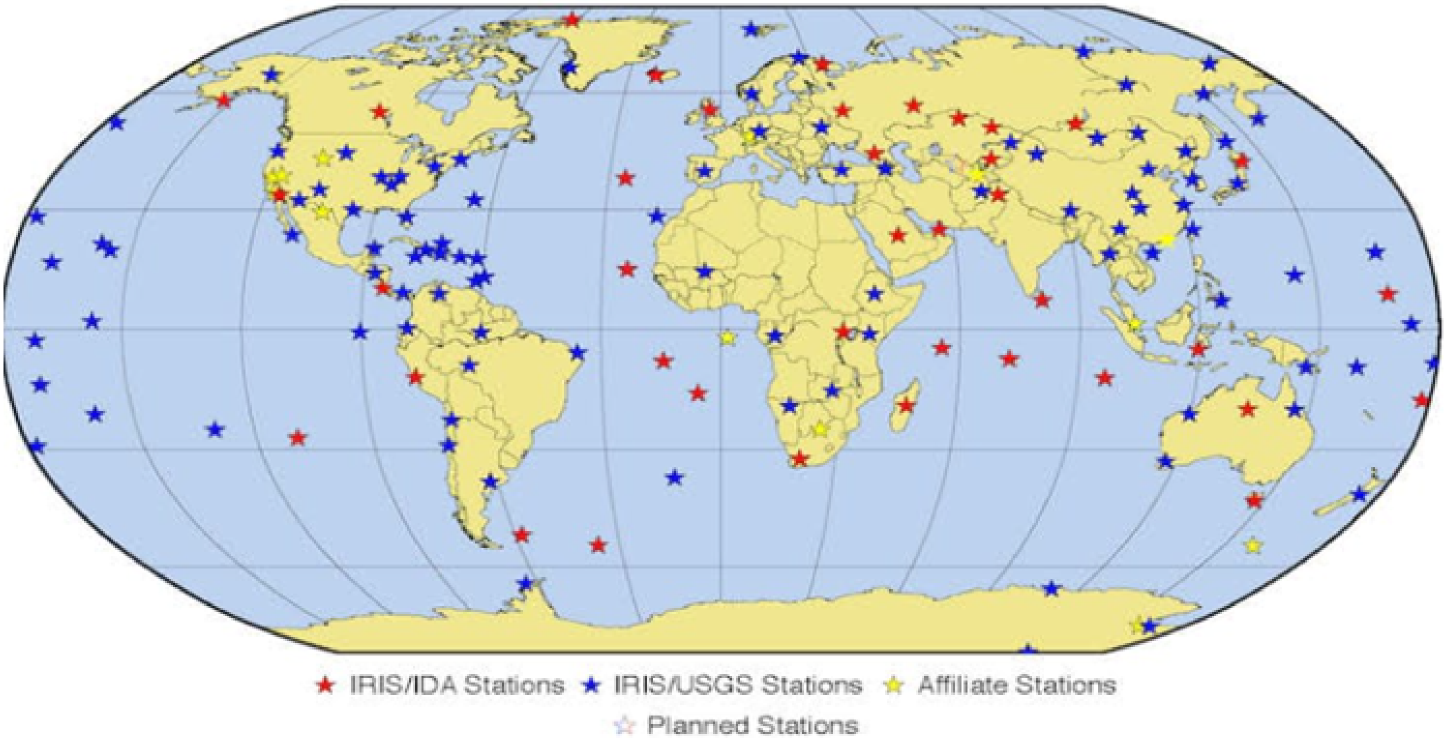


FIGURE 21. Distribution of stations pertaining to Global Seismographic Network.

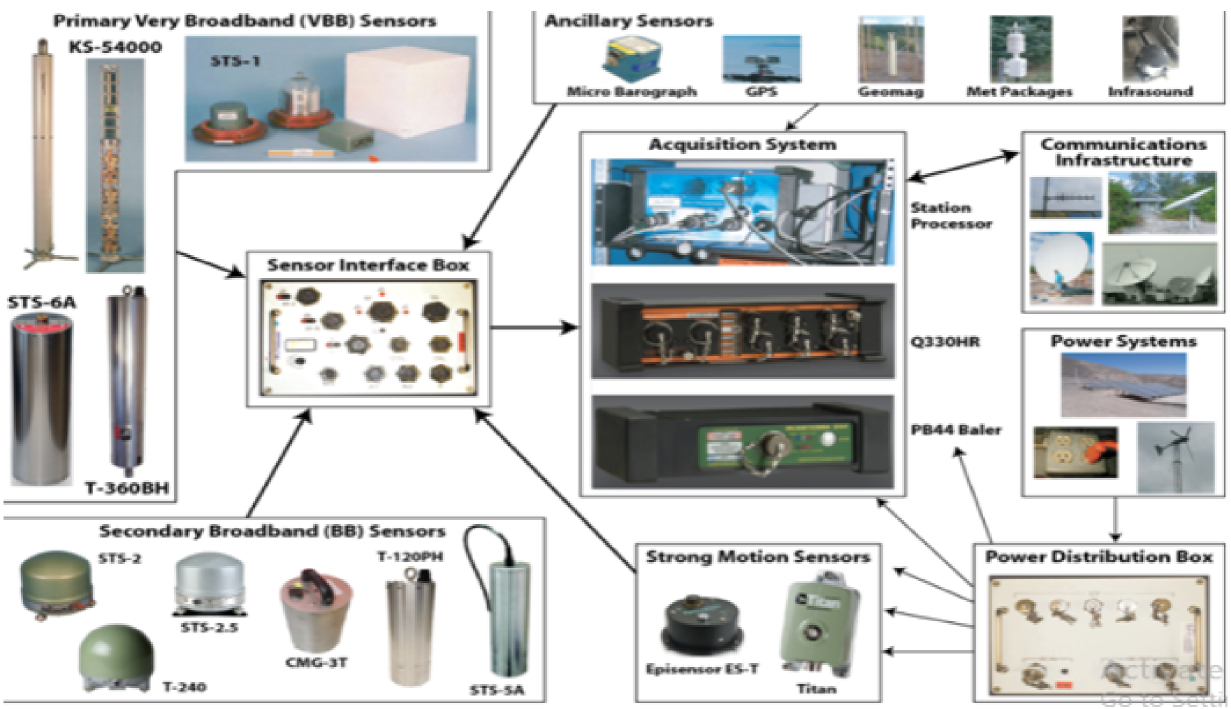


FIGURE 22. Components of Global Seismographic Network System.

Although there is no EEWS for the earthquakes occurring in the Virunga volcanic region, hospitals in Rwanda have safe assembly points where people can gather in case of an emergency or disaster. However, this good initiative is not enough compared to the technological progress of the current generation of EEWS, and the development achievement of other countries with the same earthquake challenges.

In 2005, at the 2nd World Conference for Disaster Reduction in Kobe, Japan, 168 countries ap¬proved the Hyogo Framework for Action and they agreed to: promote the goal of 'hospitals safe from disasters' by ensuring that all new hospitals are built to a level of safety that will allow them to function in disaster situations and implement mitigation measures to reinforce existing health facilities, particularly those providing primary health care.

In addition, in 2015, the member states of the United Nations endorsed the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015), where it is specified that early warning must be a priority and early warning systems have to be substantially evolved by 2030.

Therefore countries affected by the Virunga volcanic activity are first recommended to join efforts to exchange how the EEWS can be implemented to warn the residents about the likelihood of earthquake occurrence in the near future. Furthermore, the EEWS should also send a warning to healthcare care facilities for better preparation before the occurrence of destructive seismic waves. Since the residents are warned, congestion at a health facility can be reduced, and the physicians will have fewer patients to care for.

Due to the high cost of EEWS infrastructures, it would be paramount to have a cost-effective Earthquake Management Plan which can intervene, face and solve challenges linked to earthquake disasters. In this regard, the high seismic risk zones should be mapped based on past earthquakes and the safe shelters available for residents of the mapped zones. Individuals can use the alert time to Drop-Cover-Hold On or move to safer locations within a building, reducing injuries and fatalities, or if the warning time allows, evacuate hazardous buildings. Furthermore, the plan should engage trained personnel to manage logistics, communications, and transportation and provide healthcare aid services and treatment.

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