

REVIEW

## The Current Landscape of Early Warning Systems and Traditional Approaches to Disaster Detection

### El panorama actual de los sistemas de alerta temprana y los enfoques tradicionales para la detección de desastres

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#### ABSTRACT

Early warning systems (EWS) are crucial for disaster risk reduction, providing timely and reliable information to communities and authorities for proactive mitigation. Traditional methods, such as weather stations, river gauges, and seismic networks, have limitations in spatial coverage, real-time data availability, and precursor signal detection. Recent technological advancements have enhanced EWS by integrating remote sensing data from satellites, airborne platforms, and ground-based sensors, enabling real-time monitoring of phenomena like wildfires, volcanic activity, and landslides. The Internet of Things (IoT) and crowdsourced data from social media, mobile apps, and citizen reports have further improved situational awareness and response times, complementing traditional systems. Increased computational power has enabled the development of sophisticated models, such as numerical weather prediction and seismic hazard models, which predict disaster impacts more accurately. Despite these advancements, challenges remain in data interoperability, resilient communication infrastructure, and delivering clear, actionable alerts to at-risk populations. Future EWS will likely become more data-driven and interconnected, leveraging artificial intelligence, big data analytics, and IoT. Collaboration among governments, academic institutions, and local communities is essential to building robust, inclusive EWS that save lives and reduce the economic impact of disasters.

**Keywords:** Community Preparedness; Multi-hazard Approach; Predictive Modeling; Real-time Monitoring; Risk Assessment and Technological Integration.

#### RESUMEN

Los sistemas de alerta temprana (EWS, por sus siglas en inglés) son cruciales para la reducción del riesgo de desastres, ya que proporcionan información oportuna y confiable a las comunidades y autoridades para una mitigación proactiva. Los métodos tradicionales, como estaciones meteorológicas, medidores de ríos y redes sísmicas, tienen limitaciones en la cobertura espacial, la disponibilidad de datos en tiempo real y la detección de señales precursoras. Los avances tecnológicos recientes han mejorado los EWS al integrar datos de teledetección provenientes de satélites, plataformas aéreas y sensores terrestres, permitiendo el monitoreo en tiempo real de fenómenos como incendios forestales, actividad volcánica

y deslizamientos de tierra. El Internet de las Cosas (IoT) y los datos obtenidos de redes sociales, aplicaciones móviles y reportes ciudadanos han mejorado aún más la conciencia situacional y los tiempos de respuesta, complementando los sistemas tradicionales. El aumento en la capacidad computacional ha permitido el desarrollo de modelos sofisticados, como la predicción numérica del tiempo y los modelos de riesgo sísmico, que predicen los impactos de los desastres con mayor precisión. A pesar de estos avances, persisten desafíos en la interoperabilidad de datos, la infraestructura de comunicación resiliente y la entrega de alertas claras y accionables a poblaciones en riesgo. Es probable que los EWS futuros sean más impulsados por datos e interconectados, aprovechando la inteligencia artificial, el análisis de big data y el IoT. La colaboración entre gobiernos, instituciones académicas y comunidades locales es esencial para construir EWS robustos e inclusivos que salven vidas y reduzcan el impacto económico de los desastres.

**Palabras clave:** Preparación Comunitaria; Enfoque Multi-amenazas; Modelado Predictivo; Monitoreo en Tiempo Real; Evaluación de Riesgos e Integración Tecnológica.

## INTRODUCTION

In the face of the ever-increasing frequency and severity of natural disasters, early warning systems have become indispensable tools for mitigating the devastating impacts of such events. These sophisticated systems play a crucial role in alerting communities and authorities well in advance of impending catastrophes, enabling timely preparation and response efforts that can save countless lives and minimize economic losses.<sup>(1)</sup> As our understanding of natural phenomena and technological capabilities continue to advance, the importance of these systems in disaster risk reduction strategies cannot be overstated.

Traditional approaches to disaster detection have relied heavily on ground-based monitoring networks and observational data. These methods, while valuable and time-tested, often face significant limitations in terms of spatial coverage, real-time data acquisition, and the ability to detect subtle precursory signals of impending disasters. Despite these constraints, they have formed the backbone of early warning systems for decades and continue to provide critical information in many regions around the world.<sup>(2)</sup>

One of the most widely used traditional methods is the deployment of seismic networks to monitor earthquake activity. These intricate networks consist of arrays of highly sensitive seismometers strategically positioned across regions prone to seismic activity.<sup>(3)</sup> By meticulously analyzing seismic wave patterns, frequencies, and magnitudes, these systems can swiftly detect and accurately locate earthquakes, providing critical information for early warning and emergency response protocols. This data enables authorities to issue rapid alerts, potentially providing precious seconds or minutes for people to seek shelter or evacuate dangerous areas. Similarly, for monitoring volcanic activity, a diverse array of ground-based instruments is employed to detect changes in the behaviour of volcanoes.

These sophisticated tools include tiltmeters to measure ground deformation, Geographical Positioning System (GPS) stations to track surface movements, and specialized gas sensors to analyze emissions. These instruments can detect subtle deformations, changes in gas composition and flux, and other precursory signals that may indicate an impending eruption. Through integrating data from these various sources, volcanologists can build a comprehensive picture of volcanic activity, enabling timely evacuation orders and preparedness measures to be implemented.<sup>(4)</sup>

In the realm of meteorological hazards, traditional approaches heavily rely on a network of meteorological observation stations, advanced radar systems, and satellite imagery. These interconnected systems collect vast amounts of data on atmospheric conditions, precipitation patterns, and storm trajectories, allowing for the issuance of warnings for severe weather events like hurricanes, tornadoes, and floods.<sup>(5)</sup> Weather balloons, surface weather stations, and Doppler radar installations work in concert to provide a three-dimensional view of the atmosphere, enabling meteorologists to forecast dangerous weather conditions with increasing accuracy.

While these traditional methods have proven invaluable in saving lives and protecting property, they often face challenges in terms of scalability, cost-effectiveness, and the ability to provide comprehensive coverage over vast and remote areas. The installation and maintenance of extensive ground-based networks can be prohibitively expensive, particularly in developing countries or regions with challenging terrain.<sup>(6)</sup> Additionally, the rapid onset of some disasters, such as flash floods or landslides, can outpace the capabilities of these ground-based systems, necessitating the integration of more advanced technologies to enhance detection and warning times.

Modern early warning systems are increasingly incorporating cutting-edge technologies such as remote sensing, high-resolution satellite imagery, and advanced computational models to address these challenges and push the boundaries of early warning capabilities.<sup>(7)</sup> Satellite-based systems, for instance, can provide near-real-time monitoring of vast regions, detecting subtle changes in land surface, ocean temperatures, and atmospheric conditions that may signal impending disasters (figure 1).

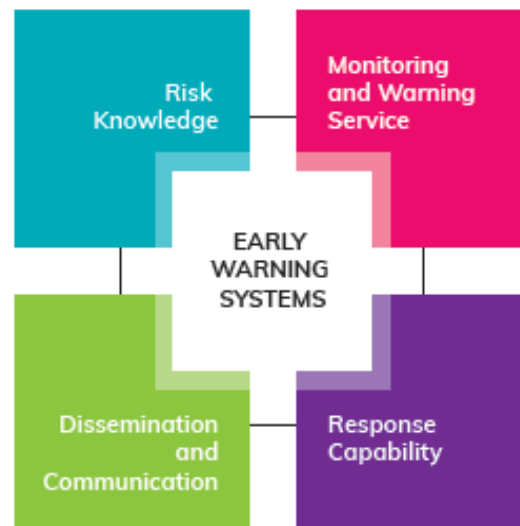


Figure 1. Components of early warning systems, adapted from UNISDR (2004)

The integration of artificial intelligence and machine learning algorithms into early warning systems has further revolutionized the field, allowing for rapid processing of enormous datasets and the identification of complex patterns that may elude human analysts. These advanced computational techniques can sift through historical and real-time data to identify trends and anomalies, potentially predicting disasters before traditional indicators become apparent. Moreover, the advent of the Internet of Things (IoT) and low-cost sensor technologies has enabled the creation of dense, distributed networks of monitoring devices that can complement traditional systems.

The objective of this study is to provide a comprehensive review of early warning systems (EWS) and traditional disaster detection approaches, evaluating their effectiveness, advancements, and integration with modern technologies. By analyzing various methodologies, including remote sensing, artificial intelligence, big data analytics, and IoT-based monitoring, the study aims to highlight the strengths and limitations of these systems in disaster risk reduction. Additionally, the research explores the role of traditional community-based warning mechanisms, their relevance in contemporary disaster preparedness, and the potential for hybrid models that integrate both conventional and technological solutions.

The study also identifies key challenges such as data interoperability, communication infrastructure, and accessibility of warning systems, offering insights into future trends and recommendations for enhancing disaster response strategies. Ultimately, the research seeks to contribute to the development of more inclusive, efficient, and data-driven early warning systems that can mitigate the impact of natural disasters and enhance community resilience.

## METHOD

This review study follows a systematic approach to identify, analyze, and synthesize relevant literature on early warning systems (EWS) and traditional disaster detection methods. The methodology consists of the following key steps:

### Research Design

A systematic literature review (SLR) methodology was employed to collect and analyze relevant studies. The research was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency and reproducibility.

### Data Sources and Search Strategy

Relevant literature was identified through electronic database searches, including Scopus, Web of Science, IEEE Xplore, and Google Scholar. The search terms included:

- “Early Warning Systems (EWS)”
- “Disaster detection methods”
- “Remote sensing in disaster management”
- “Artificial intelligence in early warning”
- “Traditional disaster detection approaches”

Boolean operators (AND, OR) were used to refine the search queries, ensuring comprehensive coverage of relevant studies.

Inclusion and Exclusion Criteria

Table 1. To ensure relevance and quality, the following inclusion and exclusion criteria were applied		
Criteria	Inclusion	Exclusion
Timeframe	Articles published from 2010 to 2024	Articles published before 2010
Language	English and Spanish	Non-English and non-Spanish articles
Study Type	Peer-reviewed journal articles, conference papers, and official reports	Non-peer-reviewed sources (e.g., blogs, editorials)
Relevance	Studies directly addressing EWS, disaster detection, or AI integration	Studies unrelated to early warning systems
Methodological Rigor	Studies with clear methodology and empirical evidence	Studies with unclear methodology or lacking empirical data

Screening and Selection Process

The study selection process followed a multi-stage approach:

- Initial Screening: Titles and abstracts of identified articles were reviewed for relevance.
- Full-Text Review: Selected articles from the initial screening were read in full to determine their suitability.
- Final Selection: Studies that met all inclusion criteria were included in the final review.

Data Extraction and Analysis

Key information from the selected studies was extracted, including:

- Study objectives
- Methodology used
- Findings related to early warning systems and disaster detection methods
- Challenges and future recommendations

A thematic analysis was conducted to synthesize findings, identifying common trends, gaps, and best practices.

Table 2. Summary of Article Selection Process	
Stage	Number of Articles
Initial search results	450
After title and abstract screening	230
After full-text review	120
Final articles included	85

Limitations and Ethical Considerations

This review may have limitations due to potential publication bias, exclusion of non-English studies, and rapid advancements in technology that may not be fully captured in the selected timeframe. All included studies were publicly available, and no human participants were involved, eliminating ethical concerns. This methodology ensures a rigorous and systematic approach to synthesizing knowledge on early warning systems and disaster detection methods.

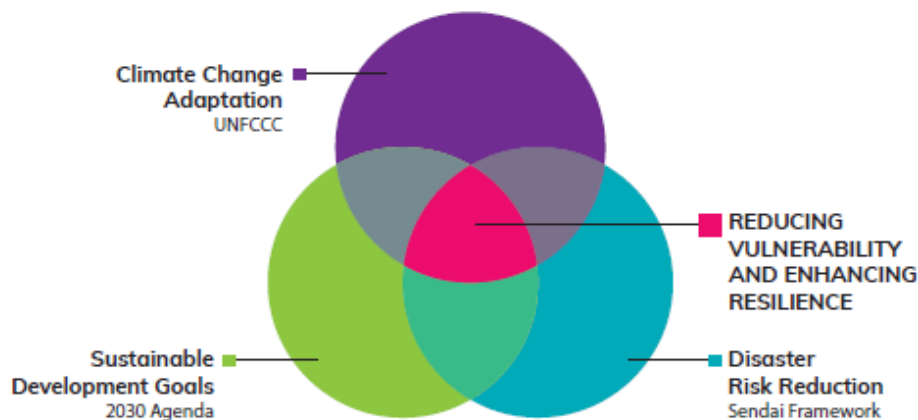
RESULTS AND DISCUSSION

Overview of Early Warning Systems

Early warning systems are critical components in disaster risk reduction efforts, designed to monitor and detect potential hazards and issue timely alerts to protect lives and minimize damage. At their core, these systems integrate various technologies and communication channels to provide advanced notice of impending disasters, enabling communities and authorities to take necessary preparedness and response actions.<sup>(1)</sup> Rather than relying solely on traditional ground-based monitoring networks, modern early warning systems leverage a range of cutting-edge technologies to enhance their effectiveness. Remote sensing and satellite imagery play a crucial role, offering improved spatial and temporal resolution for detecting precursory signals and tracking hazard development across vast geographic areas.

Numerical weather prediction models and advanced computational techniques are also employed to forecast and simulate potential disaster scenarios, providing valuable insights for decision-making.<sup>(8)</sup> The

dissemination and communication of warnings are critical components of these systems. Utilizing multiple channels, including sirens, mass media, and mobile notifications, early warning systems ensure that alerts reach relevant authorities, emergency services, and at-risk communities in a timely and effective manner. This enables the implementation of preparedness and response plans, such as evacuation procedures, emergency shelter activation, and coordination among various agencies and organizations (figure 2).<sup>(9)</sup>



**Figure 2.** Conceptual representation of the intersection between the SDGs, DRR, and CCA agendas 2015-2030, adapted from UNFCCC C (2017)

Early warning systems are designed to address a wide range of hazards, including meteorological events (hurricanes, cyclones, severe storms), hydrological hazards (floods, tsunamis, storm surges), geophysical hazards (earthquakes, volcanic eruptions, landslides), and environmental hazards (wildfires, air pollution, disease outbreaks). By providing actionable information and timely alerts, these systems empower communities and authorities to take proactive measures, reducing the loss of life, minimizing economic impacts, and enhancing overall resilience to disasters. An early warning system is an integrated set of monitoring devices and institutional arrangements to forecast and communicate potential hazards, their likelihood, and anticipated impacts in advance.<sup>(10)</sup> It is a major element of disaster risk reduction strategies aimed at saving lives and reducing economic and environmental losses.

### Goals of Early Warning Systems

The primary goals of early warning systems are to detect potential hazards, assess risks, and disseminate timely and meaningful alerts to enable proper preparedness and response by authorities and vulnerable communities. The key goals include:

1. Hazard Detection and Monitoring involves utilizing an array of advanced technologies such as high-resolution sensors, geostationary and polar-orbiting satellites, Doppler radar systems, autonomous drones, and interconnected IoT devices to continuously monitor precursors and meticulously track the development of potential hazards including severe storms, flash floods,<sup>(11)</sup> earthquakes, tsunamis, volcanic eruptions, wildfires, and other natural or man-made disasters, while also employing artificial intelligence algorithms to enhance detection accuracy and speed (figure 3).

2. Risk Analysis and Forecasting assesses the multifaceted risks posed by potential hazards through comprehensive data analysis and sophisticated modelling techniques to forecast their likely impacts on people, property, critical infrastructure, and the environment, incorporating historical data, real-time observations, and future projections to create detailed risk maps and vulnerability assessments that inform decision-making processes at various levels of governance.

3. Timely Warning Dissemination focuses on communicating accurate, actionable, and easily comprehensible warnings and alerts to authorities and at-risk populations through a diverse array of designated channels including mobile apps, SMS, social media platforms, radio broadcasts, television networks, and community sirens, ensuring sufficient lead time for response while tailoring messages to different audience needs and literacy levels,<sup>(12)</sup> and implementing redundant systems to guarantee widespread coverage.

4. Preparedness and Response Facilitation enables communities, local and national governments, and international aid agencies to develop and regularly update comprehensive contingency plans, conduct periodic drills and simulations, and take appropriate actions such as orderly evacuations, asset protection, or shelter-in-place procedures based on early warnings, while also establishing fully equipped emergency operations centers



and strategically pre-positioning essential supplies and resources to facilitate rapid and effective response.<sup>(13)</sup>



Figure 3. Goals of an EWS, adapted from UNISDR (2004)

5. Public Awareness and Education promote widespread awareness among diverse communities about potential hazards, their associated risks, and the appropriate responses to early warnings to minimize loss of life and property damage, utilizing a variety of educational tools including school curricula, community workshops, interactive digital platforms, and traditional media outlets to engage the public in ongoing disaster preparedness activities and foster a culture of resilience.

6. Inter-agency coordination facilitates seamless collaboration between scientific and technical agencies monitoring hazards and disaster management authorities at local, regional, and national levels, establishing clear communication protocols, information-sharing mechanisms, and a unified command structure for multi-hazard early warning and response operations to streamline decision-making processes and ensure effective early warning dissemination and coordinated emergency response efforts.<sup>(14)</sup>

7. Community Engagement and Participation focuses on actively involving local communities, including Indigenous groups and marginalized populations, in the design, implementation, and maintenance of early warning systems to ensure their cultural relevance, local applicability,<sup>(15)</sup> and long-term effectiveness, while also establishing community-based early warning networks that complement official systems, leverage local knowledge, and train community volunteers to act as first responders during emergencies.

8. Integration with Long-term Risk Reduction Strategies aligns early warning systems with broader disaster risk reduction initiatives, climate change adaptation strategies, and sustainable development goals, using early warning data and risk assessments to inform long-term urban planning, infrastructure development,<sup>(16)</sup> and environmental management decisions, while also promoting the integration of early warning considerations into sectoral policies such as agriculture, water management, and public health to enhance overall societal resilience.<sup>(17)</sup>

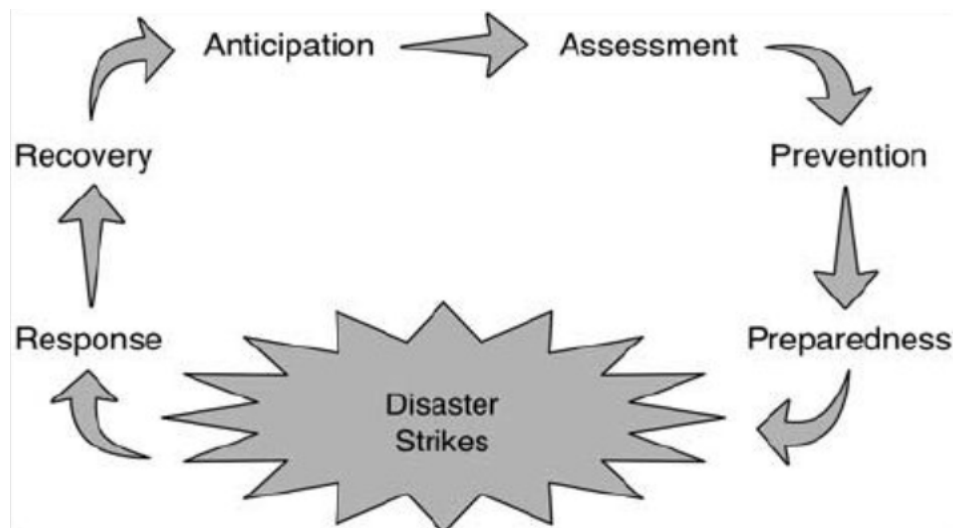
9. Accessibility and Inclusivity ensure that early warning systems and preparedness information are fully accessible to all segments of society, including people with various disabilities, the elderly, linguistic minorities,<sup>(18)</sup> and socially or economically marginalized groups, by developing multi-lingual warning messages, utilizing universal design principles in communication tools and evacuation facilities, and implementing gender-sensitive approaches in early warning dissemination and response planning to address the specific needs and vulnerabilities of diverse populations.<sup>(19)</sup> Ultimately, well-designed early warning systems save lives by providing critical lead time for communities to take protective actions before a hazardous event occurs.<sup>(20)</sup> They are a key investment in increasing a society's resilience to natural hazards and climate change impacts.<sup>(21)</sup>

### Traditional Methods for Disaster Detection

1. Meteorological Observation Networks: weather stations, rain gauges, and radar systems are deployed to monitor atmospheric conditions, and precipitation patterns, and track severe weather events like hurricanes, thunderstorms, and tornadoes. These networks are supplemented by weather balloons, satellite imagery, and sophisticated Doppler radar systems that provide real-time data on wind patterns and precipitation intensity. Advanced automated weather observing systems (AWOS) at airports offer minute-by-minute updates on visibility,<sup>(22)</sup> cloud height, and wind conditions. Additionally, networks of lightning detection sensors map strike locations and frequencies, aiding in severe thunderstorm prediction. Mobile weather stations mounted on vehicles allow for targeted data collection in storm-prone areas, while citizen science initiatives like personal

weather stations contribute to a denser network of observations, especially in urban environments.

2. **Seismic Networks:** arrays of seismometers are strategically positioned across seismically active regions to detect and locate earthquakes by analyzing patterns and magnitudes of seismic waves. These networks are complemented by borehole seismometers that reduce surface noise for more accurate readings, and ocean-bottom seismometers to monitor undersea seismic activity. Advanced array processing techniques allow for precise location of earthquake epicenters and depths. Continuous GPS stations work in tandem with seismometers to measure ground deformation over time. Interferometric Synthetic Aperture Radar (InSAR)<sup>(23)</sup> from satellites provides wide-area monitoring of surface deformation. Strong-motion accelerometers are deployed in urban areas to measure ground acceleration during significant earthquakes, informing building codes and engineering practices. Machine learning algorithms are increasingly used to differentiate between natural earthquakes and human-induced seismicity, such as from fracking operations (figure 4).



**Figure 4.** Machine learning algorithms representation

3. **Hydrological Monitoring:** stream gauges, water level sensors, and satellite altimetry are used to monitor water levels in rivers, lakes, and coastal areas, providing valuable data for flood forecasting and warning systems.<sup>(24)</sup> This is augmented by Doppler current profilers to measure water flow rates and velocities in rivers and estuaries. Remote sensing techniques, including LiDAR and multispectral imaging, are employed to map flood extents and assess soil moisture content over large areas. Acoustic Doppler Current Profilers (ADCPs) mounted on boats or stationary platforms provide detailed water column velocity data. Networks of piezometers monitor groundwater levels, crucial for understanding aquifer recharge and potential land subsidence. Water quality sensors measure parameters like temperature, pH, dissolved oxygen, and turbidity, offering insights into ecosystem health and pollution levels. Advanced hydrological models integrate these diverse data sources with weather forecasts and topographical information to predict flood scenarios with increasing accuracy.

4. **Volcanic Monitoring:** ground-based instruments like tiltmeters, GPS stations, and gas sensors are employed to detect changes in volcanic behavior, such as deformation, gas emissions, and seismic activity, which can indicate an impending eruption. This is complemented by thermal imaging cameras that detect temperature changes in volcanic craters and fumaroles. Infrasound sensors capture low-frequency acoustic waves generated by volcanic activity, providing early warning of explosions.<sup>(25)</sup> Satellite-based InSAR techniques measure subtle ground deformation over wide areas, while spectral analysis of satellite imagery can detect and quantify volcanic gas emissions.<sup>(26)</sup> Unmanned aerial vehicles (UAVs) equipped with gas sensors and thermal cameras allow for close-range monitoring of active vents without risking human lives. Continuous gravity measurements track magma movement beneath the volcano. Underwater hydrophones monitor seismic activity in submarine volcanoes. Advanced geochemical sampling techniques analyze the composition of gases and fluids emitted from volcanoes, providing insights into magma composition and eruption likelihood. Machine learning algorithms (MLAs) are increasingly used to process and analyze the vast amounts of data generated by these diverse monitoring systems, improving eruption forecasting capabilities.

### Constraints with Traditional Methods

While these traditional methods have proven invaluable, they often face several constraints and difficulties:

1. **Limited Spatial Coverage:** ground-based monitoring networks can be sparse, particularly in remote or inaccessible areas, leading to gaps in data collection and monitoring. This issue is exacerbated in mountainous

regions, dense forests, and vast desert landscapes where installing and maintaining equipment is logistically challenging. Oceanic areas, especially in the Southern Hemisphere, suffer from significant data gaps due to the scarcity of islands for station placement. In developing countries, limited resources often result in inadequate network density,<sup>(27)</sup> compromising the accuracy of regional forecasts and hazard assessments. Even in more accessible areas, urban development and private property restrictions can create ‘blind spots’ in monitoring networks. The uneven distribution of monitoring stations can lead to biased data sets, potentially skewing climate models and long-term trend analyses.

2. **Real-Time Data Acquisition Challenges:** data transmission from remote monitoring stations (RMSs) can be delayed, hindering real-time analysis and timely warning dissemination. This is particularly problematic in areas with limited telecommunications infrastructure or during severe weather events that can disrupt communication networks. Satellite-based data transmission, while offering wider coverage, can suffer from latency issues and bandwidth limitations. Power outages or equipment failures at remote sites can lead to critical data gaps during hazardous events. The sheer volume of data generated by modern, high-resolution sensors can overwhelm transmission capacities, necessitating on-site data compression or selective transmission,<sup>(28)</sup> potentially losing valuable information.

3. **High Costs and Maintenance Requirements:** establishing and maintaining extensive ground-based monitoring networks can be resource-intensive and costly, particularly in developing nations. The initial capital investment for high-quality monitoring equipment, such as weather radars or seismic arrays, can be prohibitively expensive for many countries.<sup>(29)</sup> Training and retaining skilled technicians for equipment maintenance and data interpretation presents another financial burden. In harsh environments, equipment may need frequent replacement due to accelerated wear and tear. Additionally, the need for redundancy in critical monitoring systems to ensure continuous operation further increases overall costs.<sup>(30)</sup> In many cases, the long-term funding required for sustained monitoring conflicts with short-term budget cycles and changing political priorities, leading to the deterioration of networks over time.

4. **Vulnerability to Environmental Factors:** monitoring equipment can be susceptible to damage or malfunction due to environmental factors like extreme weather, making data collection and analysis challenging. In coastal areas, salt spray can corrode sensitive instruments, while high humidity in tropical regions can lead to fungal growth on equipment. Extreme temperatures in both hot deserts and polar regions can cause electronic failures or affect sensor accuracy.<sup>(31)</sup> Wildlife interactions, from birds nesting on equipment to large animals damaging solar panels or antennas, can disrupt operations. Dust storms in arid regions can clog air intakes and abrade moving parts. Even relatively mild environmental factors like UV radiation or thermal expansion and contraction can degrade equipment over time.

5. **Limited Detection Capabilities:** some hazards, like flash floods or landslides, can occur rapidly, outpacing the detection capabilities of traditional monitoring systems. The initiation of these events often occurs at small spatial scales that may fall between the gaps of existing sensor networks. In the case of flash floods, the time between intense rainfall and flooding can be extremely short,<sup>(32)</sup> especially in urban areas with impervious surfaces or in steep mountain catchments. Landslides can be triggered by complex interactions of rainfall, soil saturation, and ground vibration that are difficult to capture with current sensor technology. Tornado formation often occurs at scales too fine for traditional weather radar to resolve in real-time. Earthquake early warning systems face challenges in accurately predicting ground motion in areas close to the epicenter due to the limited time between p-wave detection and destructive s-wave arrival. Volcanic eruptions can sometimes occur with little precursory activity detectable by current monitoring methods, especially for volcanoes with infrequent activity.<sup>(33,34)</sup> Additionally, cascading hazards where one event triggers another (e.g., an earthquake causing a tsunami) present complex detection challenges that may exceed the capabilities of systems designed to monitor individual hazard types.<sup>(35)</sup>

### Case studies and instances of effective traditional EWS

Despite their limitations, traditional early warning systems have proven instrumental in mitigating disaster impacts in various instances:

1. **The Pacific Tsunami Warning System:** this extensive network of seismic stations and ocean buoys has successfully provided early warnings for numerous tsunamis in the Pacific Ocean, including the 2004 Indian Ocean tsunami and the 2011 Tohoku earthquake and tsunami in Japan. The system utilizes a complex array of deep-ocean assessment and reporting of tsunamis (DART) buoys, which detect changes in sea level pressure indicative of passing tsunami waves. These buoys are complemented by coastal tide gauges and a network of seismometers that can rapidly detect and locate earthquakes with tsunami-generating potential. The system also incorporates advanced modeling capabilities that can predict tsunami wave heights and arrival times for coastal areas throughout the Pacific basin. In recent years, the warning system has been expanded to include improved communication protocols, allowing for faster dissemination of alerts to at-risk populations through multiple channels including text messages, sirens, and broadcast media. The system’s effectiveness



was particularly evident during the 2012 Haida Gwaii earthquake off the coast of Canada, where accurate and timely warnings were issued across the Pacific, demonstrating the improvements made since the 2004 Indian Ocean tsunami. Ongoing enhancements include the integration of GPS measurements for rapid earthquake characterization and the development of machine-learning algorithms to improve the speed and accuracy of tsunami forecasts.

2. The Mount Pinatubo Volcano Monitoring: continuous monitoring of seismic activity, ground deformation, and gas emissions at Mount Pinatubo in the Philippines provided critical warnings before the volcano's eruption in 1991, allowing for the evacuation of thousands of people. This monitoring effort, led by the Philippine Institute of Volcanology and Seismology (PHIVOLCS) in collaboration with the U.S. Geological Survey's Volcano Disaster Assistance Program, employed a multi-faceted approach to volcano surveillance. A network of seismometers detected the increasing frequency and magnitude of earthquakes beneath the volcano, indicating rising magma. Electronic distance measurement (EDM) and tiltmeter stations tracked subtle changes in the volcano's shape, revealing magma chamber inflation. Gas sampling and analysis showed increasing sulfur dioxide emissions, a key indicator of magmatic activity. The integration of these diverse data streams allowed scientists to accurately forecast the timing and scale of the eruption, leading to one of the most successful volcanic evacuations in history. The experience at Mount Pinatubo has since informed volcano monitoring practices worldwide, emphasizing the importance of comprehensive, real-time monitoring and international scientific cooperation. It also highlighted the critical role of effective communication between scientists, government officials, and the public in translating technical data into life-saving actions. The lessons learned from Pinatubo have been applied to subsequent eruptions, such as the 2010 Merapi eruption in Indonesia, where similar monitoring techniques enabled timely evacuations.

3. The Bangladesh Flood Forecasting and Warning System: this system, which integrates data from rain gauges, river gauges, and satellite imagery, has successfully provided early warnings for major flood events in Bangladesh, enabling communities to take protective measures. Developed in cooperation with international partners, the system utilizes a dense network of over 300 water level and rainfall monitoring stations across the country's major river basins. These ground-based observations are complemented by satellite-derived precipitation estimates and river width measurements, crucial for monitoring upstream conditions in neighbouring countries. Advanced hydrological models, incorporating digital elevation models and land use data, translate this information into flood forecasts with lead times of up to 10 days for some areas. The system's effectiveness was demonstrated during the severe floods of 2017, where accurate warnings allowed for pre-emptive evacuations and the protection of critical infrastructure. In recent years, the system has been enhanced with the inclusion of impact-based forecasting, which provides more specific information on the potential consequences of flooding for different sectors and communities. The integration of mobile phone technology has greatly improved the dissemination of warnings, with SMS alerts reaching millions of at-risk citizens. Community-based flood management committees have been established to interpret and act on these warnings at the local level. The success of this system has made it a model for other flood-prone countries, particularly in South Asia. Ongoing improvements include the incorporation of machine learning techniques to enhance forecast accuracy and the development of a flash flood guidance system for the country's hilly regions. The Bangladesh Flood Forecasting and Warning System (BFFWS) exemplifies how technological advancements, when combined with strong institutional frameworks and community engagement, can significantly reduce the impact of natural hazards in highly vulnerable areas. While traditional methods have their limitations, they remain an essential component of comprehensive early warning systems, often complemented by advanced technologies and improved data integration for enhanced disaster detection and preparedness.

4. Hurricane Maria - 2017: the network of weather stations, radar systems, and satellite imagery operated by the U.S. National Weather Service proved instrumental in tracking Hurricane Maria's path and issuing timely warnings to the Caribbean Islands and the U.S. mainland. These alerts facilitated evacuation efforts and preparedness measures, potentially saving lives in regions directly impacted by the powerful storm. The National Hurricane Center's cone of uncertainty forecast, updated every six hours, provided crucial information on the storm's projected path and intensity. Advanced hurricane hunter aircraft equipped with Doppler radar and dropsondes gathered vital data on wind speeds and pressure at various altitudes within the storm. Coastal buoys and tide gauges monitored storm surge levels, while river gauges tracked potential inland flooding. The integration of these diverse data sources into sophisticated numerical weather prediction models enabled meteorologists to forecast Maria's rapid intensification to Category 5 status.

5. Cyclone Amphan - 2020: the India Meteorological Department's network of weather stations, radar, and satellite data effectively tracked and provided early warnings for Cyclone Amphan, which struck the Bay of Bengal region. These alerts enabled the evacuation of millions of people in coastal areas of India and Bangladesh, significantly reducing the potential loss of life and demonstrating the life-saving capacity of traditional early warning systems. The Regional Specialized Meteorological Centre in New Delhi utilized a combination of polar-orbiting and geostationary satellites to monitor the cyclone's formation and intensification. Doppler weather

radars along the coastline provided high-resolution data on the storm's structure and precipitation patterns. Ocean buoys and coastal automated weather stations supplied real-time data on wind speeds, wave heights, and atmospheric pressure. The integration of these observations into numerical weather prediction models allowed for accurate forecasts of the cyclone's track and intensity up to five days in advance. The dissemination of warnings through multiple channels, including mobile apps, SMS alerts, and community radio, ensured widespread reach of the information.

6. Taal Volcano Eruption - 2020: ground-based monitoring instruments, such as seismometers, tiltmeters, and gas sensors, detected the precursory signals of the Taal Volcano eruption in the Philippines. The timely warnings from these traditional methods facilitated the evacuation of nearby areas and the implementation of safety measures, minimizing casualties and showcasing the critical role of these systems in volcanic hazard mitigation. The PHIVOLCS maintained a comprehensive monitoring network around Taal, including broadband seismometers that detected increasing volcanic tremors in the days leading up to the eruption. Ground deformation measurements using precise leveling and GPS techniques revealed subtle changes in the volcano's shape, indicating magma movement. Gas sensors recorded significant increases in sulfur dioxide emissions, a key indicator of rising magma. Lake water temperature and pH sensors detected changes in the crater lake, providing additional early warning signs. The integration of these diverse data streams allowed volcanologists to accurately assess the increasing likelihood of an eruption and raise the alert level accordingly. The rapid dissemination of these warnings through official channels and social media enabled the evacuation of over 300 000 people from the danger zone. This event highlighted the importance of maintaining long-term, multi-parameter monitoring systems on active volcanoes and the critical role of effective science communication in translating technical data into life-saving actions.

7. Floods in Pakistan - 2022: the Pakistan Meteorological Department's network of weather stations and rain gauges, complemented by satellite data, provided early warnings for the severe monsoon rains and flooding that affected large swaths of the country. These alerts allowed for the mobilization of relief efforts and the evacuation of affected communities, potentially saving countless lives and underscoring the significance of traditional systems in flood preparedness. The department's network of over 100 automated weather stations and 200 rain gauges across the country provided real-time data on precipitation levels and river flows. Satellite-based precipitation estimates from global meteorological agencies complemented ground-based observations, particularly in remote areas. Weather radar systems offer high-resolution data on the intensity and movement of rainfall systems. Hydrological models, incorporating digital elevation models and historical flood data, translated meteorological forecasts into flood predictions for major river basins. The Pakistan Space and Upper Atmosphere Research Commission (SUPARCO) provided satellite imagery for monitoring the extent of flooding and guiding relief efforts. Despite the unprecedented scale of the disaster, which inundated nearly one-third of the country, the early warnings issued by these traditional systems enabled the evacuation of hundreds of thousands of people from the most severely affected areas. The event also highlighted the need for further investment in flood monitoring and forecasting infrastructure, particularly in light of increasing climate change-related extreme weather events.

These recent examples illustrate the continued relevance and effectiveness of traditional early warning systems in detecting and providing timely alerts for various natural hazards, enabling preparedness and response efforts that ultimately save lives and minimize the devastating consequences of such events.

a. Earth observation and remote sensing for disaster monitoring Earth observation systems based on satellites (optical, radar, multispectral). Drones and other aerial platforms for gathering data; applications for tracking many types of disasters (such as landslides, wildfires, and volcanic activity).<sup>(35,36)</sup> These cutting-edge approaches leverage a diverse array of platforms, including satellites, drones, and aerial systems, to acquire critical data and provide situational awareness across various phases of natural disasters. Satellites play a pivotal role in Earth observation, employing optical, radar, and multispectral sensors to gather data on a global scale. Optical satellites capture high-resolution visible and infrared imagery, enabling the monitoring of events such as wildfires, vegetation changes, and floods. Radar satellites, utilizing synthetic aperture radar (SAR) technology, can penetrate cloud cover and acquire data in all weather conditions, proving invaluable for detecting ground deformation preceding earthquakes, monitoring sea ice, and identifying oil spills.

b. Multispectral imaging satellites collect data across multiple wavelengths, facilitating enhanced characterization and analysis of phenomena like vegetation health, soil moisture, and urban heat islands. Complementing satellite observations are UAVs and drones equipped with cameras and sensors.<sup>(33,35,36)</sup> These aerial platforms offer unparalleled flexibility, rapid deployment capabilities, and the ability to capture high-resolution imagery and data. They are particularly valuable for post-disaster damage assessments, mapping landslides, and monitoring volcanic activity.

c. The applications of Earth observation and remote sensing span a wide range of disaster types. Thermal infrared and optical data are utilized for wildfire hotspot detection, monitoring fire spread, and mapping burned areas. For landslides, InSAR and optical data enable slope stability analysis and landslide mapping. Optical and

radar data are instrumental in flood extent mapping, monitoring flood progression, and supporting emergency response efforts. Similarly, for earthquakes, InSAR techniques aid in surface deformation mapping, while high-resolution imagery supports damage assessment and emergency response coordination. The integration of multiple data sources, including optical, radar, and in-situ measurements,<sup>(37,38)</sup> facilitates comprehensive analysis and informed decision-making.<sup>(37,39)</sup> As these technologies continue to evolve, their integration into comprehensive disaster management strategies will become increasingly vital for enhancing resilience and mitigating the impacts of natural disasters worldwide.

### Crowdsourcing and Participatory Early Warning Systems

Crowdsourcing and participatory approaches have emerged as powerful complements to traditional early warning systems, leveraging the collective power of citizens as sensors to enhance disaster preparedness and response efforts. These approaches harness the ubiquity of mobile devices and the widespread use of social media platforms to crowdsource real-time data and situational awareness from the ground level.<sup>(40,41)</sup> Mobile applications and participatory sensing techniques have become increasingly popular tools for engaging communities in disaster monitoring and reporting. These applications allow citizens to report hazards, share observations, and document damage through text, photos, and videos. Some apps even leverage built-in sensors on mobile devices to crowdsource data on rainfall levels, seismic activity, and other environmental parameters (figure 5). Examples like the FEMA app and PetaJakarta for flood reporting demonstrate the potential of these participatory approaches to provide real-time data from the ground, fostering rapid situational awareness during emergencies.

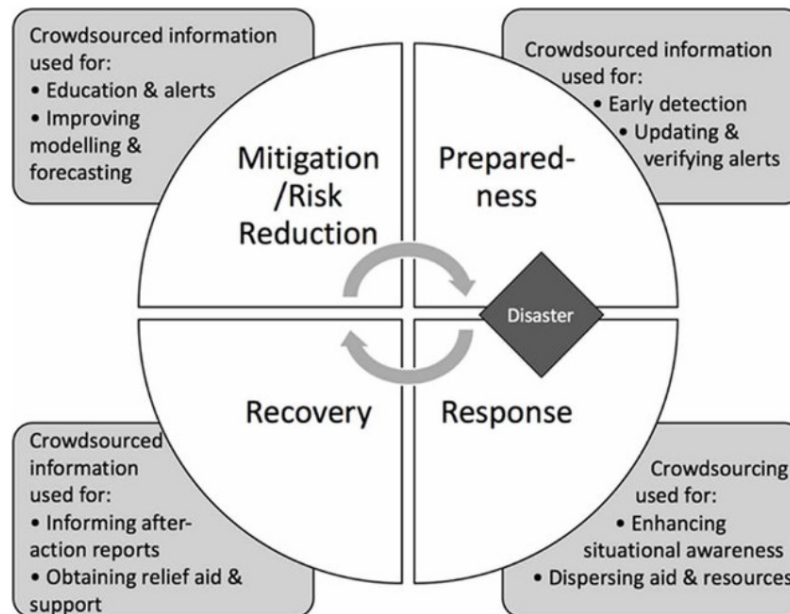


Figure 5. Crowd-sourcing phases<sup>(19,20)</sup>

Social media platforms have also emerged as valuable sources of crowdsourced data and citizen reporting during disasters. Platforms like Twitter and Facebook enable citizens to share updates, report events, and document damage through posts, images, and geotagged content. Sophisticated data mining and analysis techniques can extract valuable insights from this social media data, such as the detection of earthquakes, identification of affected areas, and monitoring of evolving situations. While these approaches offer the benefits of rapidly evolving data sources and wide reach, they also face challenges related to misinformation, information overload, and the complexity of data analysis.<sup>(42)</sup> Recognizing the complementary strengths of crowdsourced data and traditional monitoring systems, efforts are underway to integrate these diverse data sources for enhanced early warning capabilities. Crowdsourced data from citizens can augment traditional monitoring networks by providing localized, real-time data to fill spatial and temporal gaps in formal sensor networks. Data fusion techniques and advanced analytics enable the integration of multi-source data, enhancing situational awareness and enabling contextualized decision-making.

Examples of such integrated approaches include the USGS “Did You Feel It?” system, which combines citizen reports with seismic data for improved earthquake detection and impact assessment, and NASA’s FINDER (Finding Individuals for Disaster and Emergency Response) project, which leverages crowdsourcing to enhance search and rescue efforts. The benefits of crowdsourcing and participatory early warning systems are manifold.

<sup>(40)</sup> From a cost perspective, crowdsourcing offers a cost-effective way to expand monitoring capabilities, particularly in resource-constrained settings.<sup>(41)</sup> However, these approaches also face challenges that must be addressed. Data quality, reliability, and verification remain significant concerns, as crowdsourced data can be subject to errors, biases, and intentional misinformation. Privacy and ethical considerations surrounding the use of personal data must also be carefully navigated.<sup>(1,2)</sup> Despite facing challenges, the integration of crowdsourcing and participatory approaches with traditional early warning systems holds immense potential for enhancing disaster preparedness and response capabilities. Leveraging the collective power of citizens as sensors, these approaches can provide valuable real-time data, foster community engagement, and ultimately strengthen resilience in the face of natural hazards and climate-related disasters.

### Computational Modelling and Simulations

Computational modelling and simulations have emerged as invaluable tools in the realm of early warning systems, providing powerful capabilities for scenario analysis, risk assessment, and forecasting to enhance disaster preparedness and response efforts.<sup>(2,3)</sup> These advanced techniques leverage cutting-edge computational resources and sophisticated mathematical models to simulate complex phenomena and inform decision-making processes.

These models simulate the actions and interactions of individual “agents,” representing people or entities (figure 6), within a given environment. By incorporating factors such as demographics, social networks, and behavioural patterns, agent-based models can simulate evacuation scenarios, analyse evacuation routes, and optimize resource allocation during disasters.<sup>(4,43)</sup> Projects like ESCIDOC for tsunami evacuation and CEMNDRICS for hurricane response have demonstrated the potential of these simulations in testing preparedness plans and enhancing emergency response strategies.

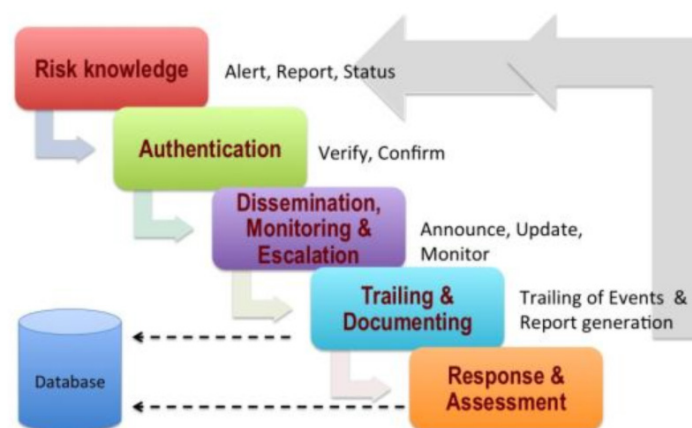


Figure 6. Community-based early warning system

In the realm of seismic hazard assessment, computational models play a crucial role in evaluating earthquake risks and potential impacts. These models utilize data on seismic activity, fault lines, and soil conditions to model hazards and assess the likelihood of earthquakes in different regions. Probabilistic seismic hazard analysis techniques, coupled with ground motion prediction equations, enable the estimation of shaking intensities and the assessment of potential losses.<sup>(5,6)</sup> Tools like FEMA’s HAZUS system leverage these models to evaluate the potential impacts of earthquakes, as well as other hazards, on communities, infrastructure, and economic activities. These insights inform mitigation efforts, emergency response planning, and resource allocation based on risk levels.

Numerical weather prediction (NWP) models have proven indispensable in forecasting severe weather events, such as hurricanes, cyclones, and floods. These mathematical models use current weather data, including observations from ground stations, radars, and satellites, to simulate and forecast future atmospheric conditions. High-resolution NWP models are critical for predicting the formation, trajectory, and intensity of severe storms, enabling timely warnings and preparedness measures.<sup>(2,6,7)</sup> Examples of such models include the HWRF for hurricane forecasting and the ECMWF global NWP system. Additionally, coupled atmospheric-hydrologic models are employed for flood prediction, combining meteorological data with hydrological models to forecast potential inundation areas.

While computational modelling and simulations offer significant benefits in terms of quantitative risk assessment, scenario evaluation, and lead time for warnings, they also face several challenges. Limitations in observational data for initializing models, uncertainties in model physics and parameterizations, and the



intensive computational requirements for high-resolution simulations can impact the accuracy and reliability of model outputs.<sup>(43)</sup> Furthermore, effectively communicating model uncertainties and probabilistic forecasts to decision-makers and the public remains a critical challenge. Despite these limitations, computational modelling and simulations have become indispensable components of modern early warning systems, providing valuable insights and decision support for disaster preparedness and response efforts.<sup>(7)</sup> As computational resources continue to advance and our understanding of complex phenomena improves, these techniques will play an increasingly vital role in enhancing our resilience to natural hazards and mitigating their impacts on communities worldwide.

### Early Warning Communication and Dissemination

Effective early warning communication is crucial for ensuring that people are informed and prepared to respond to impending disasters or emergencies. To achieve this, it is essential to employ a range of efficient communication techniques for warning distribution. One key approach is to utilize multiple communication channels and platforms to reach a wide audience. This can include traditional media such as television, radio, and newspapers, as well as modern digital platforms like social media, SMS messaging, and loudspeaker announcements. When crafting warning messages, it is important to ensure that they are clear, concise, and actionable, providing specific instructions on what individuals should do in response to the warning. Additionally, tailoring messages to specific target audiences, considering their unique needs, vulnerabilities, and preferred communication methods, can enhance the effectiveness of the warnings. Regular testing and exercising of communication systems is also crucial to ensure they are functioning properly and that people are familiar with how to respond to warnings. Establishing partnerships with community organizations, religious groups, and local leaders can further enhance the dissemination of warnings and encourage preparedness among the population.

However, several challenges and barriers can hinder effective warning communication.<sup>(44-46)</sup> These include a lack of coordination and standardization among different warning systems and agencies, technological limitations such as poor internet connectivity, language, and cultural barriers, and a lack of trust or understanding among the public about the importance of heeding warnings. To overcome these barriers, it is essential to develop clear protocols and procedures for coordinating warning messages across different agencies and platforms. Investing in robust and redundant communication systems, translating messages into multiple languages, and conducting public awareness campaigns can also help to improve the reach and effectiveness of early warning communication.

### Data Integration and Interoperability

Early warning systems have become increasingly sophisticated and integrated in recent years, adopting a multi-hazard approach to address a wide range of natural and man-made threats. These systems are designed to provide timely and accurate information about potential dangers, allowing communities and authorities to take preventive actions and mitigate the impact of disasters.<sup>(22)</sup> The current state of early warning systems reflects a complex interplay of technological advancements, data integration challenges, and the need for effective communication and response strategies.

At the core of modern EWS are four key components: risk knowledge, monitoring and warning services, dissemination and communication, and response capability. Risk knowledge involves understanding and mapping the hazards and vulnerabilities specific to a given area. This foundational element helps in designing appropriate monitoring systems and response plans. Monitoring and warning services form the technical backbone of EWS, utilizing a diverse array of data sources to detect and analyze potential threats in real time. These sources include remote sensing technologies like satellite imagery and aerial photography, ground-based sensors such as seismometers and weather stations, and increasingly, social media and crowdsourced data. The integration of these varied data streams presents significant challenges, particularly in terms of handling diverse data formats, ensuring real-time processing, and maintaining interoperability across different platforms and agencies.

The dissemination and communication component of EWS focuses on delivering timely and clear warning messages to all those at risk. Modern systems employ a multi-channel approach, utilizing SMS, radio, television, mobile apps, and traditional sirens to reach as wide an audience as possible. Advancements in technology have enabled more sophisticated communication strategies, such as geotargeted alerts based on user location and automated translation services for multilingual populations. However, the “last mile” problem - ensuring that warnings reach and are acted upon by the most vulnerable communities - remains a significant challenge.<sup>(47)</sup>

Technological advancements have played a crucial role in enhancing the capabilities of early warning systems. The application of artificial intelligence and machine learning has significantly improved prediction accuracy, allowing for more precise and timely warnings. The Internet of Things has expanded the reach and density of sensor networks, providing wider coverage and more granular real-time data. Cloud-based systems have addressed issues of scalability and accessibility, enabling better data storage, processing, and sharing



across different stakeholders.<sup>(48)</sup>

Data integration and interoperability are at the forefront of current efforts to improve early warning systems. The development of common data exchange formats, such as the Common Alerting Protocol (CAP), has facilitated better information sharing between different systems and agencies. Centralized data hubs and platforms are being established to consolidate information from various sources, while middleware solutions are being employed to ensure seamless data flow between disparate systems.<sup>(49)</sup> International cooperation plays a vital role in the effectiveness of early warning systems,<sup>(50,51)</sup> particularly for large-scale or transboundary hazards.<sup>(52)</sup> Global networks like the Global Earth Observation System of Systems (GEOSS) and regional cooperation frameworks such as the Pacific Tsunami Warning System demonstrate the importance of collaborative efforts in monitoring and responding to threats that span national borders.<sup>(53)</sup>

The development of more personalized warning systems is another emerging trend, leveraging advances in mobile technology and data analytics to provide individuals with tailored risk information and guidance. This approach has the potential to significantly improve the relevance and effectiveness of warnings but also raises important questions about privacy and data security. Current early warning systems represent a complex ecosystem of technologies, data sources, communication channels, and human factors.<sup>(54,55)</sup> As the nature of risks evolves and new threats emerge, early warning systems must continue to adapt and improve, always with the ultimate goal of protecting lives and livelihoods from the impacts of disasters.

## Resilient early warning systems

### *Providing redundancy and backup systems*

Implementing multiple data collection methods is crucial for a resilient early warning system. This approach ensures that if one source of information fails or becomes unreliable, others can still provide the necessary data to make informed decisions. For instance, a comprehensive system might combine satellite imagery for broad area coverage, ground-based sensors for precise local measurements, aerial surveys for detailed visual assessments, and crowdsourced information from citizens for real-time situational awareness. Each of these methods has its strengths and limitations, and by using them in combination, the system can maintain a more complete and accurate picture of potential hazards.<sup>(56,57)</sup>

The goal is to create a redundant system where if one communication method fails, others can still effectively deliver the warning message.<sup>(55,57,58)</sup> Establishing backup power sources is a critical component of system resilience, particularly in disaster-prone areas where power outages are common. Generators can provide immediate backup power during short-term outages, ensuring that critical systems remain operational. For longer-term resilience, especially in remote locations, solar panels offer a sustainable solution.<sup>(59,60)</sup> These renewable energy sources can be coupled with battery storage systems to provide continuous power even during extended grid failures.<sup>(61,62)</sup> This approach ensures that if one data center is compromised due to a natural disaster, cyber attack, or other disruption, the system can quickly fail over to an unaffected location.<sup>(63,64)</sup> Using cloud-based solutions for data storage and processing provides numerous benefits for system resilience. Cloud services offer scalability, allowing the system to rapidly expand its capacity during crisis events when demand for information spikes.<sup>(56,65)</sup> They also provide improved accessibility, enabling authorized users to access critical data and tools from various locations. Furthermore, reputable cloud providers typically have their own robust backup and redundancy systems, adding an extra layer of protection for the EWS data and functionality.

### **Building capacity and involving the community**

Conducting regular training programs for system operators is fundamental to maintaining a high level of readiness and effectiveness. These programs should cover both technical aspects of system operation and decision-making processes in high-pressure situations. Educating the public on warning signals and appropriate responses is a critical but often overlooked aspect of EWS effectiveness. This education should be comprehensive, covering the meaning of different warning levels, the channels through which warnings will be disseminated, and specific actions to take in response to warnings.<sup>(59,66)</sup>

Engaging local communities in system design and implementation is crucial for ensuring that the EWS is tailored to local needs, constraints, and cultural contexts. This participatory approach might involve community consultations during the planning phase, incorporating local knowledge about hazards and vulnerabilities, and adapting warning messages and dissemination methods to local languages and customs.<sup>(61,66)</sup>

Developing volunteer networks for monitoring and reporting can significantly enhance the coverage and granularity of data collection. Local volunteers, when properly trained, can provide real-time ground truthing of sensor data and early observations of developing situations.<sup>(56,63)</sup> These networks can be particularly valuable in remote areas where technological infrastructure may be limited. Implementing feedback mechanisms for continuous improvement allows the system to evolve based on real-world performance and changing needs.<sup>(67,68)</sup> This might include post-event surveys to assess the effectiveness of warnings, community feedback sessions to gather insights on system usability, and detailed analysis of system performance during both actual events.<sup>(69,69)</sup>

### Guaranteeing the resilience of EWS infrastructure:

Using robust, weather-resistant equipment for outdoor installations is crucial for maintaining system functionality in harsh conditions.<sup>(50,68,69)</sup> Equipment should be designed to withstand the specific environmental challenges of its location, whether that's extreme heat, cold, humidity, or saltwater exposure. Implementing cybersecurity measures is increasingly important as EWS becomes more reliant on digital technologies.<sup>(50,52)</sup> Regularly maintaining and updating system components prevents degradation of performance over time and ensures that the system benefits from technological advancements. This includes both hardware maintenance, such as replacing worn parts and calibrating sensors, and software updates to patch vulnerabilities and add new features. This might involve cloud-based resources that can be rapidly scaled up, or distributed systems that can share load across multiple nodes.

The system should be designed with peak demand in mind, ensuring it can maintain performance under stress. Establishing clear protocols for system recovery after failures ensures that the EWS can be brought back online quickly and in a coordinated manner.<sup>(59,62)</sup> These protocols should define responsibilities, procedures, and priorities for different failure scenarios. They should be documented, regularly reviewed, and practiced to ensure all team members are familiar with recovery processes.<sup>(4,6)</sup> Conducting regular risk assessments of EWS infrastructure helps identify vulnerabilities before they lead to failures. The results of these assessments should feed into a continuous improvement process for the EWS.<sup>(2,68)</sup>

### Future Trends and Emerging Technologies

#### *Internet of Things (IoT) and sensor networks*

The widespread deployment of interconnected sensors is revolutionizing early warning systems. This trend involves the installation of a vast array of sensors across diverse environments, from urban areas to remote wilderness locations. These sensors can monitor a wide range of parameters, including temperature, humidity, air quality, water levels, seismic activity, and more.<sup>(15,19)</sup> The interconnected nature of these devices allows for seamless data sharing and integration, creating a comprehensive monitoring network. Real-time data collection from diverse sources is a key advantage of IoT-based systems. Unlike traditional monitoring methods that might rely on periodic manual readings or satellite passes, IoT sensors can continuously stream data. This constant flow of information enables early warning systems to detect changes and potential threats as they develop, rather than after the fact. The diversity of data sources also provides a more holistic view of environmental conditions, improving the accuracy and reliability of warnings.

Enhanced spatial and temporal resolution of monitoring is another significant benefit.<sup>(17)</sup> With a dense network of sensors, it's possible to capture fine-grained data across large areas. This high-resolution monitoring can reveal localized phenomena that might be missed by more sparse observation networks. For example, a dense network of rain gauges and stream monitors can provide detailed information about rainfall patterns and flood risks at a neighbourhood level.

Low-cost, energy-efficient sensor technologies are making it feasible to deploy large-scale sensor networks. As the cost of sensors continues to decrease and their energy efficiency improves, it becomes economically viable to install and maintain extensive monitoring networks.<sup>(31)</sup> Many modern sensors can operate for extended periods on battery power or small solar panels, allowing for deployment in remote or inaccessible areas. Improved early detection of environmental changes is a crucial outcome of IoT sensor networks. By continuously monitoring multiple parameters, these systems can detect subtle shifts that might indicate an impending disaster.<sup>(33,34,36)</sup> For instance, a network of seismic sensors can detect minor tremors that might precede a major earthquake or a series of temperature and humidity sensors in a forest can identify conditions conducive to wildfires before they start.

However, the implementation of IoT and sensor networks also faces several challenges.<sup>(32)</sup> Data management is a significant issue, as these networks generate enormous volumes of data that need to be transmitted, stored, and analyzed efficiently. Privacy concerns arise when sensors are deployed in populated areas, necessitating careful consideration of data anonymization and protection measures. Security is another critical concern, as interconnected devices can be vulnerable to hacking or tampering, potentially compromising the integrity of the early warning system.

### Artificial intelligence and machine learning for disaster detection:

Pattern recognition in complex datasets is one of the primary applications of AI and machine learning in disaster detection. These technologies can analyze vast amounts of data from multiple sources to identify patterns that might be indicative of impending disasters. For example, machine learning algorithms can analyze historical weather data alongside current conditions to recognize patterns that have previously led to severe storms or floods.<sup>(37,38)</sup> AI systems can integrate data from various sources, including historical records, real-time sensor data, and satellite imagery, to create more accurate and timely predictions.

Automated anomaly detection and alert generation is a crucial applications of AI in early warning systems.

<sup>(39,40)</sup> Machine learning algorithms can be trained to recognize “normal” conditions across various parameters and quickly identify deviations that might indicate a developing threat. This automation can significantly reduce response times, allowing for earlier warnings and potentially saving lives. Natural language processing for social media monitoring is an emerging trend that leverages the power of crowd-sourced information. AI systems can analyze social media posts in real-time to detect mentions of unusual events or emerging disasters. This can provide valuable early indicators of developing situations, especially in areas with limited sensor coverage.<sup>(41)</sup>

Computer vision for satellite and drone imagery analysis is becoming increasingly important in disaster detection and monitoring. AI algorithms can rapidly analyze large volumes of visual data to detect changes in landscape, vegetation, or infrastructure that might indicate increased risk or ongoing disasters. For example, computer vision can be used to automatically detect deforestation, coastal erosion, or damage to buildings after an earthquake. However, the use of AI and machine learning in disaster detection also faces challenges.

<sup>(47,53)</sup> Model interpretability is a significant concern, as the complex algorithms used in AI systems can sometimes operate as “black boxes,” making it difficult for human operators to understand and trust their decisions.

<sup>(50)</sup> Bias mitigation is another crucial challenge, as AI systems can inadvertently perpetuate or amplify biases present in their training data, potentially leading to unequal or unfair risk assessments.

### **Big data analytics and real-time data processing:**

Integration of diverse data sources, both structured and unstructured, is a key aspect of big data analytics in early warning systems. This involves combining data from traditional sensors with information from social media, satellite imagery, historical records, and more. The challenge lies in harmonizing these diverse data types to create a coherent and comprehensive view of potential risks.<sup>(70)</sup> High-performance computing for rapid analysis is essential to process the vast amounts of data generated by modern early warning systems. This might involve the use of powerful server clusters or cloud computing resources to perform complex calculations and run sophisticated models in near-real-time.

The goal is to transform raw data into actionable insights as quickly as possible.<sup>(71)</sup> Stream processing for continuous data evaluation allows early warning systems to analyze data as it’s generated, rather than in batches. This approach enables the system to detect and respond to changing conditions almost instantly.<sup>(72)</sup> For example, a stream processing system could continuously analyze data from river level sensors, weather forecasts, and upstream conditions to provide real-time updates on flood risks.

Advanced visualization techniques for decision support are crucial for translating complex data into easily understandable formats. This might include interactive maps, 3D models, or augmented reality interfaces that allow decision-makers to quickly grasp the current situation and potential risks. Effective visualization can significantly improve the speed and quality of decision-making during critical situations. Predictive analytics for risk assessment leverages historical data and current conditions to forecast potential future scenarios. This can help emergency managers anticipate where resources might be needed most urgently or identify areas at the highest risk for specific types of disasters.<sup>(70)</sup> Predictive analytics can also be used to model the potential impacts of different response strategies, aiding in resource allocation and planning.

However, big data analytics and real-time processing also face several challenges.<sup>(51)</sup> Data quality is a significant concern, as the reliability of insights depends on the accuracy and completeness of the input data. Ensuring data quality across diverse sources can be complex and resource-intensive. Scalability is another challenge, as systems need to be able to handle ever-increasing volumes of data without compromising on processing speed or accuracy. Finally, the computational resources required for real-time big data analytics can be substantial, requiring significant investment in hardware and software infrastructure.

### **Case Studies and Best Practices**

Early warning systems have been the subject of numerous case studies, offering valuable insights into effective development, implementation strategies, and deployment across various hazard types. One notable example is Hilton’s study on developing people-centred EWS in the Philippines. Their research highlighted the importance of engaging local communities from the outset, integrating indigenous knowledge with scientific data, and using simple, locally appropriate technologies. The authors found that this participatory, bottom-up approach led to high community buy-in and effective evacuations during subsequent hazards, emphasizing the importance of viewing EWS as a social process rather than just a technological one. In terms of lessons learned and obstacles encountered, Bernard and Titov’s 2015 study on tsunami early warning systems in the Indian Ocean provided valuable insights.

They identified key lessons such as the need for redundant communication systems, the importance of public education and regular drills, and the value of integrating EWS with broader disaster risk reduction efforts. However, they also noted significant obstacles, including an initial lack of regional cooperation and data sharing, challenges in “last mile” warning dissemination to remote areas, and difficulties in sustaining political and financial support over time.

Successful EWS deployments across various danger types were exemplified in the study of Shanghai's integrated multi-hazard early warning system. This comprehensive approach, covering hazards such as typhoons, floods, and heatwaves, demonstrated several key successes. These included a centralized multi-hazard monitoring and warning center, customized warning thresholds for different city zones, multi-channel warning dissemination, linkage with emergency response plans for different sectors, and regular system testing and public awareness campaigns. The authors found that this integrated approach led to significant reductions in disaster impacts over time, highlighting the value of combining warnings for different hazard types into a unified system.

The importance of international and national policies in shaping effective EWS, highlighting strategies from the Hyogo Framework for Action 2005-2015 and the Sendai Framework for Disaster Risk Reduction 2015-2030, which advocate for people-centered EWS to enhance disaster management operations. The Sendai Framework aims to make disaster risk information widely available through Multi-Hazard Early Warning Systems to build global community resilience, while the WMO promotes impact-based forecasts and risk-informed warnings to effectively communicate hazard impacts.

Key lessons learned from EWS development include addressing the inherent uncertainty in forecasting and improving the communication of warnings. For instance, Australia's Total Flood Warning System now emphasizes human elements like comprehension and trust, and the National Fire Danger Rating System is being revamped to improve community awareness and trust in warnings, addressing issues like warning fatigue. Successful deployments in Australia include the national bushfire warning system, which categorizes fire danger into levels such as Severe, Extreme, and Catastrophic. However, challenges remain in public perception and response, as many people did not perceive themselves at risk during the 2011-2014 bushfires and adopted a 'wait and see' approach. The new National Fire Danger Rating System aims to address these issues by enhancing scientific accuracy and communication strategies to increase public confidence and prompt appropriate behaviours during fire events.

## CONCLUSION

This study highlights the critical role of early warning systems (EWS) in disaster risk reduction, emphasizing both traditional and modern approaches. Traditional methods, such as meteorological observation networks, seismic monitoring, and community-based warning mechanisms, have long been essential in detecting and responding to natural hazards. However, they often face challenges related to spatial coverage, real-time data acquisition, and technological limitations.

The integration of advanced technologies—such as remote sensing, artificial intelligence, big data analytics, and IoT—has significantly improved the accuracy, speed, and reliability of disaster detection and response. These innovations enhance predictive capabilities, facilitate real-time monitoring, and strengthen situational awareness. Despite these advancements, challenges persist in data interoperability, communication infrastructure, and the accessibility of warning systems, particularly in remote and under-resourced regions.

A hybrid approach that combines traditional knowledge with modern technologies offers the most effective pathway for enhancing disaster preparedness and response. This study underscores the importance of interdisciplinary collaboration among governments, researchers, and communities to build more robust, inclusive, and data-driven EWS. Additionally, ensuring clear and actionable warning dissemination remains a crucial factor in reducing disaster impacts.

Moving forward, efforts should focus on strengthening infrastructure, improving data integration, and enhancing community engagement in disaster risk management. As climate change continues to intensify the frequency and severity of natural disasters, investing in resilient, adaptable, and people-centered early warning systems will be essential for safeguarding lives and minimizing economic losses.

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