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Best Practice Policy Document on Disasters Risks Reduction and Early Warning Systems

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Executive Summary

Given the rising frequency and severity of disasters globally, it is imperative to establish best practices for Disaster Risk Reduction and Early Warning Systems.

In the Islamic world, the demand for effective DRR and Early Warning Systems is particularly pressing due to heightened vulnerability to natural disasters. Many Islamic countries face limited resources, insufficient infrastructure, and socio-economic challenges that exacerbate the impact of disasters. To address these vulnerabilities, it is essential to develop and promote best practices tailored to the unique needs of these regions.

Disasters in the Islamic world, such as floods, droughts, earthquakes, and cyclones, highlight the urgent need for proactive measures to mitigate their impact. These events can worsen vulnerabilities, disrupt development, and cause long-term socio-economic setbacks. The 2030 Agenda for Sustainable Development and the 9th Environment Ministers Conference of the Islamic World emphasize the importance of DRR and resilience-building through sustainable, inclusive strategies.

The EM-DAT (The International Disaster Database) data shows that floods are particularly prevalent natural disasters, driven by factors such as climate change, extreme weather, and water management challenges. Earthquakes rank second, reflecting significant risks in tectonically active regions, while storms, influenced by shifting weather patterns, rank third.

The EM-DAT analysis highlights the diverse disaster risks and significant impacts across ICESCO member countries, with nations like Indonesia, Pakistan, Bangladesh, and Iran facing frequent floods, earthquakes, and storms. These recurring disasters result in substantial human and economic losses, emphasizing the need for targeted preparedness, resilient infrastructure, and effective Early Warning Systems. Strengthening collaboration among ICESCO member countries and partnering with international disaster relief organizations is essential for improving disaster response and recovery in high-risk regions.

The proposed project aims to enhance disaster resilience by developing a Best Practice Policy Document on DRR and Early Warning Systems tailored to the unique challenges of Islamic countries. By addressing issues like limited institutional capacity, inadequate early warning infrastructure, and constrained resources, the project seeks to identify and promote feasible, context-specific best practices for disaster preparedness, response, and recovery.

In addition, the lessons learned from the COP29 emphasized climate finance, tripling commitments to developing countries to USD 300 billion annually by 2035 and aiming for USD 1.3 trillion from public and private sources. Agreements on carbon markets will expedite emission reductions, while transparent reporting and adaptation strategies were encouraged. Gender equality was prioritized, with plans for a new action plan at COP30. Stakeholder empowerment under Action for Climate Empowerment (ACE) was also reinforced. COP16 focused on addressing land degradation and drought with significant financial commitments and new initiatives, though challenges remain in formulating a unified global strategy.

This report highlights key opportunities and recommendations for DRR and Early Warning Systems. Data gaps in low- and middle-income countries hinder disaster preparedness, emphasizing the need for better data collection and sharing. Technological innovations like Artificial Intelligence (AI), Internet of Things (IoT), remote sensing and satellites, quantum computing and robotics can enhance disaster forecasting and Early Warning Systems. Integrating climate adaptation and DRR is critical to addressing climate-driven risks. Data-driven resilience planning and improved risk communication can enhance disaster response and preparedness.

DRR funding is often reactive, limiting preventive measures and failing to reach the most vulnerable areas. Policymakers should advocate for increased, proactive funding and equitable resource allocation. Data-driven decision support systems can help ensure efficient distribution of DRR funds to areas with the greatest need. Proactive funding, stronger policy enforcement, and public-private partnerships can improve DRR efforts.

Community engagement and inclusivity are essential for effective DRR, alongside expanded Early Warning Systems in underserved areas. Many DRR and Early Warning Systems initiatives do not adequately involve local communities, indigenous knowledge, or marginalized groups, limiting the effectiveness and sustainability of these efforts. Policymakers can use this report to promote inclusive DRR strategies that actively engage diverse communities, ensuring that DRR actions are context-specific, community-driven and promoting inclusivity.

1. Introduction

Effective Early Warning Systems are crucial for disaster preparedness and risk management, helping to save lives and reduce the impact of disasters. For these systems to be successful, they must engage at-risk communities directly, promote public awareness and education on risks, ensure timely and effective dissemination of warnings, and support ongoing preparedness to enable rapid response when needed (Kovalevski, 2013). Disasters can be prevented or mitigated by reducing hazards (where human activity contributes), lowering community exposure (e.g. through evacuation or land use planning), or decreasing vulnerability (e.g. by building resilient infrastructure). These measures require informed policy decisions based on accurate data about hazards, exposure, and vulnerabilities. Early Warning Systems are a crucial policy tool for reducing risks, especially where other protections are not feasible (UNDRR, 2016). Advances in weather forecasting, such as improved computing power, satellite observation, and convection-permitting models (Clark et al., 2016), have enhanced the accuracy and lead times of forecasts, making early warnings more reliable. However, directly predicting specific hazards remains challenging due to their extreme and sensitive nature. Coupled environmental models, such as those for ocean waves (Rogers et al., 2005), storm surges (Flowerdew et al., 2013), river flow (Smith et al., 2016), and wildfire risk (Dowdy et al., 2010), along with new machine learning techniques, are aiding in reducing the risks of climate related disasters.

Once the impacts of hazards are identified, appropriate policy responses, including Early Warning Systems, need to be considered. In developed countries, recurring hazards are often managed through protective measures, while less frequent hazards are addressed with warnings. However, it may be more effective to issue warnings when people can easily avoid hazards or implement protection when it is cost-effective. In developing countries, limited budgets often make early warnings the only feasible mitigation strategy. The effectiveness of an early warning depends on feasible mitigation actions that align with the social and cultural environment, as well as the available science and technology (Eiser et al., 2012). Aparicio-Effen et al. (2018) described an Early Warning Systems for heavy rain and landslides established in La Paz, Bolivia, following a major landslide in 2002. The city's geological situation and climate, combined with extensive building on hazardous slopes, had created a high-risk environment. In response, the Municipality of La Paz set up an Early Warning Operations Centre (EWOC) within the Special Office for the Integrated Management of Risks (DEGIR) to coordinate early warnings and emergency actions. Although EWOC could not predict specific landslides, it effectively facilitated preparedness, preventing any fatalities during a major landslide in 2011.

Effective Early Warning Systems must include monitoring capabilities and communication mechanisms for emergency responders. These systems enable early response, allowing protective actions to be taken before hazardous conditions occur. They must also incorporate a predictive element, ranging from general probabilities of hazards to detailed information about intensity, timing, and location (Golding et al., 2019). In addition, early warnings require not only hazard predictions but also the integration of exposure and vulnerability data to assist communities in making informed decisions (Anderson et al., 2015). This process involves multiple organisations and experts, making communication between different technical domains crucial to prevent information loss. Once potential actions to mitigate the hazard have been identified, and the necessary information is available, a system must be established to communicate this information to decision makers, including the public (Mileti & Sorensen, 1990). Typically, evacuation or shelter warnings come from emergency managers, who usually rely on data from the state weather service. The media plays a crucial role in disseminating this information and may be required to use an authoritative national source (Sciences et al., 2018). However, individuals may receive information from various public and private agencies, potentially leading to confusion. Therefore, clearly identifying the official source of information is essential to avoid miscommunication (Maxwell, 2003). In developing countries, limited fixed communication infrastructure often hampers the delivery of warnings to large populations. However, this challenge is increasingly being addressed through mobile phone technology. Van Vark et al. (2012) highlighted that the widespread use of mobile phones in Africa and India has proven effective for disseminating weather and climate information, not only due to their extensive reach but also because they enable trusted entities, such as local NGOs, to deliver the messages. With an authoritative source and a means of delivery in place, the communication chain for translating weather monitoring and forecasts into protective action resembles the conceptual model in Figure 1. Each organisation involved measures its own success, but these metrics rarely connect directly to successful impact mitigation. To optimise the warning system and ensure effective investment, it is crucial to identify which components or combinations within this chain contribute most to reducing disaster risk.

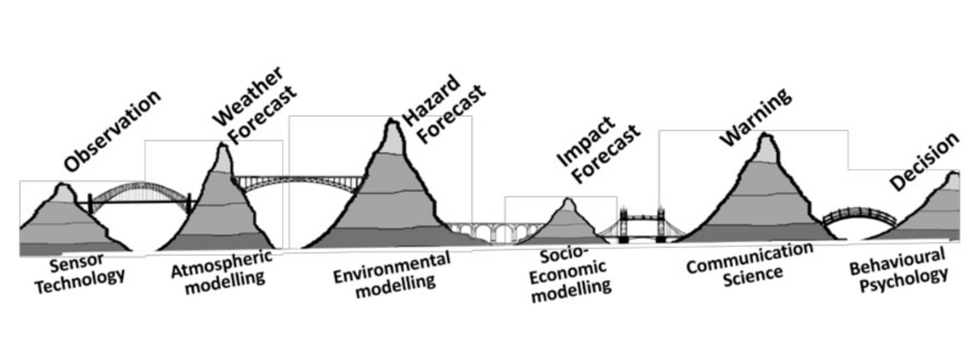

Figure 1: Conceptual value chain for weather hazard warnings, showing peaks of expertise, communication gaps ("valleys of death"), and value lost at each stage (Golding et al., 2019).

2.

Early Warning Systems

An Early Warning Systems involves the capabilities needed to generate and disseminate timely and relevant information, enabling individuals, communities, and organizations to prepare for hazards and take action in time to reduce harm or loss. An end-to-end Early Warning Systems connects those receiving warnings with those monitoring and tracking hazard information. It includes both the consistent gathering and processing of information to create alert messages and the effective transmission of these alerts to those at risk (Kovalevski, 2013). Early Warning Systems aim to reduce disaster risk by providing advanced notice of potential hazards, allowing individuals, communities, and organizations to take timely actions to minimize the impact of disasters (Garcia & Fearnley, 2012).

Early Warning Systems support planning and preparedness by providing information on potential hazards, enabling decision-makers to develop response plans, allocate resources, and take measures to reduce disaster impact (Thomalla & Larsen, 2010). Recently, the concept of multi-hazard Early Warning Systems (MHEWS) has gained international attention. These systems address multiple hazards or impacts, whether they occur individually, simultaneously, in a cascading manner, or cumulatively over time, considering their potential interrelated effects (Kovalevski, 2013; Šakić Trogrlić et al., 2022). A multi-hazard Early Warning Systems enhances the efficiency and consistency of warnings by using coordinated mechanisms and capacities to address multiple hazards. It involves multiple disciplines to ensure accurate and up-to-date identification and monitoring of various hazards (UNDRR; Union, 2023).

2.1. Global Initiatives and Investments

The UN unveiled an Action Plan for the Early Warnings for All at COP27 in Sharm el-Sheikh, committing $3.1 billion over five years to establish global Early Warning Systems for extreme weather, at a cost of only 50 cents per person annually. This initiative aims to provide universal early warning coverage by 2027, prioritizing vulnerable populations. The plan outlines measures for disaster risk knowledge, forecasting, preparedness, and communication, addressing the increasing frequency and severity of weather-related disasters driven by climate change. Despite the urgency, half of the world's countries lack Early Warning Systems, with the greatest need in developing nations. This initiative has garnered support from world leaders, international organizations, and the tech sector, emphasizing the critical role of modern science, data sharing, and community engagement in saving lives and minimizing economic losses.

The plan indicates key foundational financing mechanisms to support the achievement of the goal, including a framework developed by the Climate Risk and Early Warning Systems (CREWS) Initiative and the Green Climate Fund and the operationalization of the Systematic Observations Financing Facility (SOFF). The estimated new targeted investments of $3.1 billion over five years are divided among the four key pillars of MHEWS:

1. Disaster Risk Knowledge ($374 million): Systematically collect data and undertake risk assessments on hazards and vulnerabilities.
2. Detection, Observation, Monitoring, Analysis, and Forecasting ($1.18 billion): Develop hazard monitoring and early warning services.
3. Preparedness and Response ($1 billion): Build national and community response capabilities.
4. Dissemination and Communication ($550 million): Communicate risk information to ensure it reaches all who need it and is understandable and usable.

The Early Warnings for All initiative, led by the World Meteorological Organisation (WMO), aims to ensure global protection from hazardous environmental events by 2027, particularly addressing gaps in the least developed countries (LDCs) and small island states, where a third of the population lacks access to these critical systems. Central to this effort, WMO leads the initiative's second pillar, focusing on detection, observation, monitoring, analysis, and forecasting. Early Warning Systems are highly reliant on worldwide data-sharing mechanisms. Through advanced supercomputing modelling centres, data from the Earth's surface and space are integrated, allowing precise simulations of global weather patterns, and enabling National Meteorological and Hydrological Services (NMHSs) to provide accurate forecasts to communities. Despite progress, critical gaps persist, with only a third of WMO Members reporting multi-hazard monitoring and forecasting capabilities. Many countries lack 24/7 alert services, and just over half incorporate hazard and vulnerability data into forecasts. Coverage is particularly lacking in meteorological observations across Africa, the Pacific, and parts of Latin America. In response, Pillar 2 focuses on five targeted outcomes:

1. Improving Data Quality and Access: Establishing robust measurement networks like the Global and Regional Basic Observing Networks to support forecasting models.
2. Global Data Sharing: WMO's Information System (WIS) facilitates seamless international data exchange.
3. Enhancing Forecasting Capabilities: Leveraging AI and increased computational power to expand capabilities in nowcasting and short-term forecasting.
4. Proactive Early Action: Standards for forecasts and alerts, strengthened through regional partnerships and advanced training.
5. Building Leadership Frameworks: Governance structures to support knowledge-sharing and Disaster Risk Reduction (DRR) advancements.

The Global Basic Observing Network (GBON), part of WMO's Integrated Global Observing System, addresses data inconsistencies crucial for accurate weather forecasts. The SOFF supports GBON's implementation, particularly in LDCs and Small Island Developing States, by facilitating the generation and international exchange of necessary observational data. Additionally, the Regional Basic Observing Networks (RBON) initiative aims to enhance regional data exchange, supporting weather forecasts, climate monitoring, and DRR.

2.2. Key WMO Initiatives and Systems

The WMO Information System (WIS) serves as a central platform for global meteorological, hydrological, and climate data, enhancing collaboration among NMHSs. The WMO Integrated Processing and Prediction System (WIPPS) improves global weather, water, climate, and environmental prediction capabilities by integrating satellite, radar, and observational data into precise, high-resolution forecasting models. The COPE Disaster Champions initiative educates children about disaster risks, part of WMO's broader mission to build resilient communities. WMO Technical Commissions, including INFCOM and SERCOM, advance global meteorological and climate-related capabilities. INFCOM focuses on developing robust observational and information systems like GBON and WIS, essential for data collection and sharing, while SERCOM works to enhance the accessibility of weather, climate, hydrological, and environmental services across sectors.

2.3. Support for Developing Countries and Strategic Partnerships

The SOFF is a UN initiative targeting LDCs and SIDS to improve their capacity for collecting and sharing climate data. Similarly, the Climate Risk and Early Warning Systems (CREWS) initiative strengthens climate resilience through impact-based Early Warning Systems prioritizing vulnerable populations, advancing climate adaptation, risk reduction, and local resilience.

2.3.1. Necessity of Early Warning Systems for Disaster-Prone ICESCO Members

Early Warning Systems for natural disasters are essential for all nations, particularly for developing Islamic World Educational, Scientific and Cultural Organization (ICESCO) member states, where preparedness and response capacities are often limited. These systems can significantly reduce the impact of natural hazards by providing timely alerts that enable communities to evacuate, protect assets, and take preventive actions. A comprehensive analysis of the EM-DAT dataset from 2000 to 2024 highlights the diverse range of natural disasters impacting these countries, underscoring the critical need for robust early warning mechanisms. The following findings offer insights into disaster types, frequencies, economic tolls, and the most devastating events, emphasizing the importance of Early Warning Systems across ICESCO member states.

Trends in disasters of ICESCO Member States

Figure 2 highlights yearly trends in the occurrence of natural disasters among ICESCO member countries, with floods, earthquakes, and storms consistently being the most common hazards. The years 2020 and 2021 record the highest occurrences of natural disasters, reflecting an intensified period that may be linked to climate change and other environmental factors affecting the region. This pattern underscores ongoing challenges related to water management, seismic activity, and atmospheric conditions within ICESCO countries, highlighting the need for enhanced preparedness and tailored response strategies to mitigate the impact of these recurring events.

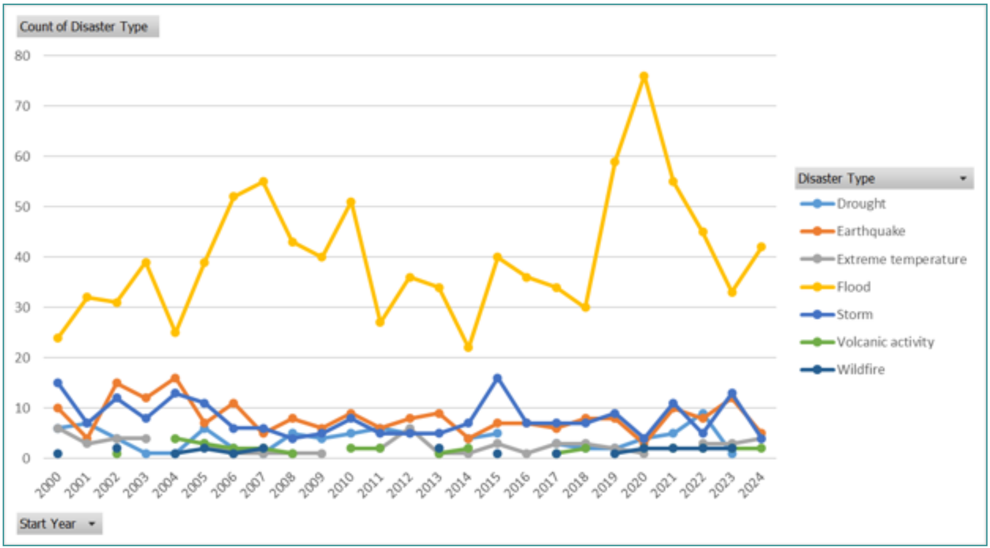

Figure 2: Yearly Trends in Natural Disaster Occurrence (source: EM-DAT for ICESCO state members, 2000-2024, Selected natural hazards: Drought, Earthquake, Extreme temperature, Flood, Storm, Volcanic activity, and Wildfire).

ICESCO Member States and predominant disasters

Figure 3 provides an analysis of the most frequent disaster types across ICESCO member countries and identifies high-risk regions for each type. Floods emerge as the most common disaster, with 1,000 recorded occurrences, followed by earthquakes (204 occurrences) and storms (200 occurrences). Floods are particularly prevalent, driven by factors such as climate change, extreme weather, and water management challenges. Earthquakes rank second, reflecting significant risks in tectonically active regions, while storms, influenced by shifting weather patterns, rank third. The countries most affected by these disasters include Indonesia, Pakistan, Bangladesh, Iran, and Malaysia. Indonesia's vulnerability to both earthquakes and floods stems from its position along the Pacific Ring of Fire and its tropical climate. Pakistan, frequently impacted by floods and earthquakes, reflects exposure to both climate-induced and tectonic hazards. Bangladesh is highly susceptible to monsoon-driven floods due to its low-lying terrain, while Iran faces considerable risk from both earthquakes and floods, shaped by tectonic and climatic factors. Malaysia's frequent floods and storms are influenced by its tropical climate and monsoon seasons. These findings emphasize the need for targeted, country-specific disaster preparedness and risk reduction strategies tailored to the predominant hazards in each ICESCO member country.

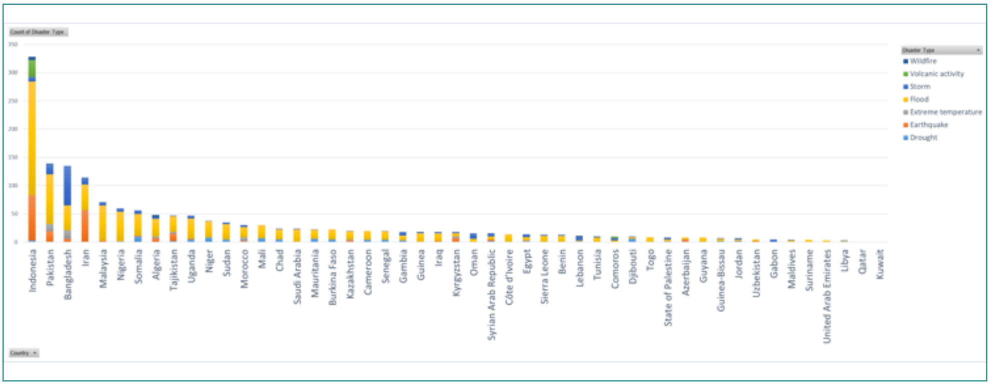

Figure 3: Yearly Trends in Natural Disaster Occurrence (source: EM-DAT for ICESCO state members, 2000-2024, Selected natural hazards: Drought, Earthquake, Extreme temperature, Flood, Storm, Volcanic activity, and Wildfire).

Affected populations in ICESCO Member States

The human toll of affected people from natural disasters is starkly illustrated in Figure 4, which shows that floods, droughts, extreme temperatures, and storms affect the largest populations across ICESCO member countries. Bangladesh, Pakistan, and Indonesia are among the most impacted. In Bangladesh, floods have the most significant impact, followed by storms and extreme temperatures, highlighting the vulnerability of its population to water-related and climatic events. Pakistan experiences the highest impacts from floods, earthquakes, and droughts, with floods posing a particular threat to its people. Indonesia is notably vulnerable to droughts, earthquakes, and floods, underscoring the need for comprehensive preparedness strategies across these types of events. Each country displays unique patterns of disaster impact, underscoring specific regional vulnerabilities and emphasizing the importance of Early Warning Systems that address these distinct risks.

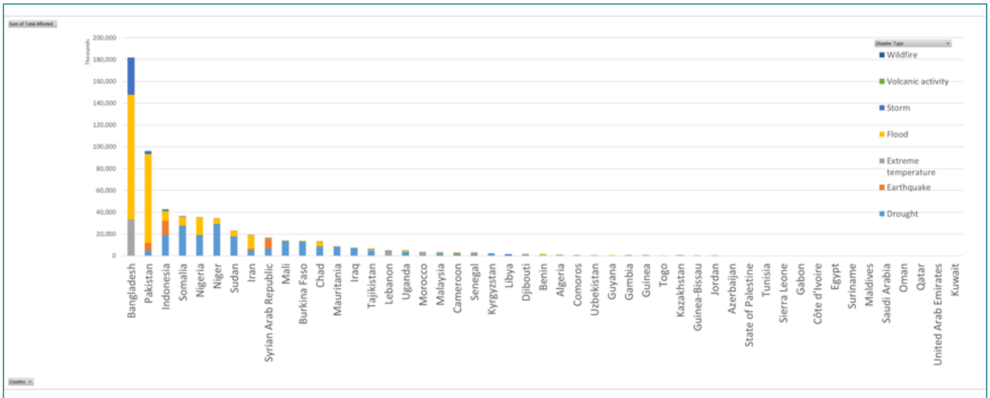

Figure 4: Human Impacts of Disasters on Vulnerable Populations (source: EM-DAT for ICESCO state members, 2000-2024, Selected natural hazards: Drought, Earthquake, Extreme temperature, Flood, Storm, Volcanic activity, and Wildfire).

Insights

The EM-DAT dataset analysis underscores the diversity of disaster risks and their profound impacts across ICESCO member countries. Countries like Indonesia, Pakistan, Bangladesh, and Iran face recurring threats from floods, earthquakes, and storms, leading to considerable human and economic losses. This analysis highlights the need for targeted disaster preparedness, resilient infrastructure, and robust Early Warning Systems, which can provide crucial time for evacuations, asset protection, and preventive actions in high-risk areas. Enhanced collaboration among ICESCO member countries and support from international disaster relief organizations are essential to strengthening disaster response and recovery, particularly in regions highly susceptible to natural hazards.

2.4. WMO Strategic Plan for 2024–2027

WMO's Strategic Plan for 2024–2027 aligns with global frameworks, including the UN Sustainable Development Goals (SDGs), the Paris Agreement, and the Sendai Framework. Key objectives include (WMO, 2023):

1. Strengthening Multi-Hazard Early Warning Systems (MHEWS): Through the Early Warnings for All initiative, this goal aims for global coverage by 2027, emphasizing vulnerable communities.
2. Enhanced Observational and Data Management Capabilities: Expanding systems like WIGOS and GBON to secure real-time data essential for accurate forecasts, ensuring accessibility for NMHSs.
3. Scientific Research and Technological Advancement in Earth System Modeling: Developing AI-driven "nowcasting" and short-term forecasting to address climate and weather extremes.
4. Building Capacity and Infrastructure for Developing Countries: Initiatives like SOFF and CREWS support NMHSs in developing nations, providing funding, training, and resources for MHEWS.
5. Sustainable Hydrological Services and Water Resource Management: Systems like HydroSOS aid in monitoring droughts, floods, and water availability.
6. Strengthening Partnerships, Governance, and Organizational Resilience: Expanding collaborative networks and governance to support climate adaptation and resilience, with an emphasis on inclusivity and gender equality.

The plan outlines challenges, such as limited access to reliable observational data, insufficient multi-hazard monitoring and forecasting in developing countries, gaps in 24/7 operational capabilities, and restrictive legal frameworks. In addressing these, WMO's Strategic Plan for 2024–2027 offers a cohesive approach, emphasizing multi-hazard preparedness, scientific advancement, inclusive capacity-building, and partnerships. It positions WMO at the forefront of efforts to mitigate climate impacts and enhance global resilience.

2.5. Key Findings from COP29 and COP16

With a central focus on climate finance, COP29 brought together nearly 200 countries in Baku, Azerbaijan, and reached a breakthrough agreement that will (UN Climate Change News, 2024):

- Triple finance to developing countries, from the previous goal of USD 100 billion annually, to USD 300 billion annually by 2035.
- Secure efforts of all actors to work together to scale up finance to developing countries, from public and private sources, to the amount of USD 1.3 trillion per year by 2035.
- COP29 also reached agreement on carbon markets. These agreements will help countries deliver their climate plans more quickly and cheaply, and make faster progress in halving global emissions this decade.
- Transparent climate reporting and adaptation are highly encouraged. Building a stronger evidence base to strengthen climate policies over time, and helping to identify financing needs and opportunities.
- It was emphasized the importance of gender equality and integrating gender considerations into climate policies. They also committed to developing a new gender action plan, to be adopted at COP30, which will guide concrete implementation efforts.
- The decisions taken at COP29 also reemphasize the critical importance of empowering all stakeholders to engage in climate action; in particular under Action for Climate Empowerment (ACE). Parties recalled the importance of integrating ACE elements into national climate change policies, plans, strategies and action, and noted the secretariat's compendium of good practices for integrating ACE elements into NDCs.
- COP16 underscored the urgency of addressing land degradation and drought, with significant financial commitments and initiatives launched, though challenges remain in formulating a unified global strategy.

3.

Policy, Governance and International Frameworks for Early Disaster Warning

Effective disaster early warning and preparedness require integrated policy, governance, and international standards. Key strategies include enhancing policy frameworks and fostering multi-level collaboration. The Sendai Framework for DRR, for instance, promotes people-centred Early Warning Systems, emphasizing community engagement, inter-agency co-ordination, and inclusive policies that address vulnerabilities across diverse populations (UN Sendai Framework). Local governments, critical in mobilizing resources, are encouraged to collaborate with NGOs and community groups to address specific community vulnerabilities and resilience needs, especially through gender-sensitive and inclusive approaches (Gladfelter, 2018). Governance structures must support local and international partnerships, facilitating timely response and adaptation to specific local conditions, as demonstrated in Nepal's Early Warning Systems, which combines institutional and community engagement but faces challenges like fragmented legal frameworks and inconsistent funding (Kafle, 2017). The Hyogo Framework for Action emphasizes "last mile" connectivity, ensuring that early warnings reach all community members, particularly those most at risk. Lessons from the Indian Ocean region underscore gaps in local and regional integration, suggesting that decentralized, resource-supported governance is vital for effective DRR (Thomalla & Larsen, 2010). Local governance is key in implementing Early Warning Systems, particularly through decentralized systems close to at-risk communities, enabling swift resource mobilization. Multi-sectoral partnerships that include government agencies, private sectors, and NGOs—endorsed by the Sendai Framework—are crucial. Policies integrating community insights with scientific data ensure timely, reliable, and accessible warnings, strengthening Early Warning Systems across all community levels (Collins & Kapucu, 2008).

International frameworks also play a pivotal role. The Sendai Framework encourages cross-national data sharing and capacity-building, which enhance preparedness and resilience across borders. Examples include Japan's tsunami collaboration with neighbouring countries and the role of community leaders in Aceh, Indonesia, in bolstering public trust and engagement in Early Warning Systems (Sufri et al., 2020). Policies should ensure coordination, accountability, and sustainable financing, as seen in Uganda, where Early Warning Systems effectiveness is hampered by inadequate funding and fragmented structures (Lumbroso, 2018). Integrating local knowledge and scientific insights with improved communication infrastructures aligns local Early Warning Systems efforts with global standards, facilitating timely and accessible disaster response across vulnerable populations. The Common Alerting Protocol (CAP) is an international standard for communicating emergency alerts and public warnings. CAP provides a consistent format for creating, transmitting, and receiving alerts, allowing integration across various warning systems and platforms, such as emergency broadcasts, sirens, and mobile alerts. CAP messages include key information, such as the nature of the emergency, its location, timing, severity, and recommended actions. A single CAP message can activate multiple alerting systems simultaneously, reducing cost, complexity, and delays while ensuring consistent messaging across all channels, including SMS, sirens, and TV broadcasts (GDPC; Botterell, 2006). The Common Alerting Protocol (CAP), designated by the International Telecommunication Union (International Telecommunication Union (ITU)) as Recommendation X.1303, is a widely recognised standard for emergency alerting, ensuring that public alerts are available, precise, reliable, secure, and fast. CAP facilitates all-hazards, all-media alerting, providing consistent information across different communication channels. CAP messages contain key facts about the emergency, such as the nature of the event, actions to take, the alerting area, timing, severity, and certainty. This standard ensures that everyone receives crucial information in the same way, regardless of the communication medium (GDPC; Malizia et al., 2009). The Common Alerting Protocol (CAP) offers several benefits: it is interoperable across many broadcast and dissemination channels, and its standard format ensures the inclusion of all key facts about an emergency. CAP is simple to implement without major investments, using an easy XML format for integration. It supports all types of hazards and emergencies, and alerts can be targeted to specific geographic areas to reach those affected. CAP allows for translation and the integration of actionable messages, ensuring consistency across different communication channels (Sciences et al., 2018; Standard, 2010).

3.1. Floods

Floods are among the most destructive natural hazards, impacting nearly 2.5 billion people globally and causing over $40 billion in annual damages. The threat of flooding is intensifying due to climate change, rapid urbanisation in vulnerable regions, ecosystem degradation, and rising sea levels. Between 2000 and 2015, there was a 24% increase in the population living in flood-prone areas, with population growth and high-density development heightening exposure to flood risks. According to the Centre for Research on the Epidemiology of Disasters (CRED), floods constituted 43% of recorded disasters from 1994 to 2013. This trend is underscored by the CRED report, The Human Cost of Natural Disasters: A Global Overview, which highlights the impact of income disparities and geographic factors on disaster outcomes. While lower-income countries face higher fatalities per disaster due to limited resources, high-income nations are better equipped to mitigate these risks, despite often facing similar exposure levels.

The Organisation for Economic Co-operation and Development (OECD) underscores the urgency of addressing flood risk through effective financial management, as urban development and climate change increase exposure to flood hazards. The Financial Management of Flood Risk report advocates a balanced approach combining risk reduction investments and risk transfer tools, such as insurance, to distribute financial burdens across both private and public sectors. Strategic land-use planning, flood defences, and incentives for private sector involvement are critical for mitigating economic strains on households and businesses, especially in low-income areas where financial protection gaps can lead to significant hardship following floods. The OECD report further emphasizes that government participation and multi-level planning are essential for creating resilient, flood-prepared societies and ensuring that financial losses are manageable.

3.1.1. Integrated Flood Management and the Role of WMO Initiatives

Flood management plays a pivotal role in mitigating flood risks and safeguarding communities. The WMO has spearheaded initiatives to enhance global flood preparedness, promoting an Integrated Flood Management (IFM) approach through the Associated Programme on Flood Management (APFM). In partnership with the Global Water Partnership, IFM aims to balance the advantages of floodplain use with risk reduction by advocating for protective infrastructure, sustainable land-use planning, and community resilience. The Flood Forecasting Initiative of the WMO works closely with National Meteorological and Hydrological Services (NMHSs) worldwide, enhancing forecasting capabilities to provide timely and accurate warnings that support disaster preparedness and enable proactive responses to flood threats.

Recognising the particular challenges posed by flash floods, WMO developed the Flash Flood Guidance System (FFGS) in collaboration with USAID, NOAA/NWS, and the Hydrologic Research Center (HRC). Flash floods account for 85% of flood-related fatalities globally due to their rapid onset, often occurring with limited warning. The FFGS empowers NMHSs with interactive tools for real-time forecasting using remote-sensed data and advanced hydrological models. By covering over 72 countries, the system significantly contributes to the global "Early Warnings for All" initiative, which seeks to minimise the human and economic toll of flash floods through enhanced forecasting and community-based response capabilities. The WMO's commitment to a proactive, integrated approach to flood management is also reflected in the End-to-End Flood Forecasting and Early Warning Systems (E2E FFEWS), which align with the Sendai Framework for DRR. These systems streamline the entire flood preparedness process, integrating data collection, accurate forecasting, effective communication, and coordinated emergency responses, ultimately fostering resilience across national, regional, and local levels.

3.1.2. Building Flood Resilience through Data, Partnerships, and Hydrological Services

Global flood risks continue to grow, with research by Tellman et al. (2021) revealing a 34.1% increase in populations within flood-prone areas between 2000 and 2018, surpassing general population growth. Vulnerable communities, particularly in Asia and Africa, are disproportionately affected due to their high population densities and socio-economic development in flood-risk zones. Rising exposure to flood hazards is further compounded by rapid urbanisation and the loss of natural flood-protective ecosystems such as mangroves and reefs. Ecosystem-based solutions are recognised as cost-effective strategies for flood mitigation, providing essential ecological benefits while supporting biodiversity; however, the persistent rise in sea levels may eventually necessitate relocations from high-risk areas. The WMO's Vision and Strategy for Hydrology addresses these growing challenges, particularly hydrological extremes, water availability, quality, and food security. Guided by the Standing Committee on Hydrological Services (SC-HYD), WMO advances operational hydrology by enabling NMHSs to provide real-time data essential for flood forecasting, drought prediction, and seasonal-to-sub seasonal water assessments, helping governments and disaster agencies to make informed decisions and mitigate losses.

In addition, the WMO Coordination Mechanism (WCM) plays a vital role in global humanitarian resilience by delivering timely hydrometeorological data to support crisis response in vulnerable areas. The Weather4UN project, an initiative by MeteoSwiss in collaboration with the Swiss Agency for Development and Cooperation (SDC) and WMO consolidates authoritative data from WMO Members to aid humanitarian decision-making with targeted, actionable information. By integrating probabilistic risk models with real-time weather forecasts, the project empowers humanitarian actors to plan responses in hazard-prone zones, enhancing WMO's support for anticipatory action and resilience in disaster-prone communities. Through such comprehensive and collaborative approaches, WMO and OECD initiatives collectively advance flood preparedness, financial risk management, and resilience, addressing both immediate response needs and long-term strategies against the growing threat of floods and other climate-related hazards.

3.2. Drought

Drought is a persistent and increasingly costly natural hazard, impacting nearly every corner of the globe with prolonged dry periods that disrupt ecosystems, food security, water resources, and economies. Unlike sudden hazards, drought develops gradually, affecting vast regions, including deserts and rainforests. From 1970 to 2019, drought was responsible for approximately 650,000 deaths worldwide and significantly impacted food security, health, and migration. In the U.S. alone, around 10% of land is affected annually, costing between $6-8 billion, while global water insecurity drains the economy by $500 billion each year. As climate change drives up the frequency and intensity of droughts, the risks to vulnerable populations are compounded by factors such as poverty and unsustainable land practices, according to the Intergovernmental Panel on Climate Change (IPCC) and WMO's Atlas of Mortality and Economic Losses from Weather, Climate, and Water Extremes.

3.2.1. Integrated Drought Management Programme (IDMP): A Comprehensive Response Framework

Recognising the need for coordinated, proactive measures, the Integrated Drought Management Programme (IDMP) was launched by the WMO and the Global Water Partnership (GWP). IDMP collaborates with over 45 partners to offer policy guidance, best practices, and technical support to countries aiming to build resilience against drought impacts. This programme, rooted in the outcomes of the High-level Meeting on National Drought Policies, encourages an integrated, cross-sectoral approach to drought management, tailored to regional and national needs. The IDMP promotes a shift from reactive crisis response to proactive risk management through three pillars:

- Monitoring and Early Warning: Establishing comprehensive drought monitoring and Early Warning Systems (DEWS) to identify trends in climate and water supply and communicate them effectively to decision-makers.
- Risk and Impact Assessment: Understanding historical and potential drought impacts, including hazard exposure and vulnerability, to inform targeted response efforts.
- Risk Mitigation, Preparedness, and Response: Implementing long-term and short-term measures for water management, agriculture, and emergency response, building a framework for ongoing drought resilience.

The IDMP HelpDesk serves as a central resource for stakeholders, providing technical support and sharing global best practices in drought mitigation and adaptation. IDMP's approach is organized around three core pillars: Monitoring & Early Warning, Risk & Impact Assessment, and Risk Mitigation, Preparedness & Response. Together, these pillars provide a comprehensive, proactive framework for drought resilience that integrates scientific data, risk management, and policy guidance.

- Monitoring & Early Warning: An effective Drought Early Warning Systems (DEWS) is fundamental to preparing for and mitigating drought impacts. DEWS integrates data on precipitation, soil moisture, groundwater levels, and reservoir statuses to create a comprehensive picture of drought conditions. This real-time monitoring allows governments and water managers to detect drought conditions early, assess potential severity, and communicate timely warnings to at-risk communities. By enabling early action, DEWS helps minimize damage and supports a shift from reactive responses to proactive management.
- Risk & Impact Assessment: Assessing drought risk involves understanding both historical and future impacts

by evaluating hazard exposure and vulnerability. This pillar aims to create a detailed picture of drought's effects across various sectors and communities by mapping hazard-prone areas and understanding factors that heighten vulnerability, such as population density, poverty, and land use practices. Improved impact assessment enables countries to implement targeted actions that address the root causes of drought vulnerability, making resilience-building efforts more effective and sustainable.

- Risk Mitigation, Preparedness & Response: This pillar focuses on strategies for reducing the impacts of drought through preparedness and response actions. IDMP promotes a balance between long-term water management solutions and short-term emergency responses, such as water rationing or crop and livestock protection measures. Long-term actions include enhancing water supply resilience, conserving groundwater, and improving agricultural practices. By encouraging countries to incorporate drought preparedness into their development strategies, IDMP supports a proactive approach that enhances resilience over time. A 2018 IDMP survey revealed progress in proactive drought policies across 28 countries, underscoring the global shift toward integrated, sustainable drought management.

3.2.2. Regional Impacts and Lessons Learned

The WMO Atlas of Mortality and Economic Losses offers insights into regional vulnerabilities, showing varied impacts of drought across continents.

- Africa faces severe drought impacts, particularly in the Sahel, where mortality remains high despite improved Early Warning Systems. Climate change and socioeconomic factors continue to amplify vulnerabilities.
- Asia has been impacted by devastating tropical cyclones, especially in Bangladesh, Myanmar, and India. Improved warning systems have reduced mortality, yet the economic and social costs remain substantial.
- South America frequently experiences flooding that disrupts agriculture and leads to economic losses, compounded by environmental degradation.
- North America and the Caribbean face significant economic losses, with the U.S. accounting for a third of global economic damages from storms and floods.
- Europe has faced severe heatwaves, notably in 2003 and 2010, which resulted in high mortality, underscoring the need for adaptive strategies for rising temperatures.

3.2.3. Advancing Global Drought Resilience through Integrated Management

Drought is a pervasive natural hazard, intensified by climate change, that poses severe risks to food security, water resources, and economies globally. Unlike other rapid-onset hazards, drought's slow development can extend its impacts over vast regions, with long-lasting socio-economic consequences. Recognizing the need for proactive and sustainable drought management, the WMO and the Global Water Partnership (GWP) established the Integrated Drought Management

Programme (IDMP). This programme aims to move away from reactive crisis responses to a structured, risk-based approach that reduces vulnerability and builds resilience.

IDMP works with a range of stakeholders across sectors—such as agriculture, water management, and climate services—to establish strategies and tools that equip communities and nations to handle the growing risks associated with drought. At the core of IDMP's mission is a focus on poverty reduction, economic stability, and climate adaptation, supported by science-based guidance and the programme's central HelpDesk, which offers resources and technical assistance to countries affected by drought.

3.2.4. Policy Development and Strategic Guidelines for Drought Resilience

The National Drought Management Policy Guidelines provided by IDMP outline a structured approach for countries to develop policies that transition from emergency crisis responses to proactive drought management. The guidelines encourage the establishment of risk-based policies focused on preparedness, public awareness, and self-reliance. This process involves coordinating across sectors, enhancing public understanding, and ensuring that policy decisions are informed by the latest scientific data and lessons learned. The guidelines propose a ten-step framework for policy development, which includes:

1. Forming a multidisciplinary drought management commission to oversee policy creation.
2. Setting clear, actionable goals that prioritize proactive management.
3. Engaging stakeholders at all levels to build cooperative solutions and mitigate conflicts.
4. Conducting a comprehensive resource inventory to assess areas of risk and capacity.
5. Developing essential policy components like monitoring, early warning, and risk assessment strategies.
6. Identifying research gaps to build an evidence-based approach.
7. Integrating scientific findings directly into policy for improved decision-making.
8. Promoting public awareness through outreach and education campaigns.
9. Providing training programs to foster resilience across communities.
10. Continually evaluating and revising policies based on real-world outcomes and emerging data.

These guidelines are designed to be adaptable, ensuring they remain relevant as climate, population, and environmental conditions evolve. By following these steps, countries can build a foundation for drought resilience that supports both immediate needs and long-term sustainability. The policy framework aligns with international standards such as the Sendai Framework for DRR, enhancing IDMP's mission to create integrated, science-driven drought policies worldwide.

3.3. Tropical Cyclones

Tropical cyclones, also known regionally as hurricanes or typhoons, are powerful, rotating storms that develop over tropical oceans, drawing energy from the warm waters. These storms feature a low-pressure centre and a calm "eye" surrounded by spiralling clouds, accompanied by violent winds, torrential rain, and storm surges. With diameters ranging from 200-500 km (reaching up to 1000 km in extreme cases), they are capable of causing extensive destruction. Tropical cyclones account for significant loss of life and property, ranking as the second-most dangerous natural hazard after earthquakes. From 1970 to 2020, these storms were responsible for 1,945 disasters, 779,324 deaths, and $1.4 trillion in economic losses, representing 17% of all weather-related disasters and one-third of disaster-related deaths and economic losses worldwide.

The terminology for these storms varies by region: "hurricane" in the Caribbean Sea, Gulf of Mexico, and North Atlantic; "typhoon" in the Western North Pacific; "cyclone" in the Bay of Bengal and Arabian Sea; "severe tropical cyclone" in the Western South Pacific and southeast Indian Ocean; and "tropical cyclone" in the Southwest Indian Ocean. This localized terminology aids communities in recognizing and preparing for the intense storms common to their areas.

3.3.1. Increasing Impacts of Tropical Cyclones and the Role of Climate Change

Climate change has intensified the frequency and destructive power of tropical cyclones, exacerbating the socioeconomic impacts on global populations, particularly in coastal areas with growing infrastructure. Historic storms like Hurricane Katrina (2005), Typhoon Haiyan (2013), and Hurricanes Irma and Maria (2017) underscore the lasting devastation these events can cause, with recovery efforts often spanning years. Rising sea levels and warmer oceans contribute to more powerful and unpredictable storms, making Early Warning Systems critical for safeguarding lives and property as coastal populations continue to rise.

3.3.2. Tropical Cyclone Naming: A Tool for Communication and Public Safety

Naming tropical cyclones enhances communication, making it easier for meteorologists, media, emergency agencies, and the public to track, monitor, and discuss individual storms. This practice reduces confusion, especially when multiple storms are active simultaneously, and aids in historical record-keeping for studying storm patterns and impacts over time. Historically, cyclone names were informal, often based on landmarks or the names of affected ships. By the mid-20th century, a more structured naming system emerged, starting with female names in alphabetical order and eventually including male names in 1979.

The WMO now standardizes the naming process globally. WMO's tropical cyclone regional bodies—such as the ESCAP/WMO Typhoon Committee and RA IV Hurricane Committee—manage annual or biennial name lists, contributed by member countries. Names are chosen for brevity, ease of pronunciation across languages, cultural appropriateness, and uniqueness within regions to prevent confusion. In the Atlantic and

Southern Hemisphere, names alternate alphabetically between male and female names, while other regions may use country-based alphabetical orders. Cyclones are never named after individuals to avoid negative associations.

3.3.3. Forecasting Tropical Cyclones: Techniques and Global Coordination

Forecasting tropical cyclones is complex due to the storms' unpredictable behaviour, including sudden changes in intensity or direction. To improve accuracy, meteorologists employ advanced technologies such as satellites, weather radars, and numerical weather prediction models. These tools allow meteorologists to forecast a cyclone's path, speed, and potential landfall locations, which is essential for preparedness. Approximately 85 tropical storms form globally each year, with about 45 intensifying into full-fledged cyclones, hurricanes, or typhoons. Of these, 72% occur in the Northern Hemisphere, with the remaining 28% in the Southern Hemisphere. This information aids National Meteorological Services in issuing early warnings and enabling timely protective actions in at-risk areas.

3.3.4. WMO's Role in Cyclone Preparedness, Monitoring, and Advisory Services

The WMO plays a central role in coordinating global tropical cyclone monitoring, forecasting, and advisory services. Through its Tropical Cyclone Programme, WMO oversees Regional Specialized Meteorological Centres (RSMCs) and Tropical Cyclone Warning Centres (TCWCs), designated to track, detect, and forecast cyclones within specific regions. These centres provide real-time advisory information to National Meteorological and Hydrological Services, ensuring that communities receive precise and timely updates. Additionally, WMO's Severe Weather Information Centre offers real-time tropical cyclone advisories, reinforcing international preparedness and supporting global response efforts. WMO's Early Warnings for All (EW4All) initiative aims to close gaps in Early Warning Systems, especially in developing regions, thereby enhancing global resilience and supporting climate adaptation strategies. By fostering international collaboration and utilizing state-of-the-art forecasting tools, WMO ensures communities worldwide are better informed, prepared, and protected against the escalating impacts of tropical cyclones. This comprehensive approach—integrating naming, monitoring, forecasting, and early warnings—reflects WMO's commitment to safeguarding vulnerable populations and reducing the devastating consequences of these powerful storms.

3.4. Heatwaves

Heatwaves, defined by prolonged periods of extreme temperatures that persist through unusually hot days and nights, are intensifying globally and are becoming one of the most pressing natural hazards due to their widespread impact on human health, ecosystems, and economies. These events can last from days to months and lead to severe consequences, including increased mortality, agricultural losses, wildfires, power outages, and degraded water quality. Urban areas are especially vulnerable, with the "urban heat island" effect driving temperatures 5–10°C higher than in surrounding regions, amplifying risks for urban residents.

Recent extreme heat events reflect a worrying trend. In 2022, China experienced an unprecedented 70-day heatwave, while heatwaves in India and Pakistan became 30 times more likely due to climate change. In the same year, the United Kingdom recorded its highest-ever temperature, reaching 40.3°C, underscoring the global and regional scale of heat extremes. Such intense heat events are particularly dangerous for vulnerable groups, including the elderly, infants, outdoor workers, and people with existing health conditions, leading to over 60,000 heat-related deaths in Europe alone in 2022.

3.4.1. Health, Environmental, and Economic Impacts

The health impacts of heatwaves are severe, with high temperatures causing heat stress, aggravating respiratory conditions, and increasing hospital admissions and mortality rates, particularly among at-risk populations. Heatwaves also have profound effects on agriculture, reducing crop yields and productivity, impacting water sanitation, damaging infrastructure, and threatening biodiversity. As global warming progresses, the frequency, intensity, and duration of heatwaves will continue to rise, disproportionately affecting low-resource communities that lack adaptive measures. In the workplace, especially for those doing outdoor labour, extreme heat severely limits productivity, with some regions approaching the physiological limits for safe outdoor work.

Heatwaves are exacerbated by other climate-driven events, such as droughts and wildfires, creating a compounded risk that disrupts ecosystems, increases food insecurity, and elevates the risk of hazardous smoke and air pollution. These interacting hazards add to the strain on public health, infrastructure, and the environment, making heatwaves one of the most challenging climate-related hazards to address.

3.4.2. WMO's Role in Heatwave Response and Early Warning Systems

The WMO plays a crucial role in global heatwave preparedness. It collaborates with National Meteorological and Hydrological Services (NMHS) worldwide to improve prediction accuracy and modernize Early Warning Systems, helping countries coordinate local Heat Action Plans. In partnership with the World Health Organization (WHO), WMO has developed a Heat-Health Warning System (WMO-No.1142), which provides practical guidance for mitigating health risks associated with extreme heat. The WMO also co-sponsors the Global Heat Health Information Network, a collaborative platform that fosters partnerships, knowledge exchange, and capacity-building among countries, ensuring communities are better equipped to manage the growing risks from heatwaves.

3.4.3. Heatwave Naming: WMO's Evaluation and Recommendations

The concept of naming heatwaves, an idea piloted by civil society groups in the United States, has been considered a method to raise public awareness. Drawing from the success of naming tropical cyclones, proponents argue that assigning names to heatwaves could make it easier for the public to understand and prepare for extreme heat events. However, the WMO has expressed caution about this approach, noting that while names can help convey the severity of weather events, heatwaves differ significantly from tropical cyclones. Unlike cyclones, heatwaves lack precise, trackable paths that allow for consistent naming, and a global or regional protocol for naming heat events does not currently exist. Furthermore, heatwaves are diffuse, affect broad areas, and are not easily defined, complicating the process of standardized naming.

The WMO also emphasizes that naming heatwaves could misdirect attention from critical messages about personal vulnerability and preparedness. Research suggests that educating the public on protective actions is more effective than naming individual heat events, which may draw focus toward the event itself rather than necessary safety measures. There is also a risk that names could create a false sense of security, leading people to underestimate the risks of unnamed heat events. Additionally, naming heatwaves could present challenges for sectors like insurance, where standardized criteria for heat-related insurance products might be required, further complicating emergency response and public messaging.

In view of these challenges, WMO advises against adopting heatwave naming practices, instead recommending an emphasis on strengthening Heat-Health Warning Systems (HHWS) that prioritize clear, actionable communication about heat risks and protective measures. WMO supports carefully piloting any future naming initiatives to assess their effectiveness on public behaviour and preparedness while ensuring that authoritative warnings through nationally designated systems remain the primary source of information. This approach allows for consistent, science-based public messaging that focuses on protective actions without the potential confusion or unintended consequences associated with heatwave naming.

3.4.4. Climate Change's Amplifying Effect on Heatwaves

The IPCC's Sixth Assessment Report confirms that human-induced climate change has driven a marked increase in the frequency, intensity, and duration of heatwaves since the 1950s. Every 0.5°C increase in global temperature leads to discernible rises in the intensity and frequency of extreme temperature events, amplifying heatwaves and extending their duration. This intensification poses broad risks: exacerbating drought conditions, increasing wildfire behaviour, worsening air quality, and straining water resources and agricultural productivity.

Heatwaves are also compounding the risks of pest invasions, diseases, and ecosystem degradation, impacting food security, human health, and biodiversity, particularly in vulnerable regions. Urban areas, that suffer from the urban heat island effect, experience intensified heat impacts, especially in rapidly urbanizing regions with limited climate-adaptive planning. Populations with minimal contributions to climate change are often the most affected, underscoring the need for equitable adaptation strategies to protect these communities from escalating heat risks. These findings highlight the urgent need for interventions that strengthen heat resilience through climate adaptation and public health preparedness, addressing the unequal burden of heat stress on marginalized populations. In sum, as heatwaves become more frequent and severe, WMO's focus on Early Warning Systems, coordinated heat action plans, and targeted public education remains central to enhancing resilience against this escalating climate-driven hazard.

4. Technological Innovations in Early Warning Systems

National and regional organisations worldwide are trying to use innovative technological solutions and developing new technical systems to detect natural hazards as quickly and efficiently as possible, providing timely information to help citizens protect themselves (Fujita & Shaw, 2019; Guo & Kapucu, 2019; Ocal, 2019). Various communication tools, including SMS, email, radio, TV, and online services, are being utilised for warning dissemination (Alias et al., 2020; Aloudat & Michael, 2011; Chen et al., 2020; Grasso & Singh, 2011; Mills et al., 2009; Sharma et al., 2015). Empirical evidence shows that these systems are effective in reducing fatalities and safeguarding property (Kull et al., 2013; Mechler, 2016; Rai et al., 2020), highlighting their significance in civil protection efforts (Alfieri et al., 2012). Mojtahedi and Oo (2017) examined the roles of Disaster Risk Management (DRM) and DRR, emphasising their distinctions and the importance of proactive strategies in reducing disaster impacts. DRM encompasses both DRR and Disaster Management (DM), where DRR is proactive, focusing on mitigation and risk minimisation, while DM is reactive, covering preparedness, response, and recovery. The study highlights the need for Early Warning Systems as a critical component of DRR, allowing timely alerts and minimising human and economic losses. The authors argue that combining proactive DRR approaches with effective stakeholder engagement enhances overall resilience, especially in vulnerable areas where Early Warning Systems can mitigate disaster impacts and support sustainable development. The research suggests that a proactive DRM framework incorporating stakeholder collaboration and advanced early warning mechanisms can significantly reduce disaster impacts by enabling better preparedness, response, and recovery efforts.

4.1. Innovative Technologies in Early Warning Systems

The United Nations Office for DRR (UNISDR, 2024) defines Early Warning Systems as capabilities for timely, meaningful alert dissemination to those at risk. High false alarm rates, however, reduce public trust, impacting the effectiveness of alerts (Basher, 2006). Successful systems thus depend on accurate detection without false alarms (Intrieri et al., 2012) and require interdisciplinary innovations such as sensor technology, data analytics, dynamic flood models, and simulation-based evacuation planning (Krzhizhanovskaya et al., 2011). Early Warning Systems, first developed in response to 1980s famines in Sudan and Ethiopia (Alcántara-Ayala & Oliver-Smith, 2019), have since evolved to address multiple hazards, including earthquakes, tsunamis, and floods, though challenges remain in adapting them for other crises, such as pandemics (Cvetković et al., 2020). Common alert methods, like sirens (Bubar et al., 2020) and public announcements via electronic media and street teams (Sorensen, 2000), each have benefits and limitations. Continuous improvement of Early Warning Systems is necessary to adapt to diverse natural and human-made threats (LaBrecque et al., 2019). Future advancements could see cell phones and satellite-based broadcasts delivering alerts to remote, infrastructure-limited areas (Glantz, 2004).

Technological innovations in information systems (IS), such as the Flood Early Warning Response Systems (FEWRS), play a crucial role in improving flood disaster management. By utilising models like the DeLone and McLean (D&M) IS Success Model, performance factors such as system and information quality are identified as key to successful multi-agency coordination during emergencies. These innovations enhance the dissemination of critical information to stakeholders, facilitating better decision-making, transparency, and effectiveness in flood response efforts. The integration of IS models with Early Warning Systems allows for more efficient use of resources, greater stakeholder collaboration, and improved flood risk mitigation (A. Hammood et al., 2021). The use of artificial intelligence (AI) in disaster Early Warning Systems, particularly through cognitive AI, represents a significant advancement in disaster management technology. Cognitive AI replicates human decision-making, enabling efficient data processing and real-time analysis, as seen in the Automatic Water Level Recorder (AWLR) sensor designed for flood Early Warning Systems. This sensor continuously monitors water levels at floodgates, automatically recording and transmitting data to decision support systems, thus enhancing response times and reducing manual errors (Asnaning & Putra, 2018). Artificial intelligence in disaster Early Warning Systems significantly enhances multi-hazard monitoring by increasing prediction accuracy, processing speed, and real-time data integration from sources like satellites and social media. Platforms such as Tamil Nadu's TNSMART use AI-driven big data analytics for accurate flood and cyclone forecasts, aiding timely response and resource allocation. However, challenges with data interoperability, sensor reliability, and privacy highlight the need for continued technological support, especially in resource-constrained areas (Poudel et al., 2024).

Satellite-based disaster Early Warning Systems play a pivotal role in detecting geological hazards by integrating big data analysis and real-time monitoring capabilities. Using multi-sensor networks and satellite communication, such systems can monitor environmental changes, such as surface displacement and water content, and transmit large-scale data through remote wireless networks. Through advanced data fusion algorithms, including the Dempster–Shafer evidence theory and machine learning, the system accurately analyses and integrates diverse data types for early warning. Cloud computing further enhances this by enabling rapid analysis of geological anomalies, allowing timely dissemination of alerts via SMS or email. This approach supports proactive and efficient responses to potential disasters, significantly improving community resilience and safety (Zhang, 2020). Satellite-based disaster Early Warning Systems have transformed how we detect and respond to tsunamis by enhancing data accuracy and real-time capabilities. Leveraging networks such as the Global Navigation Satellite System (GNSS), these systems detect ground displacements and ionospheric disturbances caused by undersea earthquakes, which are early indicators of tsunamis. Systems like the Japanese GEONET demonstrated that GNSS data could predict tsunamis within minutes, offering critical lead time for coastal warnings. The GNSS-supported Tsunami Early Warning Systems (GTEWS) network emphasizes rapid data processing and cross-national collaboration to reduce disaster impact (LaBrecque et al., 2019). Satellite monitoring has emerged as a critical component in disaster Early Warning Systems, especially for remote and hazard-prone regions. By providing real-time data transmission unaffected by terrestrial disruptions, systems like the Quasi-Zenith Satellite System (QZSS) in Japan enhance the reach of early warning alerts to at-risk communities, even in areas lacking reliable internet or cellular networks. This satellite-based approach complements ground systems, ensuring timely dissemination of emergency information, reducing response delays, and ultimately supporting effective evacuation and disaster response efforts (Potutan & Suzuki, 2023).

Big data technologies, often combined with the Internet of Things (IoT), significantly advance disaster Early Warning Systems and preparedness strategies by enabling rapid, real-time analysis of large, diverse datasets from sources like satellite imagery, social media, GIS, and sensor networks. However, their effectiveness often remains limited to high-income regions, highlighting the need for broader implementation, especially in low- and middle-income countries, to comprehensively address global disaster resilience (Freeman et al., 2019). Within smart city frameworks, big data supports predictive analytics, improves situational awareness, and allows emergency managers to allocate resources efficiently. For instance, systems like the Dartmouth Flood Observatory integrate satellite and social media data to forecast disaster impacts, while frameworks such as the IoT-assisted Disaster Risk Management Framework (IOTDRMF) improve accuracy and response times, even in low-infrastructure regions (Rahman et al., 2017; Zhou et al., 2021). Additionally, social sensing enables citizens to act as real-time data sources, which, though unstructured, provides valuable insights when processed with big data computing methods like deep learning. Challenges, such as data integration and noise management, persist, but big data facilitates proactive planning and strengthens resilience, as shown in various Early Warning Systems applications for floods, typhoons, and landslides (Li et al., 2020; Liu et al., 2023). By integrating advanced computing models like Convolutional Deep Neural Networks (CDNN) and tools such as Hadoop Distributed File Systems (HDFS), big data frameworks enhance real-time monitoring and predictive capabilities, supporting more accurate and timely responses to natural disasters (Anbarasan et al., 2020; Wang et al., 2024).

Munawar et al. (2022) examined how disruptive technologies—such as IoT, AI, big data, and smartphone applications—enhanced disaster risk management, focusing on Early Warning Systems. They found that IoT sensor networks and AI algorithms significantly improved disaster prediction and response by enabling real-time monitoring and predictive analysis. IoT networks, particularly in flood-prone areas, transmitted live environmental data to alert centres, while AI analysed historical data to forecast events like floods and earthquakes. The authors also addressed challenges, including data privacy, integration issues, and policy needs, especially in resource-limited regions. They advocated for a multi-disciplinary approach to overcome these barriers, emphasising that collaboration across sectors could make these technologies critical tools for resilient, community-focused Early Warning Systems. Munawar et al. (2021) explored the use of Unmanned Aerial Vehicles (UAVs) combined with Convolutional Neural Networks (CNNs) to enhance flood detection and disaster management. They focused on flood-prone areas along the Indus River in Pakistan, where timely flood detection is critical. By employing UAVs for aerial imagery, they generated a dataset comprising pre- and post-flood images, which was used to train a CNN model to detect and assess flood damage with an accuracy of 91%. This method provides significant benefits in capturing real-time data, even in areas where traditional surveillance may be ineffective. The study found that integrating UAVs with CNNs enables precise flood detection, facilitating efficient disaster response and reducing infrastructure and economic losses in flood-affected regions. The authors highlighted that UAV technology could offer a cost-effective early warning solution for developing countries, helping local authorities quickly map flooded areas and prioritise response efforts. This approach aligns with global disaster risk frameworks and underscores the value of advanced aerial and AI-driven technologies for rapid flood assessment and management. Habibi Rad et al. (2021) reviewed Industry 4.0 technologies in Disaster Risk Management (DRM), identifying six key technologies—AI, big data, IoT, prefabrication, robotics, and cyber-physical systems—that strengthen infrastructure resilience. AI and big data aid predictive analysis, IoT supports real-time monitoring, and prefabrication accelerates recovery efforts. These technologies align with the Sendai Framework, promoting preparedness and resilience in disaster-prone areas. The authors underscored the need for cross-sector collaboration to address challenges like data integration, and enhancing the application of digital tools for adaptive, resilient DRM.

4.2. Resilient Early Warning Systems for Disaster Preparedness

The UNDP's "Five Approaches to Building Functional Early Warning Systems" provides a comprehensive guide for enhancing disaster resilience through effective Early Warning Systems, focusing on institutional frameworks, technology deployment, community engagement, private sector involvement, and international cooperation. Establishing clear roles within institutional frameworks is crucial for a smooth Early Warning Systems operation, as it ensures that all levels of government are prepared to respond promptly, with well-defined mandates for decision-making to avoid confusion during emergencies. Advanced technologies such as satellites, radar, remote sensing, and early warning apps are essential for monitoring, forecasting, and disseminating warnings, allowing for accurate and timely data collection that supports effective disaster response and risk reduction. The document highlights successful case studies where social media and smartphone applications have enhanced Early Warning Systems through real-time information gathering and public alerts. Community involvement is also vital, as the public must be educated on risk preparedness, and communities—especially those in remote or underserved areas—must be directly integrated into response plans through last-mile communication initiatives to ensure timely warnings and effective responses. The private sector plays a critical role by contributing expertise, funding, and innovative technologies; incentivising partnerships with businesses is suggested, as private enterprises often have resources that can strengthen Early Warning Systems infrastructure and help reduce disaster costs, demonstrating the economic benefits of preparedness. International cooperation and cross-border data-sharing enable more comprehensive risk assessments and timely warnings, creating a unified approach to disaster resilience through collaborative protocols and resource sharing. The UNDP framework thus highlights that Early Warning Systems must integrate legal, social, technological, and educational components to function effectively, presenting a robust, multifaceted approach to building resilient systems that save lives and reduce disaster impacts globally.

By deploying cutting-edge tools and methods, Early Warning Systems can deliver more accurate and timely warnings, improving disaster response and saving lives. Key aspects of this approach include:

- **Data Collection and Monitoring:**
  - Technology allows for continuous data collection from a range of sources, such as satellites, weather radars, and sensors. These tools provide real-time data on various hazards like storms, floods, and earthquakes.
  - Remote sensing technology, such as satellite imagery, is particularly valuable in tracking environmental changes and detecting risks in areas that are difficult to access. This technology helps in monitoring both sudden-onset hazards, like flash floods, and slow-onset hazards, like droughts.
- **Modelling and Forecasting:**
  - Advanced modelling and simulation tools help predict potential hazards by analysing collected data. Meteorological models, for instance, can forecast the development and trajectory of storms.

- Technologies like Geographic Information Systems (GIS) play a significant role in hazard mapping, enabling better visualisation of risk areas and helping authorities make informed decisions on resource allocation and evacuation planning.
- Integrating climate models with socio-economic data allows for more detailed risk assessments, considering not only the physical impacts of hazards but also the vulnerabilities of specific communities.

- **Communication and Dissemination:**
  - Mobile technology and social media are increasingly being used to disseminate warnings quickly and widely. Mobile apps, SMS alerts, and push notifications are effective for reaching a large population, including those in remote areas.
  - Social media platforms provide a valuable means of real-time communication, enabling authorities to provide continuous updates and the public to share on-the-ground information.
  - In addition to digital methods, technologies like sirens, radio broadcasts, and television alerts remain critical, particularly in areas with limited internet connectivity.
- **Community-Based Monitoring and Crowdsourcing:**
  - Technology supports community-based monitoring by allowing local observers to report hazards and risks in real-time through mobile platforms. This enables a two-way communication flow where communities are both recipients and contributors of information.
  - Crowdsourced data from community members can complement formal monitoring systems, providing insights from areas where professional monitoring might be limited or unavailable.
- **Artificial Intelligence (AI) and Machine Learning (ML):**
  - AI and ML are increasingly applied in Early Warning Systems to enhance predictive capabilities. Machine learning algorithms can analyse large volumes of historical data to detect patterns, improving forecast accuracy.
  - AI-driven tools can predict the likelihood of disasters and their possible impacts, which aids in proactive planning and response.
- **Low-Cost and Scalable Solutions:**
  - Given resource constraints in developing regions, the deployment of cost-effective, scalable technologies is critical. Innovations such as low-cost weather stations and affordable sensors help in monitoring hazards without requiring high investment.
  - Technology partnerships with private companies and organisations can support the deployment of low-cost solutions tailored to the needs of specific communities.

The deployment of these technologies strengthens Early Warning Systems by providing more accurate risk assessments, enabling swift communication, and supporting the integration of local knowledge into disaster response planning. The document underscores that the ultimate goal of technology deployment in Early Warning Systems is to ensure that timely, relevant, and actionable information reaches all levels, from government agencies to vulnerable communities, enhancing resilience and preparedness across the board.

4.3. Global Status of Multi-Hazard Early Warning Systems

The "Global Status of Multi-Hazard Early Warning Systems (MHEWS) 2023" report evaluates progress, challenges, and gaps in multi-hazard Early Warning Systems worldwide. It highlights that MHEWS are critical for DRR, with a tenfold return on investment. Despite this, only 52% of countries currently report having MHEWS, showing a need for expanded coverage, especially in the least developed countries (LDCs) and small island developing states (SIDS). The report underscores the importance of advancing MHEWS across four core pillars: disaster risk knowledge, detection and forecasting, warning dissemination, and response preparedness. Key findings reveal that while improvements have been made, particularly in forecasting and communication, risk knowledge remains inadequate, impacting the effectiveness of warnings. The report emphasises that strong governance is essential for successful MHEWS. Countries with comprehensive DRR strategies generally have better MHEWS coverage. Integrating MHEWS into broader risk governance enables coordinated responses across various agencies, fostering resilience. Additionally, technological advancements have enabled better forecasting and data sharing; however, the report highlights that infrastructure gaps remain, particularly in Africa, Latin America, and the Pacific. International cooperation, funding, and community engagement are identified as critical areas to close the MHEWS coverage gap. The Early Warnings for All (EW4All) initiative, launched in 2022, aims to provide early warning coverage to every person on the planet by 2027, accelerating progress toward this goal. The report concludes with recommendations, urging investment in MHEWS, fostering local adaptation, and developing "no-tech" solutions for remote areas, ensuring that all communities can benefit from early warnings and take timely, lifesaving action.

"Early Warnings for All in Asia and the Pacific: Opportunities for action" report discussed the urgent need for comprehensive Early Warning Systems in Asia and the Pacific to tackle the increasing impacts of climate-related disasters. It highlights the region's extreme vulnerability, with disasters killing over two million people in the last 50 years and causing economic losses exceeding $2.4 trillion. Climate change is intensifying risks, particularly for vulnerable areas like South and Southwest Asia, Southeast Asia, and Small Island Developing States (SIDS). The report stresses that Early Warning Systems save lives and reduce damages but remain underdeveloped, especially in less-resourced countries. To address these issues, the document recommends several strategies: enhancing early warning capacities, integrating these systems into adaptation efforts, and establishing a seamless information chain from global to local levels. Emphasis is placed on a "fit-for-purpose and fit-for-budget" model, which includes sustainable financing mechanisms and regional cooperation. The WMO and the United Nations (UN) aim to extend early warning coverage to all by 2027, aligning with the

UN Secretary-General's initiative. The document also highlights technological advancements, such as AI and big data analytics, to improve risk prediction and impact-based forecasting. Regional initiatives, including the Indian Ocean Tsunami Warning and Mitigation System and partnerships like the Regional Integrated Multi-Hazard Early Warning Systems (RIMES), are shown as successful models of cooperation. The document concludes that achieving universal early warning coverage will require strong partnerships, innovative financing, and a regional approach to effectively reduce disaster impacts.

4.3.1. Developed countries initiatives

J-Alert is Japan's comprehensive national Early Warning Systems. It uses satellite communication to broadcast alerts about earthquakes, tsunamis, severe weather, and other emergencies via loudspeakers, television, radio, email, and cell broadcasts (Birmingham, 2011). The Earthquake Early Warning (EEW) system, managed by the Japan Meteorological Agency, detects initial seismic waves (P-waves) and sends out warnings before the more destructive S-waves arrive (Knightarchive, 2011). This system can provide seconds to minutes of warning, allowing people to take protective actions such as seeking cover or stopping machinery (Brown, 2024). The Emergency Alert System (EAS) and Wireless Emergency Alerts (WEA) are key components of the USA's Early Warning Systems. EAS is a national public warning system that allows the President to address the nation during a national emergency. WEA sends alerts to mobile devices about severe weather, local emergencies requiring evacuation or immediate action, AMBER alerts, and Presidential Alerts during a national emergency (Program, 2022). The ShakeAlert system, operated by the US Geological Survey (USGS), provides earthquake early warnings on the West Coast by detecting initial seismic activity and sending alerts to people and automated systems (FEMA, 2020). Australia's Australian Warning System (AWS), established in 2021, provides consistent warnings for emergencies like bushfires, floods, storms, extreme heat, and severe weather. It includes three warning levels: Advice, Watch and Act, and Emergency Warning, each with specific calls to action. The Emergency Alert system delivers warnings via telephone and SMS (Agency, 2022). Additionally, the National Emergency Management Agency (NEMA) coordinates disaster response and recovery efforts, ensuring timely and effective communication during emergencies (Meteorology, 2024; NSR, 2024). The European Early Warning and Information Systems support the Emergency Response Coordination Centre (ERCC) in monitoring global hazards such as earthquakes, tsunamis, wildfires, and tropical cyclones. These systems include the Global Disaster Alert and Coordination System (GDACS), the European Flood Awareness System (EFAS), and the European Forest Fire Information System (EFFIS) (ERCC, 2015). The EU also uses satellite maps from the Copernicus emergency management service to monitor and assess disaster impacts9. The European Natural Hazard Scientific Partnership provides 24/7 monitoring and scientific advice on a wide range of natural hazards (EUMETNET, 2024)

The Australia-Japan Quasi-Zenith Satellite System (QZSS) Emergency Warning Service project explored using QZSS for emergency warnings in Australia, focusing on bushfire and tsunami alerts. The project aimed to assess the feasibility of space-based communication for emergencies, especially in remote areas with limited terrestrial telecommunications. It involved transmitting emergency messages via satellite, developing a mobile app for message decoding and visualisation, and testing with emergency service personnel in New South Wales. Key insights from the project include the successful reception and decoding of QZSS Early Warning Systems messages using specially developed receivers and the Android MobileApp. The system could deliver timely warnings and display event locations on a map interface. Field trials demonstrated its potential effectiveness, though minor technical issues with the MobileApp's initial development phase were noted. The document highlights the potential of GNSS (Global Navigation Satellite Systems)-based Early Warning Systems as a complementary tool to existing systems, offering advantages like wide-area coverage, redundancy during infrastructure failures, and real-time location-based alerts. The report concludes with recommendations for further development, including refining the MobileApp, integrating with ground-based systems, and exploring broader adoption in Australia. The QZSS Early Warning Systems, combined with mobile app advancements, shows promise for improving emergency communication and public safety, especially in vast or remote regions where terrestrial systems may be limited (Choy et al., 2020). Additionally, Japan's innovative "BOSAI" platform promotes collaboration across public, private, and academic sectors, while some cities employ drones to monitor remote regions, like volcanoes and coastal waters. Similarly, China faces regular earthquakes due to its tectonic location and has prioritised earthquake early warnings in key areas, including large buildings, energy infrastructure, and schools. Beijing's initiative includes installing early warning devices nationwide, with a system that issues alerts within a minute of detecting a quake. China's network comprises 1,500 monitoring stations and numerous centres for data and early warning dissemination. Additionally, China has developed Early Warning Systems for other climate-driven risks like floods, droughts, and heat waves. Japan and China's approaches illustrate several key elements for effective disaster preparedness. Technological advancements are essential, with both countries investing in predictive technology like satellites and IoT for diverse hazards. Effective communication and swift dissemination of warnings are also vital, as seen in Japan's national alert system and China's extensive monitoring network. Finally, community engagement and adaptability are critical; Japan's BOSAI platform, which includes public-private-academic collaboration, underscores the importance of involving communities in DRR. Together, these practices from Japan and China provide a model for countries aiming to develop robust Early Warning Systems, aligned with the UN's "Early Warning for All" initiative.

4.3.2. Developing countries initiatives

Early Warning Systems in less developed or developing countries often face unique challenges but are crucial for mitigating the impacts of disasters. Many developing countries are working to implement Multi-Hazard Early Warning Systems (MHEWS), which aim to provide timely alerts for various types of hazards such as floods, cyclones, earthquakes, and droughts. However, as of 2022, less than half of the Least Developed Countries (LDCs) and only one-third of Small Island Developing States (SIDS) have such systems in place (UNDRR, 2024). Limited access to advanced technology and infrastructure can hinder the effectiveness of Early Warning Systems in these countries. For example, gaps in the Global Basic Observations Network (GBON) are prevalent in many parts of Africa and the Pacific. Solutions include leveraging mobile networks and internet connectivity, as well as using drones and smartphone applications for data collection. Besides, developing countries often lack the financial resources needed to establish and maintain comprehensive Early Warning Systems. International funding and partnerships are crucial to bridging this gap. Ensuring that warnings reach all segments of the population, especially in remote or rural areas, can be challenging as well. This often requires a mix of high-tech (e.g., mobile alerts) and low-tech (e.g., community radio, loudspeakers) solutions (UNDRR, 2023b). Local and Traditional Knowledge: Integrating local and traditional knowledge with modern Early Warning Systems can enhance their effectiveness. Community-based approaches and the involvement of local leaders are crucial for ensuring that warnings are understood and acted upon (UNDRR, 2023a).

Many African countries are enhancing their early warning capabilities through regional collaborations and support from international organizations. For instance, the African Centre of Meteorological Applications for Development (ACMAD) provides weather and climate information to support DRR1. Additionally, the Climate Prediction and Applications Centre (ICPAC), part of the Intergovernmental Authority on Development (IGAD), offers climate services and early warnings for droughts, floods, and other climate-related hazards. In countries like Kenya and Ethiopia, community-based Early Warning Systems are crucial. These systems often rely on local knowledge and simple technologies, such as radio broadcasts and community meetings, to disseminate warnings. Bangladesh has developed a robust cyclone Early Warning Systems that has significantly reduced cyclone-related fatalities. The system includes a network of cyclone shelters, community volunteers, and the use of mobile technology to disseminate warnings. The Philippines has implemented Project NOAH (Nationwide Operational Assessment of Hazards), which provides real-time weather data and hazard maps to help communities prepare for natural disasters like typhoons and floods. Caribbean Disaster Emergency Management Agency (CDEMA) coordinates disaster response and early warning efforts across the Caribbean region. It supports member states in developing and implementing Early Warning Systems for hurricanes, earthquakes, and other hazards. In countries like Haiti, community engagement is key to effective early warning. Local leaders and organizations play a vital role in disseminating warnings and ensuring that communities understand and act on them. As an international support and initiative, Early Warnings for All (EW4All), has been developed to ensure that everyone on earth is protected by Early Warning Systems by 2027. It focuses on improving risk knowledge, observations and forecasting, warning dissemination, and preparedness to respond. The other example of an international support and Initiative is the Global Disaster Alert and Coordination System (GDACS) which provides real-time alerts about natural disasters around the world and facilitates coordination among international responders (UNDRR, 2023a, 2023b). Technology plays a critical role in India's disaster management, with systems such as the National Disaster Management Services (NDMS) ensuring resilient communication for emergency operations, and the Early Warning Dissemination System (EWDS), demonstrated by Odisha's SATARK platform, providing real-time hazard alerts. Satellite technology, including RESOURCESAT and RISAT, enables early detection and monitoring of disasters, while drones and social media platforms support effective communication and coordination during events like the Chennai and Uttarakhand floods. Additionally, GIS and GPS applications, such as Tamil Nadu's TNSMART, offer tools for risk forecasting and disaster response planning. A knowledge-sharing platform to document and facilitate inter-state learning from these practices would further strengthen India's disaster resilience (Role of Technology in Disaster Management: NDMS, Early Warning Systems,

5.

Equitable Access Strategies for Disaster Early Warning Systems

To ensure equitable access to disaster Early Warning Systems and preparedness, strategies must address diverse community vulnerabilities, social dynamics, and technological barriers, with an emphasis on gender sensitivity and local engagement. Women and marginalised groups often face greater obstacles in accessing early warnings due to mobility constraints, caregiving responsibilities, and limited access to communication tools. Gender-sensitive approaches, such as incorporating female voices in alerts, can enhance trust and reach within communities, fostering engagement and resilience (Amaratunga, 2023; De Silva et al., 2015). Leveraging third-generation digital technologies, like mobile apps with tailored messaging, as well as low-cost and familiar technology, can improve accessibility, especially for vulnerable populations in low-resource settings. A people-centred approach is essential, focusing on training and formally involving women in risk assessment, monitoring, and decision-making processes, which strengthens community-level engagement and preparedness (De Silva, 2021; Shah et al., 2022). The Sendai Framework for DRR underscores the empowerment of women as key stakeholders, advocating for their active participation in Early Warning Systems design, policy-making, and community preparedness. Embedding these strategies within legal frameworks and integrating gender-equitable disaster preparedness into school curricula can make preparedness more inclusive and actionable for all population segments (Amaratunga, 2023). Furthermore, robust Early Warning Systems require strengthening infrastructure resilience in high-risk areas and using inclusive communication technologies, such as mobile alerts, community radio, and satellite systems, to reach socially vulnerable and isolated communities. Mapping social vulnerabilities alongside critical infrastructure accessibility can help identify resource disparities and enable targeted response efforts, ensuring that all community members have the resources to respond effectively to disasters (Gangwal & Dong, 2022; Peters et al., 2022).

Achieving equitable access to disaster Early Warning Systems and preparedness relies on integrating local and scientific knowledge to ensure inclusivity. Strategies include incorporating local knowledge through participatory methods, such as community engagement and GIS mapping, which help contextualise Early Warning Systems and enhance their relevance for diverse communities. Addressing power dynamics, communication barriers, and social inequalities is essential to overcoming obstacles to equitable access. Building trust among stakeholders and adopting locally suitable communication methods are also key to ensuring that Early Warning Systems effectively reach vulnerable populations, enabling timely and inclusive disaster response efforts (Hermans et al., 2022). Instead of considering the community as the "last mile" in an end-to-end Early Warning Systems, it is more accurate to view it as the "first mile," where warning information must be received and acted upon. Informed communities understand key risks and are the first responders in safeguarding their households and vulnerable individuals ((IFRC), 2020b; Basher, 2006). Many communities are capable of independently driving Early Warning Systems at the local level without external input, while others are prepared to receive warnings and organise an appropriate response ((IFRC), 2013). The Hyogo Framework for Action (HFA) promotes a "people-centred" approach, where communities are not only receivers but also producers and facilitators of early warning information ((ISDR), 2007).

A Community Early Warning Systems (CEWS) involves a community-led effort to systematically gather, compile, and analyse information, allowing for the dissemination of actionable warning messages that help reduce harm or loss from hazards (Matta et al., 2023). The term "Community Early Warning Systems" (CEWS) helps distinguish between community-based and community-driven systems. While an Early Warning Systems can be established within a community without being community-owned or led, the most lasting impact is achieved when the community has a strong understanding of the system (Parashar & Shaw, 2012; Reid et al., 2010). CEWS focus on community empowerment and ownership at every stage, bridging the gap between receiving warnings and taking action. By placing communities at the centre of the system, CEWS enables anticipatory action, ensuring that warnings are accessible and actionable and that responses are feasible and relevant ((IFRC), 2020a). Juan Carlos Villagran de León (2006) reviewed Early Warning Systems within Disaster Risk Management (DRM), highlighting

the increased disaster frequency and vulnerability caused by inadequate alignment between development and environmental factors. Using the 2004 Indian Ocean tsunami as a key example, they illustrated the consequences of lacking effective Early Warning Systems. Traditionally, Early Warning Systems followed three phases—monitoring, forecasting, and warning dissemination; however, the authors proposed a four-phase model, adding a response phase to enable rapid action post-warning. They compared centralised systems, reliant on national agencies, with decentralised approaches engaging local communities, thereby improving resilience through local involvement. Emphasising people-centred Early Warning Systems, the study advocated for clear communication, public education, and preparedness, with four essential components: risk knowledge, a reliable warning service, clear messaging, and strong response capabilities. The authors identified challenges, including the need for hazard-specific approaches and limited resources in developing regions, concluding that improved governance, legal support, and cross-sector collaboration are crucial for effective disaster mitigation.

6.

Private Sector Contribution to Disaster Early Warning Systems

The private sector significantly boosts disaster Early Warning Systems and strengthens infrastructure resilience through funding, technological innovation, rapid response, and capacity-building efforts. The World Meteorological Organisation (WMO) promotes public-private engagement (PPE) as essential for effective multi-hazard Early Warning Systems and DRR, encouraging collaboration between National Meteorological and Hydrological Services (NMHSs) and private entities to enhance data acquisition, forecasting, and information dissemination while protecting public interests ((WMO), 2014; Fakhruddin). Increasingly, private firms contribute to Early Warning Systems infrastructure, competing with public services in critical areas like data management and innovation. Noteworthy initiatives include New Zealand's Canterbury Geotechnical Database, developed by Tonkin + Taylor company to aid Christchurch's earthquake recovery, and the Kaikōura earthquake's rapid-response damage mapping, where private sector tools improved response time through real-time data sharing with government agencies. In Fiji, partnerships with mobile networks support tsunami warnings, improving communication via mesh network extenders for robust emergency alerts. Projects like Fiji's Coastal Inundation Forecasting integrate meteorological, hydrological, and oceanographic data, underscoring cross-sector collaboration in knowledge and expertise (Fakhruddin).

In the Caribbean, post-Hurricane Maria, partnerships among government agencies, the Red Cross, and regional entities like CDEMA strengthened community-level disaster preparedness and trust, enhancing data sharing and resilience. Economic assessments reveal the value of Early Warning Systems investments, where each dollar yields substantial socio-economic returns, up to $6 in the Pacific and $40.85 over a decade in Asia; in Bangladesh, communities express a willingness to pay for improved Early Warning Systems, highlighting the need for expanded private sector investment in DRR (Fakhruddin & Schick, 2019). Effective PPE for DRR hinges on cross-sectoral dialogue to clarify roles and encourage investment in DRR technologies, which enhances coordination and strengthens community resilience, making private sector involvement indispensable to successful DRR strategies globally (Ahsan et al., 2020).

Private-public partnerships have become essential, with frameworks like the Sendai Framework for DRR highlighting these collaborations to promote risk-informed development and effective Early Warning Systems. Private entities, such as research institutions and corporations, drive advancements in hazard monitoring, data analysis, and communication, crucial for Early Warning Systems functionality. For instance, partnerships in flood-prone areas demonstrate how private companies can support governments in creating monitoring networks and community-driven warning systems, effectively reducing disaster impacts (Clegg et al., 2022). Moreover, the private sector facilitates training and capacity-building within communities, fostering a participatory Early Warning Systems model that empowers local populations to respond proactively. Successful initiatives reveal that community-based systems, often sustained by private sector involvement, lead to better resource allocation and coordination during disasters (Coles & Quintero-Angel, 2018). The private sector plays a vital role in DRR, particularly as climate change, globalisation, and urbanisation heighten disaster risks. With future investments largely from private sources, effective risk management increasingly relies on partnerships with the public sector. Traditionally led by governments, DRR now involves collaborations that integrate disaster risks into business continuity and supply chain resilience strategies. Initiatives from UNISDR emphasise that resilient businesses underpin resilient communities and ecosystems, urging risk-sensitive investments and building standards that surpass minimum codes to mitigate disaster impacts. Early adopters in the private sector are already creating tools, sharing critical data, and innovating products for resilience, supported by government incentives. Initiatives like UNISDR's voluntary commitments indicate a global shift towards comprehensive DRR and preparedness (Johnson & Abe, 2015).

In Asia, regional organisations like ASEAN, SAARC, and APEC are pivotal in enhancing private sector involvement in DRR and fostering cooperation between governments and businesses to strengthen resilience in a high-risk region. Case studies, such as the Indian Ocean Tsunami (2004) and Cyclone Nargis (2008), illustrate how regional frameworks can support private sector engagement across disaster management phases. Key recommendations include promoting cross-border collaboration, establishing clear private sector guidelines, and ensuring accountability for trust-building. Regional agreements, like ASEAN's Disaster Management Framework and SAARC's Rapid Response Protocol, provide a foundation for deploying private sector resources while knowledge-sharing platforms enhance best practices in preparedness. Through these partnerships, the private sector helps build resilient infrastructure, supporting sustainable economic growth across Asia (Chatterjee & Shaw, 2015). In Bangladesh, private sector contributions are crucial in enhancing disaster Early Warning Systems and building resilience in infrastructure. The private sector's involvement, often referred to by corporate social responsibility (CSR) and business continuity needs, has diversified to include several models, such as supporting community resilience, developing infrastructure, and increasing knowledge through training. These contributions include private companies providing resources for community projects like rainwater harvesting and solar-powered water treatment systems, which support communities' self-sufficiency and disaster readiness. Private companies in Bangladesh also contribute to resilience by incorporating DRR elements into workplace safety initiatives, spurred by incidents like the Rana Plaza collapse, which highlighted the importance of safe infrastructure. Partnerships between private entities and government or NGOs further promote DRR, particularly in high-risk areas like Dhaka, where flood and cyclone resilience is crucial (Izumi & Shaw, 2014). The private sector, especially the insurance industry, is essential for enhancing disaster Early Warning Systems and DRR in Europe. Insurance models vary—ranging from private-led (e.g., Germany, Netherlands) to state-controlled (e.g., Switzerland)—with government-mandated policies often increasing coverage and supporting DRR (Joerin & Luo, 2015). In Africa, the private sector's role in DRR and Early Warning Systems is growing, though primarily reactive, often following disasters. Limited government resources make private sector involvement essential, particularly through business continuity management (BCM) and corporate social responsibility (CSR) initiatives, which enhance resilience and community stability. Business continuity planning, especially in sectors like telecommunications, supports Early Warning Systems and minimises operational disruptions. The UNISDR recommends expanding public-private partnerships, data-sharing, and aligning CSR with DRR goals to foster sustainable development and strengthen resilience across high-risk communities (van Niekerk et al., 2015).

7. Lessons from Recent Disasters for Early Warning Systems

Recent disasters like the 2004 Indian Ocean Tsunami, the 2013 Uttarakhand floods, HUDHUD Cyclone (2014), and Kashmir floods (2014) underscore the critical role of advanced Early Warning Systems in mitigating disaster impacts. These events revealed gaps in public awareness, data accessibility, and real-time responsiveness, prompting technological advancements. Tools such as GIS, AI, and multispectral satellite imaging now enhance Early Warning Systems capabilities, providing real-time mapping and damage assessments crucial for rapid response. Community-centric Early Warning Systems and integrated systems like Andhra Pradesh's Early Warning Dissemination System (EWDS) have further strengthened preparedness, especially in high-risk coastal regions. However, challenges in data interoperability, timely communication, and public engagement remain. Addressing these gaps through continued innovation and collaborative Early Warning Systems strategies is essential to protect vulnerable populations and minimize economic losses (Rajyalakshmi et al., 2021).

Various countries have adopted robust flood management techniques to counter the rising risks of severe flooding, leveraging both structural and non-structural methods. In the USA, for example, policies integrate infrastructure like reservoirs and embankments with forecasting and insurance systems, which together mitigate flood impacts effectively (Ma et al., 2019). Italy has developed a comprehensive civil protection system with real-time monitoring of torrent debris flows, featuring forecasting and early warning functions that provide both monitoring and immediate alert capabilities. Similarly, Japan's disaster management administration includes a multi-level, community-based Early Warning Systems supported by local and national government coordination (Cheng, 2008). The European Union has introduced a real-time flood prediction guide that combines numerical rainfall models, hydrological frameworks, and flood forecasting models to enhance prediction accuracy and improve response efficiency (A. Hammood et al., 2021). Flood Early Warning Systems in Europe and Africa have demonstrated varied effectiveness across regions such as Belgium, Egypt, and Mali, where unique regional needs shape each system. In Belgium's Flanders region, an Early Warning Systems developed after severe 1998 flooding employs advanced forecasting and a dense gauge network, providing high-resolution data with extended lead times. In Egypt's Red Sea area, where flash floods occur with little warning, Early Warning Systems depends on local knowledge and community engagement, though real-time data limitations pose challenges. Meanwhile, in Mali's Inner Niger Delta, Early Warning Systems helps forecast seasonal flood variations crucial for agricultural planning, highlighting Early Warning Systems's role in enhancing community resilience and resource management. The study underscores that tailored, locally adapted Early Warning Systems—whether simple or complex—are highly effective, particularly when they integrate community involvement, offering climate adaptation benefits that support sustainable, region-specific responses across various stakeholders (Cools et al., 2016).

Early Warning Systems in DRR often focus on rapid hazard detection and response, but they can overlook underlying socio-economic vulnerabilities that intensify disaster impacts. The Sendai Framework for DRR (2015–2030) emphasises a people-centred, multi-hazard approach that integrates socio-economic factors, aiming to build community resilience and reduce vulnerabilities (Alcántara-Ayala & Oliver-Smith, 2019). In addition, Early Warning Systems systems utilisation depends on real-time data that are received from sophisticated remote sensing technologies to monitor and forecast potential hazards, enabling timely alerts and preparatory measures to protect lives and property. Notable disasters, such as the 2004 Indian Ocean Tsunami and Hurricane Katrina in 2005, highlighted gaps in previous systems, underscoring the necessity for community-based Early Warning Systems that actively involve local governments and employ geo-visual tools for more effective disaster management. In fact, Hurricane Katrina highlighted social inequities in New Orleans, where levee failures and a top-down emergency response disproportionately affected poorer communities (Elliott & Pais, 2006). Similarly, the 2018 Volcán de

Fuego eruption in Guatemala and the Palu earthquake and tsunami in Indonesia revealed the limitations of Early Warning Systems in regions with inadequate funding, infrastructure, and political commitment (Lavell & Brenes, 2019). Early Warning Systems components include monitoring water quality, contamination detection, and forecasting risks like droughts and floods, crucial for regions in Africa, the United States, and Europe. The key functions of Early Warning Systems encompass data gathering, analysis, communication, and coordinated response, supported by institutions such as the UN, FAO, and WMO, with contributions from NGOs and national governments. Although challenges like high operational costs and data accessibility remain, Early Warning Systems continues to be vital in enhancing global resilience against both natural and human-made disasters (Quansah et al., 2010). Poland's Government Centre for Security (GCS) Alert system uses text messaging to warn residents of imminent health or safety threats, particularly from severe weather. Leveraging Poland's extensive mobile network, these free alerts reach all users in affected areas, prompting timely actions like moving vehicles to safer spots and thereby reducing damage. While effective, the system faces inclusivity challenges, especially among vulnerable groups without mobile access, highlighting the need for ongoing improvements to ensure comprehensive disaster preparedness and risk reduction (Goniewicz & Burkle Jr, 2019).

Following the 2004 Indian Ocean tsunami, Indonesia's Tsunami Early Warning Systems (InaTEWS) has made significant strides, yet local-level challenges persist, particularly in enhancing disaster preparedness. Obstacles include limited public awareness, insufficient institutional frameworks, and a need for clearer communication protocols to enable swift responses, especially in regions prone to near-field tsunamis. Pilot projects like GTZ-GITEWS have shown success by blending technological advances with community education, focusing on natural warning signs and evacuation drills to strengthen "last mile" communication. Exercises such as IOWave09 in Aceh demonstrated improvements in local readiness but also underscored the necessity for continuous capacity-building and cross-sector collaboration. Lessons from recent Indonesian earthquakes near Sumatra reinforce the importance of integrating TEWS with community-led preparedness to create a resilient early warning framework (Spahn et al., 2010). Japan's flood Early Warning Systems (FEWS) combine advanced risk knowledge, monitoring, forecasting, warning dissemination, and preparedness to mitigate frequent flood risks from monsoons and typhoons. However, local municipalities face limitations in resources, technical capacity, and effectively reaching vulnerable populations, which impacts the system's overall effectiveness. Despite extensive efforts in mapping flood hazards and assessing social vulnerabilities, challenges persist in maintaining up-to-date, accessible preparedness plans, particularly for groups like the elderly and disabled. Recent disasters, such as Typhoon Hagibis in 2019, illustrate the urgent need for timely, community-specific warnings. The study suggests that strengthening socio-economic vulnerability assessments, enhancing interagency coordination, and improving public education and real-time communication can build more resilient communities and improve FEWS performance in high-risk areas (Cao et al., 2024). Thailand's approach to early warning and disaster management underscores the importance of holistic institutional frameworks that incorporate socio-political and environmental factors. Following the 2004 Indian Ocean Tsunami and the 2011 floods, Thailand established a multi-layered governance structure, including the Disaster Prevention and Mitigation Act (2007) and the National Disaster Warning Center (NDWC). These systems coordinate with the Thai Meteorological Department, the Royal Navy, and local committees to provide warnings. Despite advancements, challenges like jurisdictional overlaps and resource limitations persist, highlighting the need for consistent legislation, local insight integration, and sustained public awareness to enhance resilience and mitigate disaster impacts (Fakhruddin & Chivakidakarn, 2014).

In response to the increasing frequency and severity of climate-related natural disasters, the United Nations launched the "Early Warning for All" initiative, aiming to establish global Early Warning Systems by 2027. Lessons from Japan and China, both leaders in disaster preparedness, offer valuable insights for implementing resilient and effective early warning strategies worldwide. Japan, located along the disaster-prone Pacific Ring of Fire, has developed a highly advanced disaster preparedness framework. Following its devastating 2011 earthquake and tsunami, Japan has strengthened its Early Warning Systems, strict building codes, and response strategies. Key technologies include weather satellites, ground monitoring centres, high-speed computing, and a smartphone app that provides real-time weather updates. Japan also uses the "Fugaku" supercomputer, one of the fastest globally, to predict severe weather events like typhoons weeks in advance.

8.

Opportunities and Recommendations

As highlighted and summarized in recent reports from the United Nations Office for DRR, the Intergovernmental Panel on Climate Change, and the World Bank's Global Facility for Disaster Reduction and Recovery (GFDRR), and the COP29 held in Baku in November 2024, the main gaps and challenges in DRR, along with suggested opportunities and recommendations from this report, are outlined below:

8.1. Data Gaps and Accessibility

Many regions, particularly in low- and middle-income countries, lack reliable data on hazards, vulnerabilities, and exposure. This limits the ability to predict and prepare for disasters. Policymakers and practitioners can use this report to prioritize investment in data collection, open data sharing, and technology that makes real-time data collection more accessible to decision-makers.

8.2. Technological Innovations in DRR and Early Warning Systems

Investment in the following technologies, tools and platforms are highly encouraged:

- **Artificial Intelligence (AI) & Machine Learning (ML):** Advanced models analyze real-time and historical climate data to improve disaster forecasting for floods, wildfires, and hurricanes.
- **Remote Sensing & Satellites:** High-resolution satellite imaging enhances real-time monitoring of weather, sea levels, and soil moisture, aiding Early Warning Systems. Satellites also can be used for monitoring sand and dust storms which can help proactively to combat dissertification.
- **Internet of Things (IoT) Devices:** Smart sensors track air quality, water levels, and seismic activity, providing localized, real-time data for targeted disaster response.
- **Mobile Alerts:** SMS and app notifications deliver timely, community-specific warnings, ensuring rapid action for at-risk populations.
- **Quantum computing:** This can enhance machine learning models by enabling more efficient optimization algorithms. Quantum-enhanced machine learning models could improve predictive accuracy in Early Warning Systems, offering insights into patterns that classical machine learning might struggle to detect.
- **Robotics offers** powerful enhancements to Early Warning Systems by improving real-time monitoring, supporting rapid response, and strengthening disaster preparedness efforts. The capabilities of autonomous drones, ground robots, and underwater systems can advance the field of disaster management by enabling faster, safer, and more efficient responses, ultimately reducing vulnerability and enhancing resilience in communities worldwide.

8.3. Integration of Climate Change Adaptation and Desertification

DRR often operates separately from climate change adaptation efforts, even though climate impacts (like extreme weather, drought, etc) directly influence disaster risk. This report can guide initiatives that integrate climate change adaptation into DRR planning, encouraging cross-sector collaboration to address climate-driven risks comprehensively.

A recent COP16 conference in Riyadh emphasized enhancing adaptation and resilience to drought and to combat Desertification, which aims to restore 1.5 billion hectares of land by 2030.

8.4. Community Engagement and Inclusivity

Many DRR initiatives do not adequately involve local communities, Indigenous knowledge, or marginalized groups, limiting the effectiveness and sustainability of these efforts. Policymakers can use this report to promote inclusive DRR strategies that actively engage communities, ensuring that DRR actions are context-specific and community-driven.

8.5. Lack of Early Warning Systems and Preparedness Measures

While Early Warning Systems have improved, they remain limited in certain high-risk areas, especially in rural or underserved communities. This report can serve as a basis to expand and fund Early Warning Systems, focusing on improving last-mile connectivity and ensuring all communities are covered by reliable alerts and preparedness training.

8.6. Funding and Resource Allocation

Funding for DRR is often reactive rather than proactive, limiting resources for preventive actions. Additionally, funding often does not reach the most vulnerable areas. Policymakers can leverage this report to advocate for increased and more proactive DRR funding and ensure that resources are allocated equitably to areas with the highest need. In addition, appropriate data-driven decision support systems are needed to assist policymakers in allocating DRR fund and resources efficiently.

8.7. Implementation and Enforcement of Policies

Even when policies exist, implementation is often inconsistent due to lack of enforcement, resources, or coordination across agencies. The report can help identify gaps in policy implementation, suggesting frameworks and strategies for strengthening enforcement and accountability at local and national levels. Climate and disaste policies need to be more integrated. They need to be Inclusive and Community-Centered based Policies and they also need to include Financing Mechanisms for Resilience.

8.8. Practical Innovations in DRR and Early Warning Systems

- Community-Based Early Warning Systems: Community-centered approaches in Early Warning Systems are gaining traction, with training provided to local populations on how to respond to alerts. This bottom-up approach increases trust, reduces response time, and ensures that warnings are culturally relevant and accessible.
- Public-Private Partnerships (PPPs): Partnerships between government agencies, private tech firms, and NGOs have accelerated the adoption of new DRR tools. For example, partnerships with telecommunications companies ensure the rapid dissemination of Early Warning Systems alerts via SMS and mobile apps.
- Risk Communication Strategies: New risk communication frameworks make warnings simpler and more actionable, using clear, concise language to convey urgency. Governments and NGOs use behaviour-informed messaging to ensure people understand warnings and know how to respond.
- Data-Driven Resilience Planning: Big data and GIS mapping are used to create detailed risk assessments and inform urban planning and development. Vulnerable areas can be identified more precisely, and communities can plan accordingly, reducing their exposure to future hazards.

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ANNEX A: List of technologies used in the report related to DRR and Early Warning Systems

Technology	Description	The role in DRR and Early Warning Systems
Artificial Intelligence (AI) and Machine Learning (ML)	refer to technologies that enable computers to simulate human intelligence and learn from data. AI involves creating systems that can perform tasks typically requiring human cognition, while ML focuses on algorithms that allow computers to improve their performance through experience, without explicit programming. These technologies are used in various applications, such as predictive analytics, automation, and enhancing decision-making processes.	AI and ML enhance DRR and Early Warning Systems by improving disaster prediction, real-time data processing, and risk assessment. They enable more accurate forecasts, faster response times, and optimized resource allocation. AI and ML also assist in decision-making by simulating scenarios and providing insights, while their continuous learning capabilities refine predictions over time. Additionally, AI improves communication through tailored alerts, ensuring timely warnings reach affected communities. These technologies make DRR and Early Warning Systems more proactive, efficient, and effective in mitigating disaster impacts.
Remote Sensing & Satellites	involve the use of satellites and sensors to collect data and images from the Earth's surface, atmosphere, and oceans without direct contact. These technologies capture information in various wavelengths, such as visible light, infrared, and radar, allowing for the monitoring of environmental conditions, weather patterns, and natural disasters.	Remote sensing by providing real time data can track changes in the environment like deforestation, urbanization, and sea level rise. Satellites also play a key role in DRR and Early Warning Systems, damage assessment, and resource allocation, improving decision-making and response times during crises.
Internet of Things (IoT)	It refers to a network of physical devices, vehicles, appliances, and other objects embedded with sensors, software, and connectivity, allowing them to collect and exchange data over the internet. These devices can be anything from smart thermostats and wearables to industrial machines and environmental sensors.	In the context of DRR and Early Warning Systems, IoT devices, like flood sensors, temperature monitors, and air quality detectors, provide real-time data that can help predict disasters, improve response times, and enhance the overall effectiveness of warning systems.

Quantum computing	It is an advanced field of computing that uses the principles of quantum mechanics, which is the science of the very small particles (like atoms and photons). Unlike traditional computers that use bits (representing either 0 or 1), quantum computers use qubits, which can represent and store multiple states at once due to the phenomenon of superposition. Quantum computing has the potential to process complex problems much faster than classical computers by solving problems that would otherwise take traditional computers too long.	In the context of DRR and Early Warning Systems, quantum computing could improve simulations and predictions related to climate change, disaster forecasting, and optimization of emergency response plans by processing vast amounts of data more efficiently. When Quantum computing integrated with IoT and Remote Sensing & Satellite technologies, it improves the accuracy and speed of disaster risk identification and assessments.
Robotics	Robotics refers to the design, construction, operation, and use of robots—automated machines that can perform tasks without human intervention. Robots can be programmed to carry out a wide range of actions, from simple repetitive tasks to complex operations involving advanced sensors and artificial intelligence.	In the context of DRR and Early Warning Systems, robotics plays a crucial role by deploying autonomous machines such as drones, ground robots, or underwater robots to carry out tasks like disaster monitoring, damage assessment, search-and-rescue operations, and providing real-time data from hazardous or hard-to-reach areas.

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