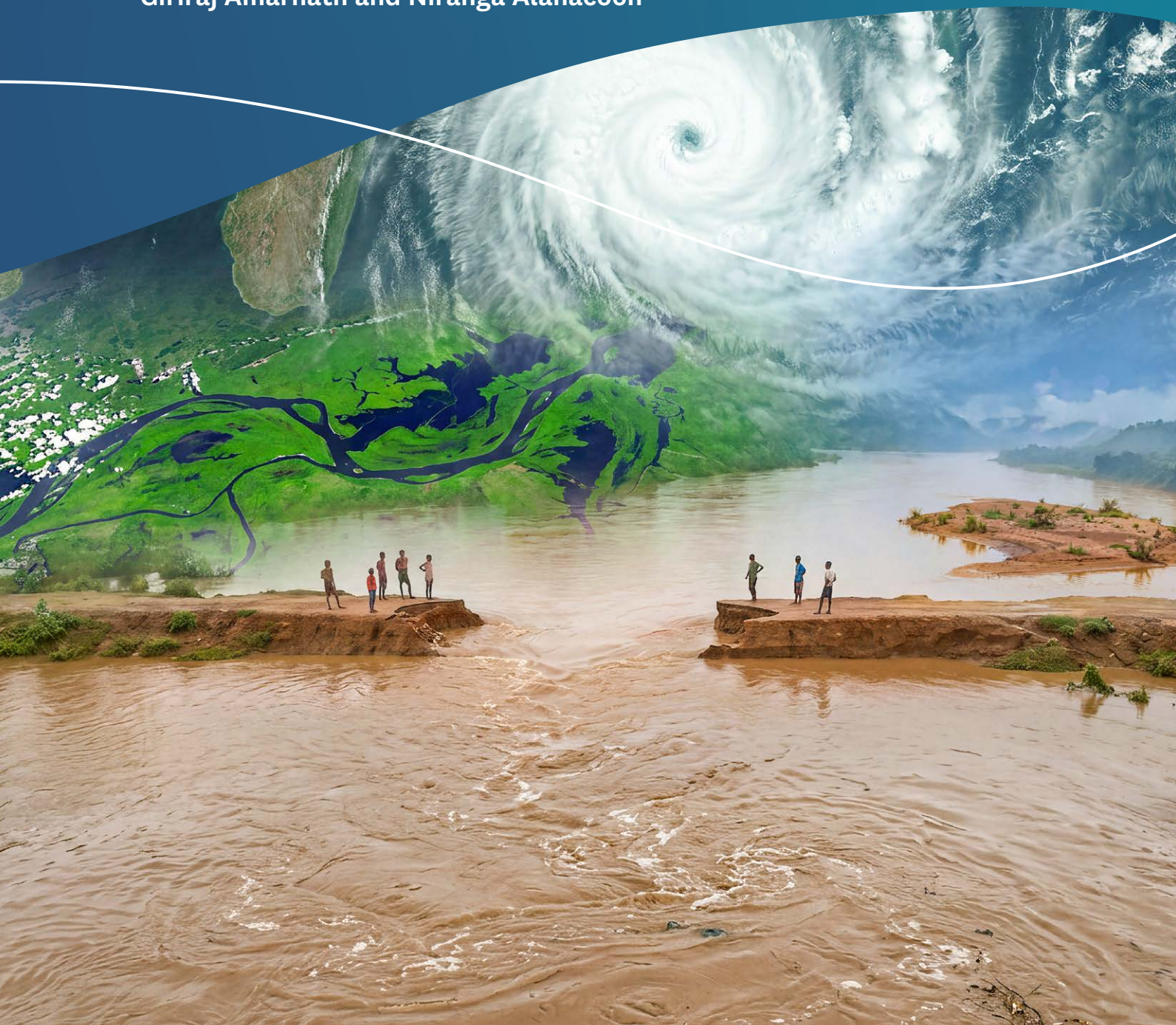
IWMI International Water Management Institute

The State of Early Warning Around the World

A synthesis of findings presented during the IWMI webinar series *Eyes on the Storm*, aimed at promoting ongoing action towards achieving the United Nations' Early Warnings for All (EW4All) initiative

Giriraj Amarnath and Niranga Alahacoon



Authors
Giriraj Amarnath, Principal Researcher – Disaster Risk Management and Climate Resilience, and Research Group Lead – Water Data for Climate Resilience, International Water Management Institute (IWMI), Colombo, Sri Lanka
Niranga Alahacoon, Regional Researcher – Remote Sensing and Disaster Risk Specialist, IWMI, Colombo Sri Lanka

Author contributions
Conceptualization: Giriraj Amarnath; Methodology: Giriraj Amarnath, Niranga Alahacoon; Validation: Giriraj Amarnath, Niranga Alahacoon; Formal analysis: Giriraj Amarnath, Niranga Alahacoon; Investigation: Giriraj Amarnath, Niranga Alahacoon; Resources: Giriraj Amarnath; Data curation: Niranga Alahacoon; Writing – original draft: Giriraj Amarnath, Niranga Alahacoon; Writing – review & editing: Giriraj Amarnath, Niranga Alahacoon; Visualization: Niranga Alahacoon, Giriraj Amarnath; Supervision: Giriraj Amarnath; Project administration: Giriraj Amarnath; Funding acquisition: Giriraj Amarnath.

Photography
Front cover: A tropical cyclone bears down on a flooded river basin while, below, families displaced by floods gather: the chain of early warning from satellite to last mile. Composite of a NASA Earth Observatory image of Cyclone Batsirai over Madagascar (February 2022); a Landsat satellite view of flood extent; and a community in Zambia after the floods of January 2023. Photos: NASA Earth Observatory; NASA/USGS Landsat; AI-generated, Zambia. Composite: IWMI.

Back cover: Counting the cost: a road bridge washed away by floodwaters, with an automatic weather station in the foreground. The observations such stations provide are what turn global forecasts into local warnings. Photos: AI generated. Composite: IWMI.

Design and layout
Mario Bahar, Gracewinds Advertising

Citation
Amarnath, Giriraj, and Niranga Alahacoon. 2026. *The State of Early Warning Around the World*. International Water Management Institute (IWMI). https://doi.org/10.5337/2026.232.

ISBN
ISBN 978-92-95131-10-1 (PRINT)
ISBN 978-92-95131-11-8 (PDF)

© 2026 International Water Management Institute. Some rights reserved. This work is licensed under a Creative Commons Attribution 4.0 International License (CC BY 4.0).

Disclaimer: This publication has not been independently peer reviewed. Responsibility for opinions expressed and any possible errors lies with the authors and not the institutions involved. The boundaries, colors, denominations and any other information shown on maps do not imply any judgment on the legal status of any territory, or any endorsement or acceptance of such boundaries, on the part of IWMI, its funders, or its partners.

IWMI encourages the use of its material provided that the organization is acknowledged and kept informed in all such instances.

Acknowledgments

This report synthesizes the Eyes on the Storm webinar series convened by the International Water Management Institute (IWMI) in 2025–2026 to advance the United Nations' Early Warnings for All (EW4All) initiative. It would not have been possible without the generosity of the many people who shared their knowledge and time.

We thank the more than 95 presenters, moderators, and discussants (see Annex 1) for sharing their expertise throughout the series and informing the relevant sections of this report. Any remaining errors are the authors' own. The series attracted more than 1,400 participants worldwide.

The webinar series was a collaboration between IWMI and the International Telecommunication Union (ITU), the World Meteorological Organization (WMO), COPE Disaster, the International Federation of Red Cross and Red Crescent Societies (IFRC), the Risk-informed Early Action Partnership (REAP), the UK Met Office, the United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP), the United Nations Office for Disaster Risk Reduction (UNDRR), and the Coalition for Disaster Resilient Infrastructure (CDRI). We thank each partner for co-designing sessions, nominating speakers, and extending the reach of the series to their own networks.

We thank Carolyn Fry, Writer and Communications Consultant, for drafting the report from the webinar recordings and transcripts and for her patience through successive rounds of review. At IWMI, Sushila De Silva, Juliane Reissig, and Dominique Perera of the Communications and Knowledge Management team, along with Sanjeewa Amarasekara Razali Iyne of the Information and Communication Technology (ICT) Unit, coordinated the webinar series. Research Officer Kalpani Jaymini helped compile the materials, and former intern Ranoja Dickowita helped host the sessions. We also thank Ian Overton and John Simaika for their critical review of the draft, and Andrew Ebell and Saanya Amalean for their timely support with the report's design and layout.

The images, maps, and figures reproduced here are credited to their sources beside each figure, and we thank the organizations and individuals who granted permission for their use. This work was partially supported by the CGIAR Climate Action Program and by Japan's Ministry of Agriculture, Forestry and Fisheries. The authors are grateful for the support of the CGIAR Trust Fund contributors (www.cgiar.org/funders).





Contents

Acronyms and Abbreviations IV

Foreword 1

Foreword 2

Summary 3

Key Recommendations 4

Galvanizing Action to Save Lives 6

- How the Concept of Early Warnings Evolved 6
- Four Pillars Underpin Effective Early Warning 7
- Progress Toward Achieving EW4All by 2027 9

Part 1: The Foundations of Early Warning 11

- The Four Pillars: Key Challenges and Potential Solutions 11
- How Technology is Fundamental to Early Warnings 14

Part 2: Successes and Challenges of Multi-Hazard Early Warning Systems 19

- Advancing Early Warning for Heatwaves 19
- Managing the Threat of Destructive Floods 23
- Accelerating Action on Drought 27
- Strengthening Early Warning for Landslides and Tsunamis 31

Part 3: The Key to Resilient Communities 37

- Building Resilience through Community-Led Early Warning Systems 37
- Preventing Crises from Escalating 46

Part 4: Harnessing Transformative Technology 49

- Applying the Power of Artificial Intelligence for EW4All 49
- Employing Eyes in the Sky 53

Part 5: Inclusivity, Behavior, and Communication 58

- Embedding Equity and Inclusion in Early Warning Systems 58
- Translating Warnings into Action 61
- Bridging the Last Mile 65

Part 6: Investing in Preparedness 69

- Nurturing Public-Private Partnerships 69
- Financing Before Disaster Strikes 72
- Putting Early Warning Center Stage 76

Conclusion 78

References 79

Annex 1. List of Experts Consulted During the Eyes on the Storm Webinar Series 82

Acronyms and Abbreviations

ADB	Asian Development Bank
AI	Artificial Intelligence
AIDMI	All India Disaster Mitigation Institute
ARC	African Risk Capacity
AU	African Union
AUC	African Union Commission
AWARE	Early Warning, Early Action, Early Finance (platform)
CDRI	Coalition for Disaster Resilient Infrastructure
CEEW	Council on Energy, Environment and Water
CIMH	Caribbean Institute of Meteorology and Hydrology
CMCC	Euro-Mediterranean Centre on Climate Change
CREWS	Climate Risk and Early Warning Systems
CSO	Civil society organisation(s)
DMC	Disaster Management Centre (Sri Lanka)
ENACTS	Enhancing National Climate Services
EW4All	Early Warnings for All (United Nations initiative)
EWCM	Early Warning Connectivity Map
FAO	Food and Agriculture Organization of the United Nations
FEWS NET	Famine Early Warning Systems Network
GESI	Gender Equality and Social Inclusion
GHHIN	Global Heat Health Information Network
GLOF	Glacial Lake Outburst Flood
GloFas	Global Flood Awareness System
GNDR	Global Network of Civil Society Organisations for Disaster Reduction
GSMA	Global System for Mobile Communications Association
ICIMOD	International Centre for Integrated Mountain Development
IDNDR	International Decade for Natural Disaster Reduction
IFRC	International Federation of Red Cross and Red Crescent Societies
IIED	International Institute for Environment and Development
IMD	India Meteorological Department

ISRO	Indian Space Research Organisation
ITU	International Telecommunication Union
IWMI	International Water Management Institute
MedEWSa	Mediterranean and pan-European forecast and Early Warning Systems against natural hazard
MHEWS	Multi-Hazard Early Warning Systems
NBRO	National Building Research Organisation
NCMRWF	National Centre for Medium Range Weather Forecasting
NDEM	National Database for Emergency Management
NDMA	National Disaster Management Authority
NEPS	NCMRWF Ensemble Prediction System
NGO	Non-governmental organization(s)
NHPC	National Hydroelectric Power Corporation Limited
SADMS	South Asia Drought Monitoring System
SAR	Synthetic Aperture Radar
SIDS	Small Island Developing States
SOFF	Systematic Observation and Financing Facility
UNCCD	United Nations Convention to Combat Desertification
UNDRR	United Nations Office for Disaster Risk Reduction
UNESCO–IOC	Intergovernmental Oceanographic Commission of UNESCO
WCSSP	Weather and Climate Science for Service Partnership
WFP	World Food Programme
WISER-EWSA	Weather and Climate Information Services Early Warning for Southern Africa
WMO	World Meteorological Organization
ZMD	Zambia Meteorological Department

Foreword

Water is the medium through which most climate disasters arrive. The people who suffer first, therefore, are farmers, herders, and fishing families and their communities, whose livelihoods depend on knowing what the next season will bring. That is why an institute founded to improve the management of water has placed early warning at the center of its work, and why we convened *Eyes on the Storm*.

When IWMI launched the webinar series in March 2025, our aim was to give the people building early warning systems, from national meteorological services to village disaster committees, a place to compare notes. More than 95 practitioners representing the World Meteorological Organization (WMO), United Nations Office for Disaster Risk Reduction (UNDRR), International Telecommunication Union (ITU), International Federation of Red Cross and Red Crescent Societies (IFRC), space agencies, insurers, hydropower operators, grassroots networks, and national agencies exchanged lessons on successes and setbacks. The series drew more than 1,400 participants worldwide. This report distils those conversations.

The picture is one of real progress as well as unfinished business. Sixty per cent of countries now report a multi-hazard early warning system, double the share a decade ago, and countries with comprehensive systems record disaster mortality nearly six times lower. Yet three in ten people who experienced a hazard in the past five years received no warning at all, and the last mile between the message and the household is where the chain most often breaks.

Three lessons stand out. Technology is no longer the binding constraint; ensemble forecasts, radar satellites, and Artificial Intelligence (AI)-assisted flood models are in operational use from Zambia to the Hindu Kush. Warnings are only useful when they are trusted and acted upon; practitioner after practitioner in these pages makes the same point, that an early warning system is built far more on communities than on technology. And slow-onset hazards, drought above all, remain underprioritized because they arrive quietly. This is why IWMI launched the Drought Action Catalyst at the UN Convention to Combat Desertification (UNCCD) Conference of the Parties (COP) 17 in 2026.

I hope governments and their partners will use this synthesis as a benchmark against which to assess their own early warning systems across the four pillars of the Early Warnings for All (EW4All) framework, as a catalogue of proven practice to adapt rather than reinvent, and as a case for investing before disasters strike. Its recommendations are achievable within the 2027 horizon of the UN Early Warnings for All (EW4All) initiative.

I thank the CGIAR Climate Action Program and Japan's Ministry of Agriculture, Forestry and Fisheries for their support, our co-convening partners, the speakers who gave their time, and Dr. Giriraj Amarnath and the IWMI team who turned a webinar series into a body of evidence. The storms will keep coming. This report helps ensure that fewer of them become disasters.



Mark Smith
Director General, International Water Management Institute (IWMI)

सत्यमेव जयते

डॉ. टी. श्रीनिवास कुमार
Dr. T. SRINIVASA KUMAR

सचिव
भारत सरकार
पृथ्वी विज्ञान मंत्रालय
पृथ्वी भवन, लोदी रोड़, नई दिल्ली–110003
SECRETARY
GOVERNMENT OF INDIA
MINISTRY OF EARTH SCIENCES
PRITHVI BHAWAN, LODHI ROAD, NEW DELHI-110003

Foreword

The Indian Ocean tsunami of 26 December 2004 was a defining moment in the history of disaster risk reduction. In the absence of a regional tsunami warning system, the disaster claimed nearly 230,000 lives across 14 countries, including approximately 35,000 in Sri Lanka and over 10,000 in India. The tragedy underscored the urgent need for robust, science-based early warning systems and regional cooperation to safeguard vulnerable communities. I had the opportunity to be part of the team that subsequently established the Indian Tsunami Early Warning Centre at the Indian National Centre for Ocean Information Services (INCOIS). From those early efforts, India has emerged as one of the three Tsunami Service Providers for the Indian Ocean region, capable of disseminating tsunami advisories to coastal authorities within minutes of a potential tsunamigenic earthquake. This journey, from a critical gap in regional preparedness to a robust early warning capability, exemplifies what sustained investment in science, technology and institutional capacity can achieve.

The Ministry of Earth Sciences, Government of India, has continued to advance this vision across the spectrum of natural hazards. Significant progress has been made in strengthening India's forecasting and early warning capabilities. The India Meteorological Department (IMD) has advanced numerical weather prediction to increasingly finer spatial resolutions, including 6 km and, more recently, 1 km resolution. The National Centre for Medium Range Weather Forecasting (NCMRWF) has strengthened ensemble-based prediction capabilities, enabling more comprehensive assessment of forecast uncertainty and the likelihood of extreme weather events. Equally significant has been the evolution of impact-based forecasting and warning systems for cyclones, which, together with improved preparedness, coordinated response and timely evacuation, have contributed to a remarkable reduction in loss of human lives. These achievements reflect nearly two decades of sustained investment in scientific research, technological innovation and operational capacity.

At the same time, the challenges ahead remain considerable. The effectiveness of an early warning system cannot be measured merely by the accuracy of a forecast or the speed with which a warning is issued; it must ultimately be measured by whether the warning reaches the most vulnerable communities and enables timely, appropriate action. Strengthening the last-mile dissemination of warnings and translating information into effective responses therefore remain critical priorities.

The report *Eyes on the Storm* is particularly valuable in bringing together the experiences and perspectives of practitioners, national institutions and partners, especially from the Global South. Its integrated treatment of the four pillars of early warning systems reinforces the fundamental principle that these pillars must function as an interconnected value chain. The report also makes an important contribution by highlighting that much of the requisite science and technology is already available; the priority now is to strengthen institutional arrangements, partnerships, governance and implementation so that these capabilities translate into meaningful protection for people and communities.

India strongly supports the United Nations' *Early Warnings for All* initiative and remains committed to contributing its scientific expertise, technological capabilities and institutional experience towards this global endeavour. We remain ready to share our experience and collaborate with countries seeking to strengthen their early warning capabilities.

I congratulate the International Water Management Institute (IWMI) and all its partners on bringing out this timely and important report. I commend *Eyes on the Storm* to policymakers, scientific institutions, disaster management authorities and development partners, and hope that it will contribute meaningfully to advancing the global ambition of ensuring that every person, everywhere, is protected by effective early warning systems.

(T. Srinivasa Kumar)

Tel. : +91-11-24629771, 24629772 ❑ E-mail : secretary@moes.gov.in

Summary

This report is based on the webinar series Eyes on the Storm, hosted by the International Water Management Institute (IWMI). Comprising 16 sessions, the series convened experts from around the world to share insights and lessons learned from their efforts to conceptualize, develop, and implement early warning systems (IWMI 2025). The aim was to strengthen disaster preparedness across multiple hazards, sectors, and regions in line with the United Nations' Early Warnings for All (EW4All) initiative. EW4All was launched in 2022 by UN Secretary-General António Guterres, with the aim of ensuring everyone on Earth is protected from hazardous weather, water or climate events through early warning systems by the end of 2027.

The Eyes on the Storm webinar series was convened by IWMI at the midpoint of the EW4All delivery period. In gathering together policymakers, practitioners, and representatives from the private sector and civil society—from all over the world—it sought to keep up the momentum for achieving the ambitions of EW4All. Specifically, it aimed to pinpoint current issues and gaps, identify best-practice approaches and techniques, and share knowledge— focusing on building resilience in vulnerable regions. The presentations highlighted progress in many aspects of early warning—including advances in forecasting hazards using Artificial Intelligence (AI). However, they also shed light on multiple challenges to both issuing warnings and ensuring those on the receiving end respond appropriately.

Natural hazards come in all shapes and sizes—encompassing heatwaves, floods, wildfires, droughts, landslides, earthquakes, tsunamis, and more. Climate change is increasing the intensity and frequency of many hazards, making the need for early warning systems greater than ever. This year, a double earthquake in Venezuela killed thousands, droughts led to wildfires across southern and western Europe, glacial collapse and flash floods devastated communities in Nepal and Tibet, and a super-charged El Niño began to emerge. Disasters in the first half of 2026 alone, according to Munich Re, caused worldwide losses estimated at USD 112 billion. Early warning systems have a huge role to play in cutting financial losses from disasters in future.

The experiences and case studies presented in this report highlight just how complex the process is of issuing warnings and ensuring people act appropriately in response. It requires understanding of when and where a hazard may occur and how intensively; who it may affect; how to make warnings inclusive and understood by all; and how to ensure that those receiving warnings take appropriate action to safeguard themselves and their assets. It calls for expertise in meteorology, technology (including remote sensing and AI), gender and inclusivity, psychology, finance, and governance. An effective early warning system cannot simply be imposed on those likely to be affected; its development requires the involvement of everyone—from communities on the frontline of hazards, to scientific institutions, humanitarian organizations, finance and insurance providers, and government at local to national levels.

Time is running out for the world to meet the UN's ambition of EW4All by the end of 2027. However, since the start of the initiative, EW4All has sparked positive political will, strengthened international cooperation, mobilized financing, and accelerated the implementation of early warning systems across many parts of the world. By presenting this synthesis as 2027 approaches, the hope is to keep up the momentum for building effective and inclusive early warning systems. Drawing on the case studies presented during the Eyes on the Storm webinar series, we outline a series of recommendations for how best to achieve the EW4All ambition. Everyone deserves timely warnings of impending natural hazards, clear guidance to protect lives and livelihoods, and the resources to act before disaster strikes.

Key Recommendations

Improve access to accurate and reliable environmental forecasts

Ensure that decision-makers and practitioners can access high-quality meteorological, hydrological, and climate forecasts at resolutions appropriate to their use, which comply with agreed standards and encompass uncertainty ranges. Reliable and interoperable data products underpin early warning systems and enable institutions to make timely decisions.

Expand observation networks in climate-risk hotspots

Invest in additional weather, hydrological, and other environmental monitoring stations, particularly in underserved and high-risk areas. Combining ground observations with satellite and other remote observation data will help to calibrate models, improve the accuracy of forecasts, and strengthen countries' ability to identify emerging hazards at the required spatial and temporal scales.

Translate hazard forecasts into intelligence on locations most at risk

Integrate forecasts with data on exposure, vulnerability, infrastructure, and livelihoods to identify high-risk communities, assets, and sectors, and inform appropriate action in advance of a hazard occurring. Early warning systems must move beyond simply identifying where a flood, drought or other hazard may occur, towards understanding who and what is at risk.

Provide early warning of multiple and cascading threats

Design systems that can assess and warn of interacting and cascading hazards. Farmers and vulnerable communities rarely experience risks in isolation – drought, heat, floods, disease outbreaks, market disruptions, conflict, and food insecurity can reinforce one another. Acknowledging that multiple hazards frequently occur simultaneously can ensure that communities plan and prepare for real-life scenarios.

Systematically connect early warning with anticipatory action

Link hazard forecasts to predefined actions so that governments, humanitarian organizations, and communities can act before a crisis escalates. This calls for clearly-delineated hazard thresholds and pre-agreed actions so that predictions are connected directly with actions to safeguard lives, health, agriculture, water resources, and infrastructure.

Prioritize the last mile in national early warning investments

Focus resources on the communities that remain least likely to receive or act on warnings, particularly remote and marginalized populations. Early warning systems should combine digital technologies with low-tech, no-tech, and traditional communication channels to overcome connectivity and access gaps.

Make early warning systems people-centered and locally led

Co-create early warning systems with communities so that messages reflect local risks, languages, knowledge, and communication preferences. Trusted local actors, including community leaders and resilience agents, can help translate warnings into actions that people understand and trust.

Design early warning systems for inclusion from the outset

Ensure early warning systems systematically account for differences in gender, age, disability, language, income, and other factors that affect people's ability to receive and act on warnings. Disaggregated data should be used to identify who is being excluded and to ensure that communication formats, technologies, and response plans meet diverse needs.

Harness emerging technologies while strengthening institutional capacity

Capitalize on Artificial Intelligence (AI), advanced Earth observation technologies, the Internet of Things (IoT) and new modelling approaches to improve data integration, forecasting, and decision support. This must go hand in hand with capacity development and improved access to appropriate infrastructure, particularly for disaster management and climate service institutions in the Global South.

Mobilize finance before disasters occur

Treat early warning as an investment in risk reduction and resilience, with dedicated and sustainable financing, rather than relying on post disaster funding. Governments, development partners, insurers, investors, and the private sector should explore mechanisms that link early warning investment to wider resilience, climate, and disaster-risk financing. Private sector involvement should expand to cover all aspects of the early warning value chain.

Mainstream early warning within governance

Embed early warning within national systems of governance, ensuring that clear coordination mechanisms and well-defined institutional responsibilities connect scientific agencies, emergency management, local government, communities, humanitarian actors, and the private sector. Early warning must be integrated into routine national and subnational planning if the world is to achieve the ambition of Early Warnings for All.

Galvanizing Action to Save Lives

How the Concept of Early Warnings Evolved

Human efforts to warn people of impending natural disasters have evolved down the centuries. In ancient times, Pacific islanders used bird behavior, changes in sea level, and unusual cloud formations to forecast cyclones. During the 18th and 19th centuries, Japan drew links between offshore earthquakes and tsunamis and began developing warning systems for coastal communities. And following World War II, radar was adapted to track storms, and meteorological services greatly improved.

During the 1970s and 1980s, there was a notable rise in the human and economic toll from natural events such as earthquakes, floods, droughts, and hurricanes. Among others, the Bhola cyclone of 1970 killed between 300,000 and 500,000 people in East Pakistan (now Bangladesh), making it the deadliest tropical cyclone in recorded history (WMO 2020). The Tangshan earthquake of 1976 killed at least 242,000 people in China (Wikipedia 2026). The Armero volcanic eruption and destructive mudflow in Colombia in 1985 killed some 25,000 people (Pannell 2025).

Evidence that human activities were affecting levels of greenhouse gases in the atmosphere—with the potential to affect the global climate—was also emerging at this time. In 1990, the newly founded Intergovernmental Panel on Climate Change's (IPCC) First Assessment Report noted an observed global warming of 0.3–0.6°C over the preceding century, and concluded that climate change was a global challenge requiring international cooperation (IPCC and WMO 1992). The report's findings formed the basis for the scientific understanding that increased global temperatures would bring about more frequent and severe extreme weather events in future.

To reduce the impact of natural disasters worldwide—particularly in developing nations where the impacts were greatest—the UN declared the nineties the International Decade for Natural Disaster Reduction (IDNDR). It sought to enhance understanding of natural hazards, promote national disaster-reduction policies, foster international cooperation and knowledge sharing, encourage use of technology to reduce risks, and integrate disaster risk reduction into planning for development.

A key understanding that arose from the IDNDR was that human disasters were not simply 'natural' but were worsened when communities were particularly vulnerable or not prepared. There was a growing understanding that scientific knowledge and technology—such as hazard mapping, early warning systems, and better construction—could greatly reduce risk. This helped to drive a shift from disaster response primarily focusing on relief and recovery, to greater efforts to prepare for and mitigate the potential impacts from natural hazards.

In 2005, a year after the Indian Ocean tsunami had killed almost 228,000 people and wrought economic losses exceeding USD 10 billion, the Hyogo Framework for Action 2005–2015 was adopted. The first comprehensive global plan for reducing disaster risks, it sought to substantially reduce losses in lives, property, infrastructure, and livelihoods. It helped to integrate disaster risk reduction into development planning, highlighted the need for stronger implementation and accountability, and paved the way for the Sendai Framework 2015–2030 for Disaster Risk Reduction, a more detailed and inclusive strategy.

Building on the work of the preceding decades, the Sendai Framework (UNDRR 2015) provides seven targets, to:

- Substantially reduce global disaster mortality by 2030, aiming to lower the average per 100,000 global mortality rate in the decade 2020–2030 compared to the period 2005–2015;
- Substantially reduce the number of affected people globally by 2030, aiming to lower the average global figure per 100,000 in the decade 2020–2030 compared to the period 2005–2015;
- Reduce direct disaster economic loss in relation to global gross domestic product (GDP) by 2030;
- Substantially reduce disaster damage to critical infrastructure and disruption of basic services, among them health and educational facilities, including through developing their resilience by 2030;
- Substantially increase the number of countries with national and local disaster risk reduction strategies by 2020;
- Substantially enhance international cooperation to developing countries through adequate and sustainable support to complement their national actions for implementation of the present Framework by 2030; and
- Substantially increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to people by 2030.

The EW4All initiative (Figure 1) is a drive to implement the Sendai Framework's early warnings targets. In launching the initiative, the UN sought to ensure everyone on Earth would be protected from hazardous weather, water or climate events through life-saving early warning systems. At a time when extreme weather events are escalating, and the risk of multiple hazards occurring simultaneously is growing, EW4All is also helping to drive international and cross-institutional collaboration and accelerate investment to address nations' vulnerability to climate change by strengthening their resilience to all natural hazards.

Four Pillars Underpin Effective Early Warning

The EW4All initiative is built on four pillars: knowledge of disaster risk; detecting, observing, monitoring, analyzing, and forecasting; communicating and disseminating warnings; and preparedness and capability to respond (Box 1). Introduced in 2003 at the 2nd International Conference on Early Warning (UNOOSA, n.d.), the Four Pillars of Early Warning framework was formalized in the UN's 2006 *Global Survey of Early Warning Systems*, which assessed existing gaps in capacities and opportunities for building a comprehensive global early warning system for all natural hazards.

Today, the framework is widely accepted as an effective way for nations to build and operate effective and inclusive Multi-Hazard Early Warning Systems (MHEWS). According to Johan Stander, Senior Director of Services for the World Meteorological Organization (WMO), effective early warning is only possible if there is a strong connection between these four components. "The full value cycle requires active engagement, interaction between and involvement of all actors including national and local governments, and a wide range of stakeholders at all levels," he says.

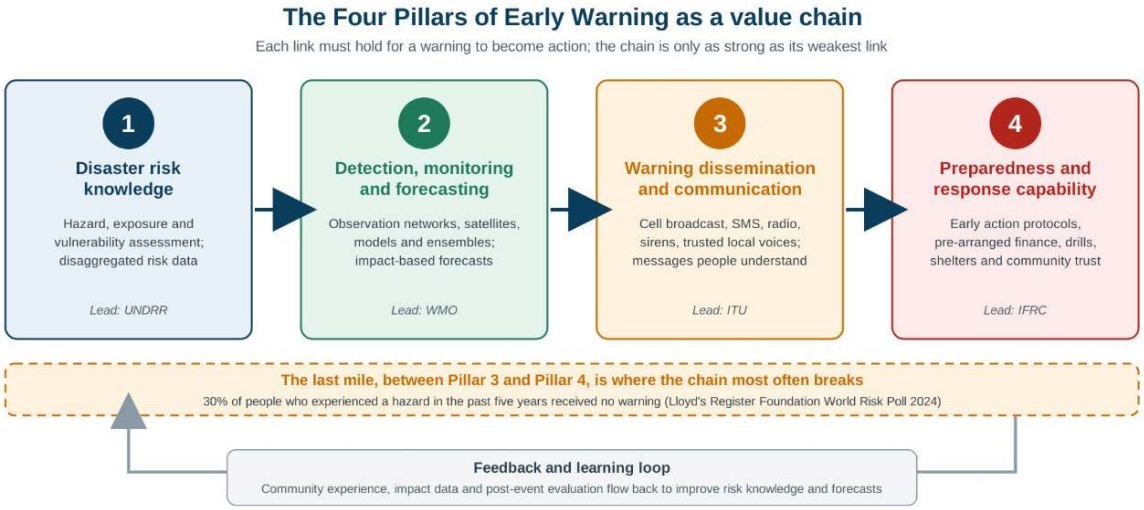


Figure 1. EW4All's Four Pillars of Early Warning as a value chain. Each link must hold for a forecast to become action, and the last mile between dissemination and response is where the chain most often breaks.
Source: Authors' creation based on the UN Early Warnings for All framework and the WMO Warning Value Chain

Box 1. EW4All's Four Pillars of Early Warning framework

1. **Knowledge of disaster risk**
   This involves undertaking risk assessments to understand the likelihood of different kinds of hazards occurring; how exposed communities are to those risks; and the levels of vulnerability among those communities.
   Led by the United Nations Office for Disaster Risk Reduction

2. **Detecting, observing, monitoring, analyzing, and forecasting**
   This demands continuous monitoring of the indicators for hazards (such as using seismographs to record ground movements in areas at risk from earthquakes or analyzing rainfall and temperature anomalies in drought-prone areas), collecting data in real time, and detecting threats in a timely manner, forecasting their trajectories and issuing warnings.
   Led by the World Meteorological Organization

3. **Communicating and disseminating warnings**
   This requires warnings of forecast hazards to be disseminated in a timely and understandable way to communities at risk, using multiple communications channels (via real time data shared between national agencies; radio broadcasts; mobile phone messages; loudspeaker and public address systems; sirens; and social media push notifications, among others), with messages tailored for different audiences (such as young people, or those who are illiterate, for example).
   Led by the International Telecommunication Union

4. **Preparedness and capability to respond**
   This involves ensuring that authorities and communities know how to act when warnings are issued. It calls for preparatory activities, such as emergency planning, educating people about potential hazards, and warning signals, drills, and capacity building within vulnerable societies.
   Led by the International Federation of Red Cross and Red Crescent Societies

Progress Toward Achieving EW4All by 2027

EW4All began by targeting 30 of the world's Least Developed Countries (LDCs) and Small Island Developing States (SIDS), selected due to being highly vulnerable to climate-related and natural hazards, and often suffering disproportionately large impacts from events. These were:

- **Asia and Pacific:** Bangladesh, Cambodia, Fiji, Kiribati, Lao (People's Democratic Republic), Maldives, Nepal, Samoa, Solomon Islands, Tonga;
- **Africa:** Chad, Comoros, Djibouti, Ethiopia, Liberia, Madagascar, Mauritius, Mozambique, Niger, Somalia, South Sudan, Sudan, Uganda;
- **Latin America and Caribbean:** Antigua and Barbuda, Barbados, Ecuador, Guatemala, Guyana, Haiti; and
- **Central Asia:** Tajikistan (WMO 2023a).

The initiative's partners are working with each country or state to identify the minimum core capabilities required to provide an effective early warning service, to develop tools and technical guidance, to rapidly mobilize resources (Box 2), and achieve a high level of political engagement. The aim is to develop, run pilot studies for, and refine MHEWS in these countries, forging strong partnerships between governments, UN agencies, non-governmental organizations (NGOs), and donors in the process. By demonstrating the results from models in these target nations, the hope is to build momentum in many more places.

Since EW4All was launched, measurable progress has been made. *The Global Status of Multi-hazard Early Warning Systems 2025* report, produced by UNDRR, states that 119 countries—60% of all countries—now report the existence of a MHEWS (Figure 2). This is a 113% increase over the past decade. However, coverage gaps remain, especially among SIDS, with only 43% of them reporting having systems in place. Comprehensiveness scores for system capabilities have increased by an average of 45% across all regions. While Africa has seen the greatest progress since 2015, with a 72% increase in comprehensiveness, it remains the region with the lowest scores (UNDRR 2025a).

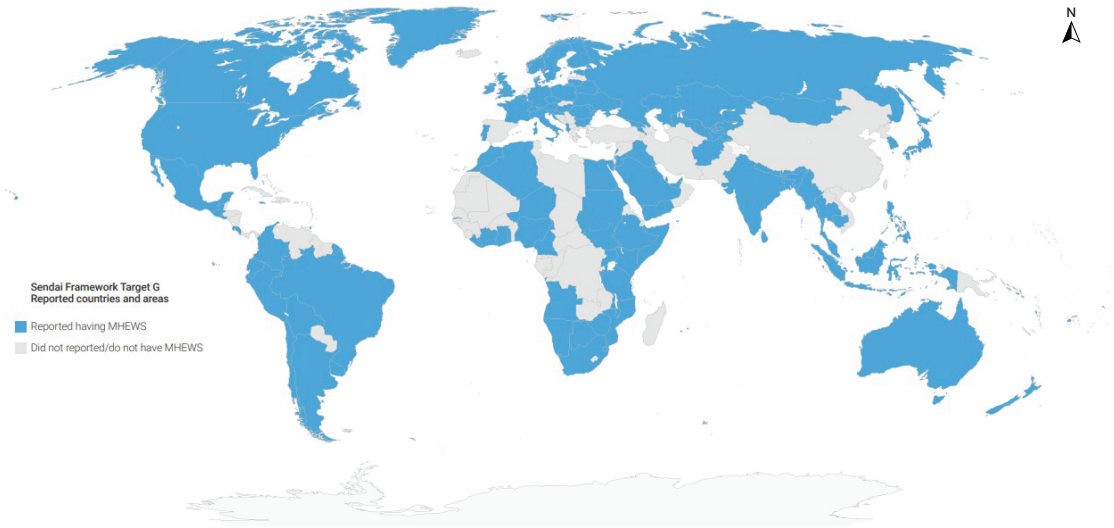


Figure 2. Global coverage of multi-hazard early warning systems in 2025: 119 countries (60%) now report a MHEWS, but only 43% of Small Island Developing States and Africa still record the lowest comprehensiveness scores.
Source: UNDRR 2025a

The key next steps are for the EW4All initiative to ramp up its engagement and partnerships to expand the number of countries that are investing in early warning systems. To this end, EW4All is now prioritizing its efforts to rapidly identify appropriate countries and states in which to target new interventions; engage with regional and national partners in those locations; enhance national ownership of early warning system initiatives; and focus on immediate priorities.

"To accelerate action built on progress and ensure that EW4All is scaled up effectively, countries must lead the way in embedding early warning capabilities into national systems, and we must ensure that our support is tailored to their realities," says WMO's Stander. "We call this next phase 'Broadening the tent', and the *Eyes on the Storm* webinar represents an important step in the next phase," he adds.

Box 2. Financing available to strengthen early warning systems

Climate Risk and Early Warning Systems
It funds projects in the LDCs and SIDS to establish risk-informed early warning services (WMO 2023).

Systematic Observations Financing Facility
It supports countries that have severe shortfalls in weather and climate observations, prioritizing LDCs and SIDS (Systematic Observations Financing Facility, n.d.).

Green Climate Fund
It is the world's climate fund for developing countries (Green Climate Fund, n.d.).

Adaptation Fund
It finances projects and programs that help vulnerable communities in developing countries adapt to climate change (Adaptation Fund, n.d.).

Global Environment Facility (GEF)
It supports developing countries and economies to mitigate the impacts of climate change while implementing sustainable economic development (GEF, n.d.).

Part 1: The Foundations of Early Warning

The Four Pillars: Key Challenges and Potential Solutions

The Four Pillars—knowledge of disaster risk; detecting, observing, monitoring, analyzing, and forecasting; communicating and disseminating warnings; and preparedness and capability to respond—provide the structure for the EW4All initiative. These principles are being applied globally to reduce disaster risk and drive sustainable development in vulnerable regions.

Pillar 1: Translating disaster risk knowledge into inclusive policy and investment

Currently, Pillar 1 is the least resourced of all the pillars and is the one that the EW4All member states (countries that have committed to developing MHEWS) are reporting they are struggling most to see advances in. One reason it is such a challenge for countries to translate disaster risk knowledge into effective policies and investments—and ultimately into early warning systems—is that knowledge about risk is often uncertain and complex. Understanding slow-onset hazards (drought, for example) and compounded risks (such as if hurricane strikes during a pandemic) can be particularly difficult.

"It's really important that risk knowledge is produced in such a way that it enables people to take action," explains Loretta Hieber Girardet, Chief, Risk Knowledge, Monitoring and Capacity Development at UNDRR. "There's a disconnect now between the producers of risk knowledge and the decision-makers, so even when technical agencies produce excellent data, it's not always packaged in actionable formats. Additionally, we tend to see a focus on hazards, but not enough of a focus on understanding vulnerability and the exposure of at-risk populations to hazardous events," she adds.

Filling this knowledge gap is critical for effective end-to-end early warning systems that reach the last mile. There are some good examples of where risk knowledge has been integrated into policies and programming for early warning, often where member states and governments have mandated it. For example, in the Philippines, the government has mandated the integration of disaster risk reduction into local development plans, with the requirement that cities and municipalities include hazard maps, climate change projections, climate impact models, and georeferenced exposure and vulnerability data.

In Bangladesh, mortality from cyclones has dropped dramatically in the past 30 years, thanks to its successful MHEWS. Here, it is part of the planning requirements that governments and stakeholders have access to reliable and localized risk data to guide infrastructure planning, preparedness, and response. Bangladesh has also successfully integrated historical impact data for use in hydrological forecasting and agricultural planning.

Despite such pioneering examples, there continue to be cases where disaster risk management is leaving people behind. For example, during the devastating wildfires that occurred in Los Angeles in early 2025, people with disabilities were the ones most likely to perish. This is because although systems were in place to issue warnings, mechanisms to ensure that early action was taken to evacuate or help people with disabilities were not.

"This is an area in which we collectively need to do better," admits Hieber Girardet. "Through EW4All, we are developing tools to help ensure that when early warning systems are developed or enhanced, gender, disability, and other social dimensions are taken into account. Gap analysis tools are one example, but we're also looking at people-centered early warning design. There is also a need to gather intersectional and disaggregated data, and to use that data to ensure that the programming is really targeting those who are most in need," explains Girardet.

Pillar 2: Scaling up the observational and forecasting capacity in vulnerable regions where large gaps exist in infrastructure and data

Under Pillar 2, WMO is currently focusing on scaling up funding and resources to Burundi, Chad, Comoros, Ethiopia, Haiti, Mozambique, Somalia, South Sudan, and Sudan, all fragile and conflict-affected settings that are home to some of the world's most vulnerable communities. These nations are on the frontline of the climate crisis but have contributed little to its underlying causes. And they have little information about, or resources to prepare for and respond to, hazardous events. WMO is leveraging the Systematic Observation and Financing Facility (SOFF) to scale up funding to these priority countries; however, the observation and forecasting of hydrology is particularly underfunded at present.

"For every USD 1 invested in disaster risk reduction, we can save USD 15 in avoided losses and USD 5 in humanitarian response costs. This underlines the case for scaling up resources and funding to these areas," says Erica Allis, Chief, Partner Engagement and Coordination Division (Disaster Risk Reduction), WMO. "It's also important to note that countries with less comprehensive multi-hazard early warning systems have a disaster-related mortality ratio that is nearly six times higher than that of countries with comprehensive systems. Collaboration is key, as there's not one institution that can solve these kinds of challenges alone," she adds.

A particular issue is how to support digital transformation and to assist countries to access vital datasets. Internet access, better connectivity, and cloud solutions are all issues which can potentially be resolved by working with private sector partners such as Microsoft and through targeted capacity building. WMO has 159 specialized centers that actively exchange data and process forecasts, and which can assist in this regard.

"A key element of our work is supporting twinning between more developed and less developed countries, as well as South-South collaboration. This is to enable the merging, tailoring, and downscaling of datasets to scales relevant to decision making within countries. It's essential that we have partnering arrangements, such as between meteorological services and humanitarian agencies and local actors … as through such collaboration and joint work together, you're able to build more trust," says Allis.

Pillar 3: Ensuring warnings reach everyone, including remote and vulnerable communities

Currently, there is still a great gap in the provision of early warning systems covered by Pillar 3. So, any communication channel that can alert people to an impending hazardous event needs to be used. However, mobile technologies potentially offer the greatest opportunity when it comes to disseminating warnings, as more than 95% of the world's population is now covered by a mobile network and eight out of ten people own a mobile phone. This means all those people have a personal siren system in their pocket.

"One of the technologies we particularly promote is cell broadcast because it's a very easy way of reaching people," explains Vanessa Gray, Head of Climate and Emergency Telecommunications within the International Telecommunication Union's (ITU) Development Sector. "Messages can be sent directly to the phone and they cannot be ignored as they come with a very loud noise. And, we can send millions of messages without the problem of congestion—which is different from SMS messages—and they're geolocated, so people in an at-risk area can be reached," elaborates Gray.

It is important that the governments responsible for disseminating alerts work with mobile network operators to take advantage of the available networks. An important organization in this regard is the Global System for Mobile Communications Association (GSMA). Having standards that ensure messages are written in the same format and can be sent across different communication channels is important. For this, the Common Alerting Protocol is used. And, engagement with community organizations, along with institutions such as the Risk-informed Early Action Partnership (REAP) and International Federation of Red Cross and Red Crescent Societies (IFRC) are critical to ensure that those who do not have mobile phones are not left behind.

Satellite communication is showing promise in terms of reaching people in remote areas through Direct-to-Device Services. These can complement mobile network services by extending their reach to people in underserved rural areas or even at sea. They also have the potential to provide back-up services—for example, if mobile towers are destroyed in a storm. "The objective is that people will be able to access these services on their phones, and they will not realize whether the message has been sent by mobile network or satellite service. We're working with different developers of these systems to see how we can implement them in the countries that most need the services," says Gray.

Pillar 4: Making sure that warnings translate to action on the ground

In hazardous situations, people's level of risk is often influenced by inequality, poverty, and access to information and warnings; so having a deep understanding of the risks that individual communities face and why is critical for delivering on Pillar 4. There has been some warning about most of the costliest or deadliest disasters in recent decades but the warning has not necessarily been heard by everyone or, if it has been heard, they haven't always known what to do or had safe places to go to.

"We take a community perspective and then look backwards up the delivery chain and link in with what the other partners are doing," says Jonathan Stone, Manager, Climate, Environment and Resilience at IFRC. "We're currently focusing on three things. The first is investing in infrastructure and local response

capacity, everything from ensuring people have had some training in receiving warning messages to making sure there are safe spaces for people to go and that these have prepositioned supplies. The second is around developing clear early action protocols and, where possible, pre-agreed financing in the form of smart investments. And finally, we focus on trust and awareness. Trust isn't just something that's built between those directly interacting with communities—such as ourselves or other community-based organizations—but it has to be built into all parts of the system. And I think that this very public initiative, where all of us are in it together and trying to improve the situation, is critical for improving trust. We don't need a perfect system. We just need something that works most of the time that people can trust and make decisions based on," explains Stone.

Bangladesh provides a good example. The Bangladesh Red Crescent Society successfully activated the country's 'early action protocol' recently during heatwaves in Dhaka. Created using information from organizations such as WMO, the Bangladesh Meteorological Department, IFRC, UNDRR, and others to understand who would be most at risk, the protocol included pre-set triggers. Once the trigger for a heatwave was exceeded (based on a particular temperature for a certain number of days), pre-agreed financing became available from IFRC that went directly to the Bangladesh Red Crescent Society.

"They were able to use the finance to activate cooling centers, comprising places with air conditioning or different-shaped buildings that are naturally cooler, where people could go to cool down their core body temperature. There was ambulance support as well as water stations, where volunteers raised awareness of the risks of dehydration and protection measures. The Society targeted school children, outdoor workers, and the elderly – three large groups that were the most vulnerable. … It is a real example of how at the city and community levels, people can get straight to action and make a real difference," says Stone.

How Technology is Fundamental to Early Warnings

Data and models underpin modern day MHEWS. First, data is needed on potential hazards such as floods, droughts, storms or earthquakes, to facilitate prediction of an extreme event. Sources for these include rainfall and river gauges, satellite monitoring, ocean buoys, seismic sensors, and so on. But to be effective, early warning systems need to also incorporate an understanding of vulnerability and potential impacts across the range of sectors. So, data is also required on poverty levels, housing, infrastructure (including hospitals, access roads, and sewerage), and financial and economic indicators. Timeliness, accuracy, and the ability to integrate different kinds of data are all important. The raw data is made useful for forecasting by a wide range of analytical and predictive models, at global to local scales, some of which are already incorporating AI and machine learning. Though the past two decades have seen a welcome shift in focus from simply providing top-down forecasts of weather or other natural hazards, towards impact-based forecasting, further effort is needed.

India uses probability to predict the unpredictable

India is becoming more vulnerable to extreme weather. Not only are events such as floods, heatwaves, and cyclones happening more frequently, the intensity of rainfall and flooding is also rising. With some events unprecedented in the historic weather record, forecasting weather accurately is becoming increasingly difficult.

"The Mumbai deluge of July 25–27, 2005 delivered 994 mm of rainfall in 24 hours—a significant proportion of seasonal rainfall in one day. Heavy rainfall during the monsoon is nothing unusual for Mumbai, but this was extraordinary and came out of the blue," says Raghavendra Ashrit, Scientist at India's National Centre for Medium Range Weather Forecasting (NCMRWF).

The centre is using the NCMRWF Ensemble Prediction System (NEPS) to forecast extreme events with greater accuracy. Multiple simulations are run to produce a range of possible predictions that indicate the probability of different weather events occurring (Figure 3). With a 12 km resolution, NEPS can better represent small-scale features associated with severe weather events. "The probabilistic approach allows us to isolate and pinpoint where the likelihood of a heavy rainfall event is occurring," says Ashrit.

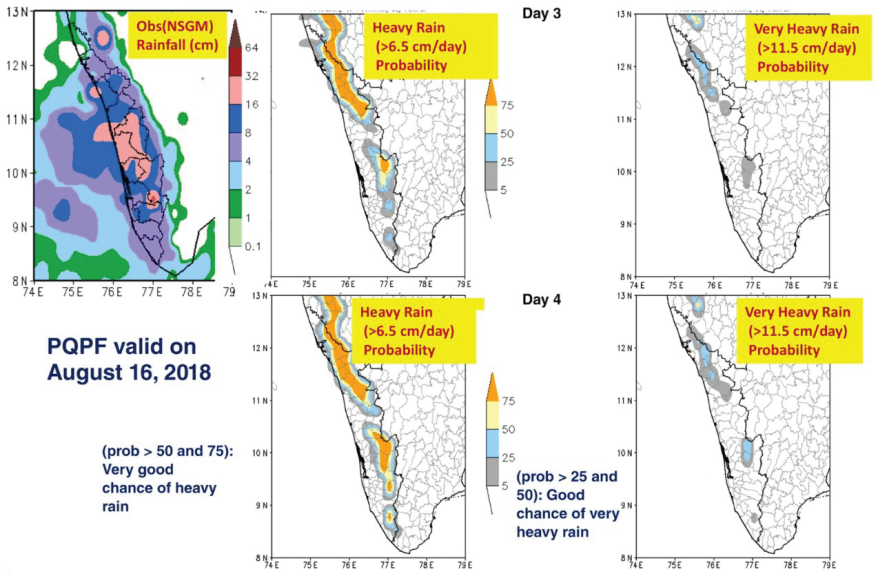


Figure 3. Predicting the unpredictable: NCMRWF Ensemble Prediction System probability that 24-hour rainfall will exceed successive thresholds, from a monsoon case. Probabilistic forecasts pinpoint where extreme rainfall is most likely.
Source: Ashrit et al. 2020

Not forecasting and issuing warnings ahead of an extreme event can result in disaster, while warning and then having no extreme event materialize can prompt people to not act on future warnings. NCMRWF aims to strike the right balance by closely observing models and their behavior across particular regions and seasons, following WMO guidelines for monitoring and defining extreme weather events, working closely with forecasters, and cross-referencing its predictions with other centers such as the UK Met Office.

The Indian Meteorological Department uses color-coding to highlight the potential severity of extreme events. Yellow indicates a low level of disruption but warns people to be watchful. Orange alerts people to be prepared for potentially serious impacts. And red signifies that people should take action to avoid anticipated extreme weather that poses a threat to life and property.

How Caribbean SIDS are embracing impact-based forecasting

The Caribbean is one of the most hazardous areas of the world, exposed to tropical cyclones, floods, landslides, droughts, and seismic and volcanic activity. Climate change is worsening the situation by affecting ocean temperatures and currents, changing rainfall patterns, and worsening the impacts from the natural climate phenomena El Niño–Southern Oscillation (ENSO). This can bring drought and heatwaves to the region during the cycle's warm phase (El Niño), and flooding and hurricanes during its cool phase (La Niña). Socioeconomic factors, such as inequality, poverty, economic dependence, and a limited capacity to prepare for and recover from shocks make some populations highly vulnerable to hazards. For example, widespread poverty and informal housing contributed to the high death toll from the 2010 earthquake in Haiti.

The Caribbean Institute of Meteorology and Hydrology (CIMH) is at the forefront of building EW4All into the region. The education, training, and research arm of the charitable Caribbean Meteorological Foundation, its mission is to improve and develop meteorological and hydrological services, and raise awareness of the benefits of such services, for the economic well-being of the 16 SIDS it serves (Anguilla, Antigua and Barbuda, Barbados, Belize, British Virgin Islands, Cayman Islands, Dominica, Grenada, Guyana, Jamaica, Montserrat, St. Kitts/Nevis, St. Lucia, St. Vincent and the Grenadines, Trinidad and Tobago, and Turks and Caicos Islands). It does this through training, research, investigations, and by providing related specialized services and advice.

The Institute's computational capabilities have enabled it to strengthen its numerical weather prediction skills and climate forecasts. In the past 15 years, it has begun working on systems integration. This work, has revealed, for example, that any country in the region can be impacted by multiple climate events in a particular month. And this has led it to consider MHEWS that embrace both physical climate and socioeconomic elements. "We have been spending a lot of time with development partners in health, disaster management, water energy, tourism, and so on, trying to find ways to use weather and climate forecasts to predict impacts to different sectors. In some cases, you cascade from one sector to another sector. For example, a heavy rainfall event that may be good for agriculture could also create problems for health, as vector-borne diseases thrive in wetter than usual conditions," explains CIMH Principal, David Farrell.

The Institute is accepting how AI and machine learning technologies can help it match climate events to economic shocks, by looking for patterns, such as whether there is a lag between a climate shock and an economic impact, and how the impacts of a hazard cascade across different sectors. The idea is to be able to make complicated decisions at a faster pace. A challenge is how to get economic data at the right frequency; many countries post economic data annually, but climate events occur monthly and seasonally. "We're asking how you bridge that gap and get countries to make that data available, at the timescales required to support decision making. This is the direction we're going in as we seek to mitigate the impacts of weather and climate on the resilience of Islands in the Caribbean," says Farrell.

Enhancing impact with the Warning Value Chain

The UK Met Office uses science and data on weather and climate, along with expert insights, to help people make decisions that keep communities safe, well, and prosperous. Since 2014 it has helped to implement the Weather and Climate Science for Service Partnership (WCSSP) to address the impacts of extreme

weather and climate change. Part of this ongoing work involves collaborating with other UK organizations as well as research institutes in the Philippines, Malaysia, Indonesia, and Vietnam, to try and reduce the impacts of severe weather in Southeast Asia.

WSSCP is developing new state-of-the-art modelling systems for southeast Asia, including high resolution convective scale forecast models which provide better predictions of extreme weather events than current global models. It holds monthly engagement sessions where the partners discuss how the model has performed for recent cases, with the aim of finding out, for example, if it has helped to influence the development of warnings or enhanced the understanding of uncertainties around high impact weather events. "We have a very informal but valuable discussion with our partners, around where the information has been more or less useful," says Joanne Robbins, Weather Impacts Science Manager for the UK Met Office.

This evaluation work involves using WMO's Warning Value Chain framework, which facilitates the understanding of how information flows from observations and forecasting, to the prediction of hazards and their impacts, to the communication of a warning, and the response of the people at risk. The partners ask questions such as: How good do we feel the weather forecast was? Did we have information that told us about the hazards that were critical for this event? How was the warning generated, and were the severity and the timing right? Did it reach people and were appropriate decisions made based on that warning?

"This is some of the work we're doing to try and make data more accessible but also to understand the barriers to and enablers of making data accessible. We're also simultaneously trying to make that data more relevant, so that ultimately the value we are trying to achieve through the Value Warning Chain is achieved, and is seen by the stakeholders who ultimately have to make critical decisions," says Robbins.

Turning global data into local action in Zambia

Zambia relies on global climate models when producing local weather forecasts. These can provide forecasts at the national level but there are high uncertainties, and there can be time lags between what the models say will happen and when it actually takes place. It is challenging to forecast at national or regional level with confidence, and even harder to forecast weather events at the local level. Ensuring that people on the ground understand what the provided forecast means for them can also be difficult.

Gathering its own local weather data and forging collaborations with climate research institutes outside of Africa are helping Zambia to improve its local weather forecasting. Automated weather stations have been installed across each of the country's 116 districts, and data from the stations is being combined with satellite-based weather and climate reanalysis to provide more reliable local weather forecasts, particularly for farmers. Such ground observations (Figure 4) are the foundation on which national services across the Global South are building local forecasting capacity.

The Department is also collaborating with the University of Leeds on the Weather and Climate Information Services Early Warning for Southern Africa (WISER-EWSA) project, focused on enhancing early warning systems, such as for thunderstorms in urban areas. A two-week training program was held where meteorologists, academics, economists, and user-engagement specialists created real time warnings of severe weather, delivered those to partnering user groups, and co-evaluated the effectiveness of those warnings. At the end of the program, 100% of the participants agreed that their ability to interpret weather information had increased.



Figure 4. Closing the observation gap: an automatic weather station in Sri Lanka. Ground observations like these, combined with satellite and reanalysis data, are what allow national services such as Zambia's to turn global model output into reliable local forecasts for farmers.
Photo by Department of Meteorology, Sri Lanka

"The WISER project has helped us to collaborate with the community, so that when we make a forecast, we disseminate it to the communities, and the communities then translate it to their local inhabitants so they are able to better understand the forecast," says Kenneth Sinachikupo, a meteorologist at ZMD.

Using seasonal and subseasonal forecasts to support action

El Niño often brings warmer, drier weather to Singapore, while La Niña frequently causes heavy rainfall. The timing of when these events occur is important. If El Niño comes in the dry season, it can bring about heatwaves, while if La Niña arrives in the monsoon season, intense rainfall can ensue. "This knowledge is something we can use without complicated models to help us prepare," explains Thea Turkington, Deputy Principal Research Scientist at the Centre for Climate Research in Singapore.

The Centre uses seasonal (a few months ahead) and subseasonal (a few weeks ahead) forecasts to calculate the probability of these extreme weather events arising and to promote appropriate action on the ground. For example, it provides seasonal outlooks for extreme rain to the Asian Coordinating Centre for Humanitarian Assistance on Disaster Management (known as the AHA Centre). While the forecasts cannot pick up all extreme rain events, especially those that lead to small scale, localized flooding, the information can guide the AHA Centre on areas that it should monitor in the subsequent weeks.

Another use of seasonal forecasting is to help mobilize finance early on. People often need money in the immediate aftermath of an extreme event, but it can take time for funds to become available to them. "You can use seasonal forecasting to highlight some potential extreme events and get the system moving and then use more detailed weather forecasts to actually trigger the final action. I talk with the people that could potentially use the forecasts and identify with them the thresholds and variables they should be using to help them take action," says Turkington.

Part 2: Successes and Challenges of Multi-Hazard Early Warning Systems

Advancing Early Warning for Heatwaves

Heatwaves are becoming an increasing challenge to human health and ecology. The decade from 2015–2024 was the hottest on record globally, with temperatures exceeding the pre-industrial level by 1.55°C. Heatwaves are already a regular occurrence in many parts of the world, and forecasts suggest that beyond 2025, hazardous hot spells could be between 3 and 21 times more frequent.

Rising risk from extreme heat

Extreme heat is a growing threat that is putting billions of people at risk from preventable death and illness. With rising heat, the body's ability to thermoregulate is impaired, which leads to physiological strain that can exacerbate existing health conditions and lead to heat stroke. This happens when thermoregulatory processes are insufficient, so heat gains exceed losses and the body temperature rises uncontrollably. Extreme heat also causes indirect impacts on health, such as by increasing the transmission of disease, causing wildfires that affect air quality, and disrupting critical infrastructure and technology.

The need for warnings to protect health has, in part, driven efforts within meteorology to monitor, define, and warn of heatwaves. The WMO defines a heatwave as 'a period where local excess heat accumulates over a sequence of unusually hot days and nights' (Figure 5). Meteorological organizations tend to monitor rising intensity and issue warnings once a threshold is breached. One key statistical tool is the Generalized Pareto Distribution (GPD). It is used to model the 'tail' behavior of temperature distributions, enabling researchers to estimate the probability of heat events that are rare but highly impactful.

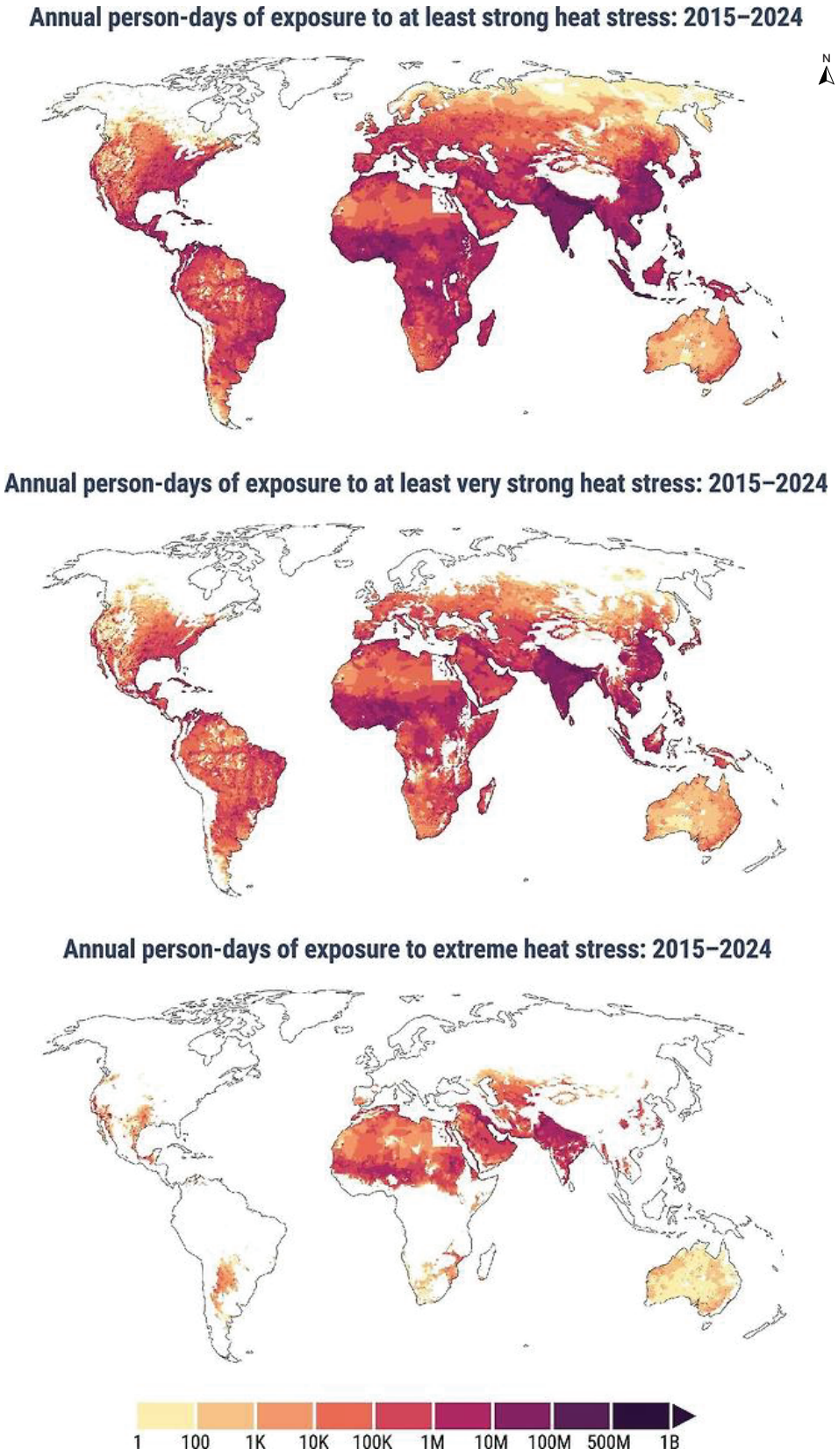


Figure 5. Annual person-days of exposure to heat stress over the last ten years, showing the expanding footprint of dangerous heat on the human population.
Source: Emerton et al. 2026

Managing heatwaves in India

Improving meteorological capabilities

In India, with the population of cities increasing and the urban heat island effect becoming more challenging, finer-resolution forecasts are needed. With this in mind, India Meteorological Department (IMD) recently introduced new weather prediction systems at 6 km and 1 km resolution to improve the accuracy of its medium- and short-term weather forecasts. The new models have also enhanced the temporal resolution to better capture diurnal changes. They will complement the capabilities of its existing 12 km and 3 km resolution systems.

The Department has also established a dedicated center on AI and machine learning (a branch of AI related to systems that can learn from past data to process new data and make predictions, classifications, and decisions) at the Indian Institute of Tropical Meteorology (IITM) in Pune. It also plans to introduce 2,000 new automatic weather stations and 60 Doppler weather radars, both of which will improve its ability to monitor weather and identify hazardous conditions.

Mitigating the impacts of extreme heat

A problem India faces when it comes to managing heat is its diversity. It has many agroclimatic regions, and individual areas need to respond to the particular threat facing them at any given time. Administratively, it comprises 28 states and 8 union territories, which are divided into 734 districts. The National Disaster Management Authority (NDMA) encourages Heat Action Plans to be developed at city level and implemented through municipal officers.

“We focus on the plans being as much at the granular level as possible. Positively, the Government of India has recently added heat to the existing list of 12 hazards on which public funds can be spent. This means that 25 billion dollars of funds that we have allocated for disaster risk management over five years can also be expended on heat. This is giving a great fillip to Heat Action Plans, early warning systems, and IMD’s efforts, among other inputs,” says Safi Ahsan Rizvi, Advisor (Mitigation), NDMA.

At the broader level, every year around mid-March before the hot season, district-level officials meet and discuss actions to take, such as providing cool-water stations, reducing working hours (especially for workers from outside), and closing schools that are open through the summer months at 10.00 or 11.00 before the worst of the heat. They issue advisory notices 30 days before a heat event is anticipated, as well as share the IMD three-day forecasts if a heatwave is expected.

Apart from mitigating the impacts of heat on people, actions are taken to mitigate the impacts on livestock (which outnumber India’s 1.4 billion human population by three times), crops, water, and infrastructure. These issues are managed at national levels by various ministries. For example, the Ministry of Agriculture is promoting the use of heat-resistant crop varieties and is planning to install a further 6,000 automatic weather stations, primarily for crop insurance purposes.

Building resilience to extreme heat

The Council on Energy, Environment and Water (CEEW), a not-for-profit policy institution and think tank based in New Delhi, provides data-driven research and analysis to influence policy on energy, environment, and water. In 2025, it published the study How extreme heat is impacting India: Assessing district-level heat risk, which highlighted that 57% of Indian districts, home to three-quarters of the population, now face high to very high heat risk (Figure 6) (Prabhu et al. 2025).

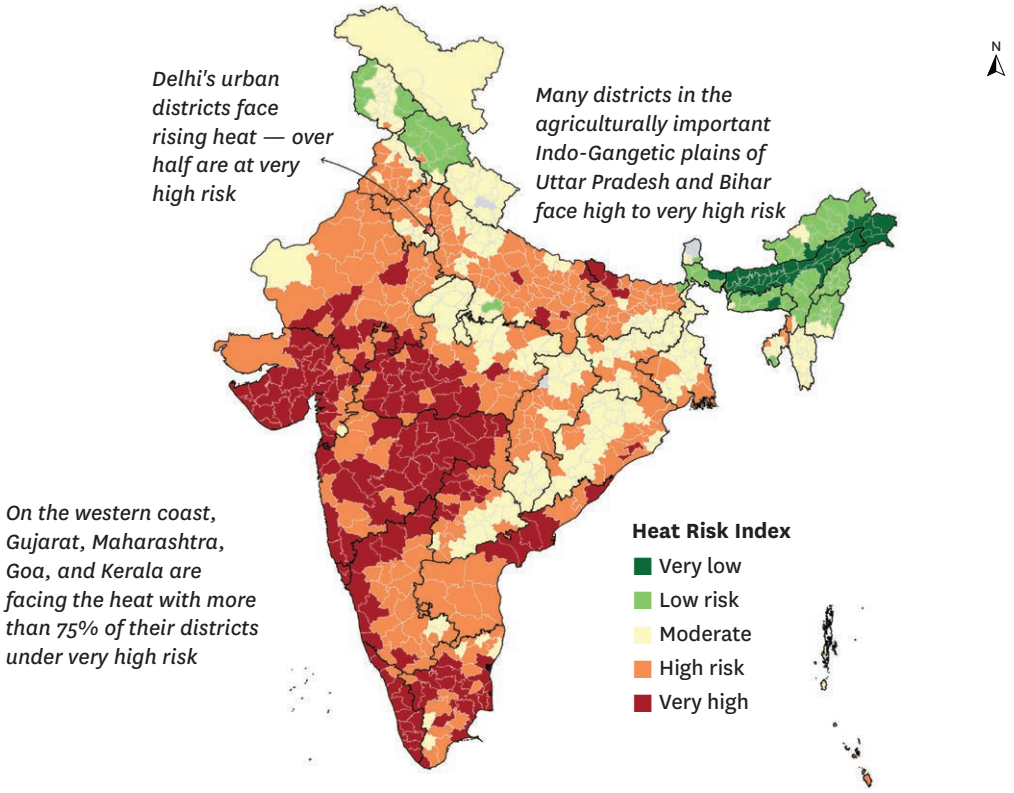


Figure 6. District-level heat risk in India: 57% of districts, home to three-quarters of the population, face high to very high heat risk, driven in part by a sharp rise in warm nights.
Source: Prabhu et al. 2025

"The study highlights the fact there has been a massive increase in the number of very hot days in India in the last 10 years compared to the baseline of 30 years before that," says Vishwas Chitale, Senior Programme Lead – Climate Resilience at CEEW. "But what is more staggering is that there has been an even greater increase in the number of warm nights, compared to the increase in very hot days. Often warm nights go unaddressed, unacknowledged, because you cannot see the impact as you see the sun during the daytime, but it has severe health impacts," he adds.

The study was based on a heat-risk index, incorporating data on 34 variables such as how humidity had increased and how the number of warm nights had changed across the 734+ districts of India. The heat-risk index is available through CEEW's climate resilience atlas tool, which is designed to help communities anticipate climate risks and act early on. The institution has also been supporting 300 cities to develop Heat Action Plans and has produced a video series promoting options for increasing people's resilience to heat, which include parametric heat insurance, cool roofs, net zero cooling shelters, and emergency heat stroke rooms.

Southeast Asia's Global Heat Health Information Network

Encompassing scientists, practitioners, and policymakers, the Global Heat Health Information Network's (GHHIN) Southeast Asia Hub is a platform supporting the region to collectively prepare for, and protect populations from, the health impacts of extreme heat. It particularly focuses on urban heat and the challenges of the urban heat island effect on the region's huge urban conglomerations; occupational health and heat at work, particularly for people who suffer from prolonged exposure to heat; and traditional and cultural practices that can be learned from and drawn on. The Network was officially launched at the GHHIN Southeast Asia Heat Health Forum in 2025, which convened over 250 delegates from diverse disciplines.

"The Global Heat Health Information Network is a big resource that's available to everybody and is voluntary, independent, and member-driven. It's a really fantastic resource when it comes to heat and health. But we need advisories to be contextual – there is no one size fits all. This is what the Southeast Asia hub has been created for and is trying to do in this region," says Sally Jane Edwards, Coordinator, Health and the Environment, World Health Organization (WHO; western Pacific region).

Managing the Threat of Destructive Floods

Floods continue to be one of the most destructive climate-related hazards, threatening people, infrastructure, and economies. However, enhanced technologies and forecasting skills are contributing to improving nations' capacities to predict hazards and warn of them before the disaster strikes. Involving grassroots communities in planning for floods, meanwhile, is helping to ensure that warnings are well received and heeded by all sections of society.

Mapping flooding at the global scale

GloFas supports national and regional forecasts

The Global Flood Awareness System (GloFAS) provides free geospatial information at the global scale (5 km x 5 km pixels) to enable countries and communities to prepare for, respond to, and manage floods. Specifically, it provides daily updated maps highlighting expected flooding up to 30 days in advance and wet/dry anomaly-based seasonal streamflow outlooks up to four months ahead. A component of the Copernicus Emergency Management Service of the European Commission's Joint Research Centre, GloFas resources are designed to complement information provided by national and regional hydrological and metrological services. A user-based service, it currently has around 20,000 users around the world.

> **The objective of GloFAS is to provide information to enable the preparation for, response to, and management of floods at the global scale. We aim to provide complementary information to national and regional hydrological and metrological services.**
>
> **— Stefania Grimaldi**
> Hydrological Forecaster and Scientist at the European Centre for Medium-Range Weather Forecasts.

GloFAS forecasts are produced using the latest ensemble of Numerical Weather Prediction (NWP) forecasts of the ECMWF Integrated Forecast System (IFS). A hydrological model transforms the meteorological forcing forecasts into hydrological forecasts. The model takes into consideration rainfall, runoff, snow

melt, evapotranspiration, water infiltration into the soil, river routing and lakes, as well as accounting for human activity, such as water abstraction and dams. Flood products can be accessed via an interactive Map Viewer (Figure 7), and data can be downloaded to suit individual purposes. Webinars and tutorials (in French and English) are available for those needing support using the data. GloFas is continuously enhanced, with the latest upgrade released in mid-2026 (CEMS, n.d.).

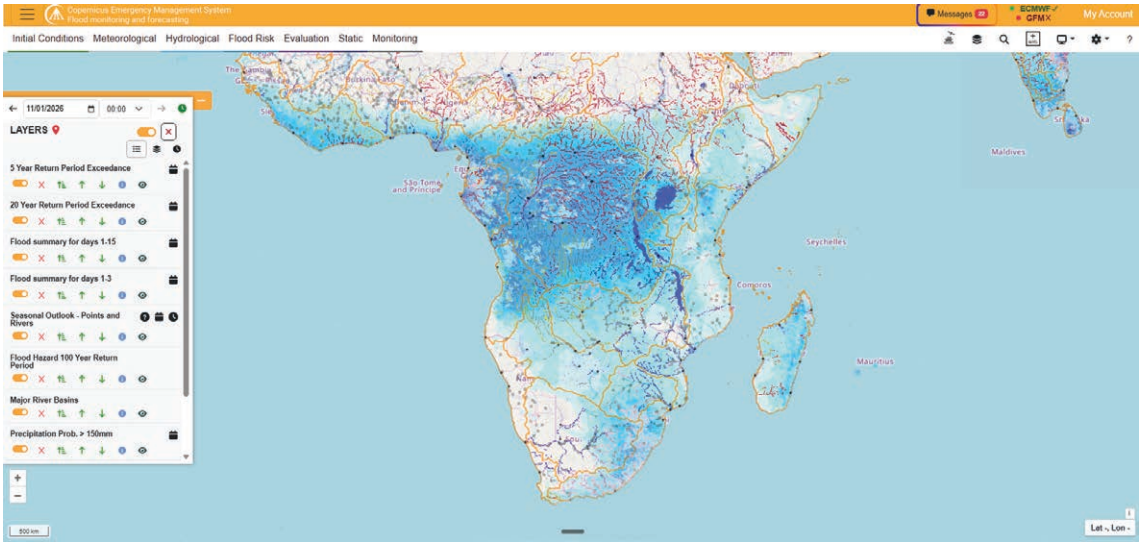


Figure 7. GloFAS ensemble hydrograph showing the probability of river flows in Africa exceeding flood thresholds up to 30 days ahead.
Source: CEMS n.d. GloFAS Map Viewer, Copernicus Emergency Management Service

Google's response to flood queries

Receiving one billion queries a year seeking information on floods motivated Google to establish a flood forecast hub. In particular, it wanted to be able to provide requested information on how to drive between locations in areas that were either flooded or likely to become flooded. The company decided to employ AI to help find a solution.

> **We collected all of the hydrology data that we could find in the world and we trained a machine learning model with all of that data. And we used it to develop the Google Flood Hub. It displays coloured hexagons in places where we make predictions, which users can zoom in on to display a hydrograph.**

— Grey Nearing
Research Scientist, Google.

While the Google Flood Hub is aimed at lay users, Google also supports institutions such as WMO, IFRC, and private humanitarian NGOs. It does so both passively by providing data, and actively by working with

the organizations to understand user needs and adapt its data products and models to specific users. As a starting point, institutional users can access Google's Runoff Reanalysis and Reforecast (GRRR) dataset, which provides historical, high resolution simulations of river discharges, facilitating researchers to analyze past flood events and develop more accurate AI-driven hydrological models. It is made available through Google Colab, which offers free access to specialized processors.

Strengthening flood action at national scale

Putting water at the heart of climate action

To date, only 60% of the countries have reported having MHEWS up and running (UNDRR 2025c). Supporting countries without such systems that are most in need is the aim of the Water at the Heart of Climate Action initiative. It combines local knowledge and global technology in Ethiopia, South Sudan, Sudan, and Uganda¬—which share the Nile River basin —to help communities understand and act on floods before they become disasters.

A key aim of the project, which is a collaboration between WMO, IFRC, the Netherlands Red Cross, UNDRR, WMO, and SOFF, is to build on existing capabilities rather than double up on capabilities.

With this in mind, the project's starting point in each country has been to conduct national capacity assessments. This has enabled it to identify multiple available systems that could potentially benefit from enhanced hydrological measurements, particularly discharge data. A second focus has been on ensuring that forecasting is impact based rather than simply outlining a forthcoming hazard. To this end, it has been seeking to connect forecasts with social and other databases to understand potential impacts on everything from people to power generation, and transport to telecommunications.

"We want to make sure that not only is there is minimum loss of life, but also that economic impacts are reduced," says Dr Ramesh Tripathi, Project Officer at WMO.

> **When we are moving from dry to wet conditions, getting additional information from the status of the basin on soil moisture is crucial to get good flood forecasting.**
>
> **— Luca Brocca**
> Director of Research, National Research Council's Research Institute for Geo-Hydrological Protection, Italy

Getting the measure of flood forecasting in Zambia

In Zambia, floods are a frequently occurring and highly destructive natural hazard. The floods of 2023 were particularly significant, affecting nine provinces and displacing over 154,608 people. Rural livelihoods, in particular, suffer significant impacts from flooding (Figure 8). This is because the vast majority of small farmers depend on rainfed agriculture, making them susceptible to climate shocks. Balancing conditions That facilitate flood forecasting, with those that present barriers to doing so, is a challenge for the Water Resources Management Authority in Zambia.

The government in Zambia is well aware of the damaging impacts of floods on people, infrastructure, and the economy and has prioritized early warnings. Three integrated frameworks exist, combining climate information, technology, and early action, that are helping it to prevent flood events from becoming disasters. Zambia also benefits from supportive partnerships to access financing and strengthen capacity within the country. Meanwhile, community mindedness, along with social media and the widespread use of mobile phones support efforts to disseminate flood-related data.

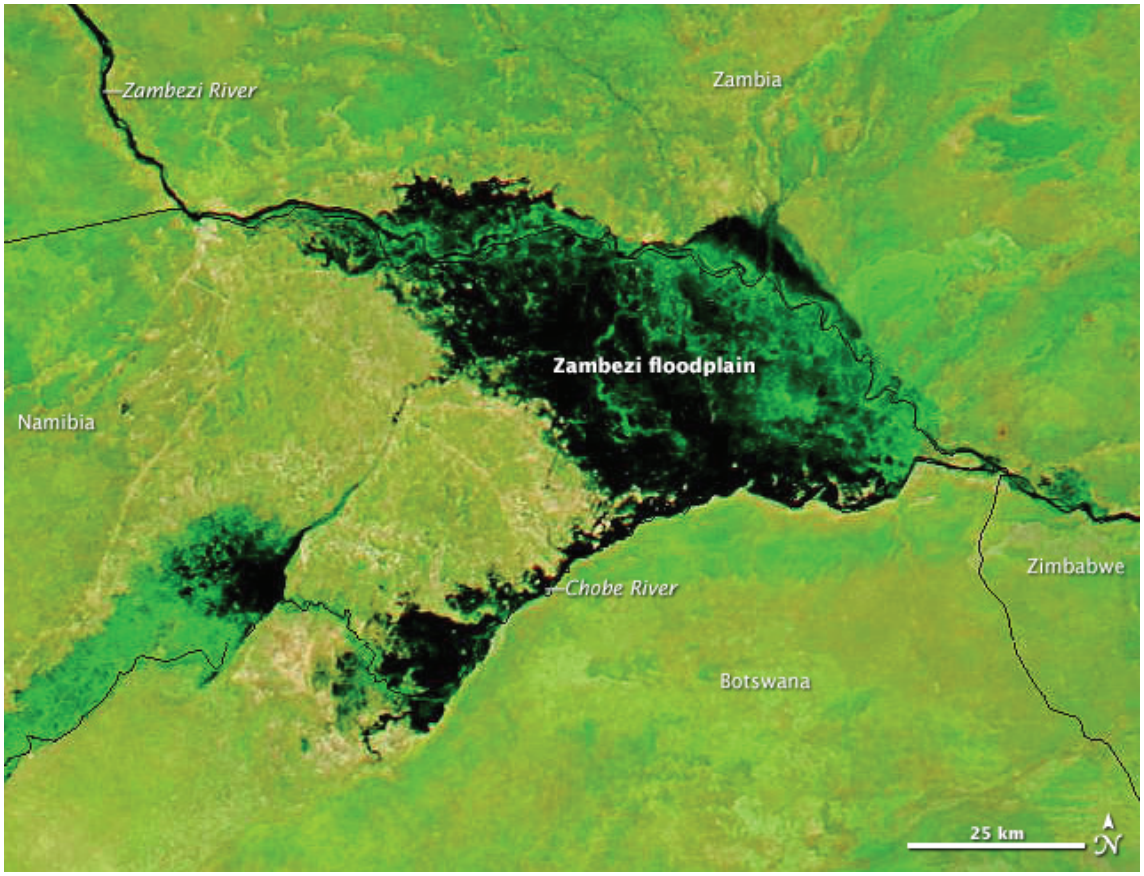


Figure 8. Mapping floods from space: The Moderate Resolution Imaging Spectroradiometer (MODIS) aboard Aqua captured widespread flooding in Namibia's Zambezi Region on May 13, 2014.
Source: NASA images courtesy of the LANCE/EOSDIS Rapid Response team.

Alongside these enablers to flood forecasting, a variety of barriers remain. Inadequate investment means that weather monitoring stations are not always able to provide detailed monitoring of ground flows and discharges, which has led to data gaps. As this data is fed into early warning systems—sometimes leading to erroneous predictions—public trust in flood forecasting has been affected. The technical capacity to undertake modelling and knowledge management are also lacking in the country. Moreover, some communities are very remote, making disseminating meaningful warnings to them a challenge.

"Things are improving,' says Douglas Lubaba, Acting Water Resources Operations Manager at the Water Resources Management Authority in Zambia. "For example, we use the GloFas early warning system, and we used to find the resolution challenging. The spatial resolution was too large when it came to forecasting impacts at local scales. So, localization was an issue, but GloFas has improved this. Also, by working with other partners we have managed to enhance our early warning systems," he adds.

Accelerating Action on Drought

The lived reality for millions of people across Africa, South Asia, and beyond, drought is often slow in onset and silent in spread. It disrupts agriculture, food security, and access to water, having serious impacts on the fabric of rural economies and communities. Because it is often invisible as it develops, it is frequently underprioritized in policy planning and investment. However, with appropriate data and technology (Box 3), governance systems, financing tools, and community capacity in place, it is possible to act before a crisis escalates.

A decade of drought achievements

Drought affects everyone, cutting across all sectors from drinking water, to irrigation for agriculture and hydropower for energy. The Global Drought Snapshot produced by the United Nations Convention to Combat Desertification (UNCCD) shows that in 2023 alone, more than 20 countries declared drought emergencies, including the UK, Germany, Canada, USA, China, Kazakhstan, India, Sri Lanka, Indonesia, and Uruguay (Tsegai et al. 2023). Drought severity levels around the world are significant, and forecasts for the future are not promising. By 2030, an estimated 700 million people will be at risk of being displaced by drought. And by 2050, some 4.8–5.7 billion people are forecast to live in areas that are water scarce for at least one month each year, up from 3.6 billion today.

However, the world has not been ignoring the signs that action is needed on drought. The High-Level Meeting on National Drought Policy, launched by WMO, UNCCD, and Food and Agriculture Organization (FAO) of the United Nations in 2013, helped to drive a shift towards proactive drought management. Since then, many initiatives such as the Integrated Drought Management Programme launched by WMO and the Global Water Partnership (GWP), International Drought Resilience Alliance founded by Spanish and Senegalese leaders, and CGIAR Drought Action Catalyst led by IWMI, have helped drought action to gain momentum.

> **Ranging from wastewater reuse to nature-based infrastructure and risk insurance programs, significant capabilities have been achieved in the last ten years.**
>
> **— Giriraj Amarnath**
> Research Group Leader – Water Data for Climate Resilience and Principal Researcher – Disaster Risk Management and Climate Resilience, at IWMI.

Box 3. Drought Action Catalyst

Between 2000 and 2024, over 1.6 billion people in 117 countries were affected by droughts that caused 25,000 deaths and more than $240 billion in economic losses (IWMI, n.d.). Clearly, greater efforts are needed to mitigate the impacts of drought and reduce suffering on the ground. To this end, IWMI developed the Drought Action Catalyst to support on-the-ground action to reduce the suffering caused by droughts over the next decade. It was launched at the 17th session of the Conference of the Parties to the UNCCD, held in Mongolia in August 2026 (IWMI 2026).

The platform will create a network of government agencies, development organizations, research institutions, private sector innovators, NGOs, and civil society organizations (CSOs) with combined expertise and experiences spanning multiple countries and drought events. It will mobilize partnerships and alliances to promote co-designed drought management initiatives that help local communities manage the specific risks they face from droughts and become more resilient to them (Amarnath et al. 2026).

"Managing drought effectively requires three cornerstones: monitoring and early warning system; vulnerability and impact assessment; and drought preparedness, response, and mitigation. Great strides have been made in drought mitigation and preparedness in recent years—from implementing drought monitoring systems to helping manage pests and diseases, introducing drought-tolerant varieties, and establishing financing—and our experiences have shown a lot of pathways for achieving impact. We hope to build on this momentum through the catalyst, with partnerships providing the engine," says Giriraj Amarnath, Research Group Leader – Water Data for Climate Resilience and Principal Researcher – Disaster Risk Management and Climate Resilience, at IWMI.

> **Drought is not just an environmental, meteorological issue, it is a developmental, humanitarian, economic, and political challenge, and it must be addressed as such.**
>
> **— Rachael McDonnell**
> Deputy Director General – Research for Development, IWMI.

How key institutions are advancing drought early warnings

Meteorological drought forecasting supports action on the ground

Droughts are slow, creeping phenomena, which has historically made it challenging to know when one is on its way. Multispectral images from an array of satellite-based sensors have helped to overcome this and form the foundation of modern drought monitoring and early warning systems. Specific numerical ratios, or indices derived from the imagery are able to capture when a meteorological drought—essentially a deficit in rainfall or snowfall over time—begins to occur and how it subsequently changes.

Primary satellite-derived indices are the Standardized Precipitation Index (which measures the 'abnormality' of rainfall for a particular time period) and the Standardized Precipitation-Evapotranspiration Index (which uses precipitation and temperature data to measure the 'water balance'—essentially the difference between the water available and the amount that would evaporate from the soil and transpire from plants if water were unlimited). Other sensors such as those measuring soil moisture or vegetation health, density, and growth can help to show when drought begins to affect crops.

The WMO, which passed a resolution in 2024 for its 193 members to strive to adopt such indicators, used the technology to develop the Global Drought Mosaic. This gathers data from drought monitoring systems around the world to get a comprehensive picture of where droughts are occurring and their severity. Such work supports Anticipatory Action (a proactive humanitarian approach that mitigates the impacts of disasters by taking preventative measures before a shock unfolds) by helping to provide data on the most appropriate thresholds to use as triggers. For example, if the rains remain below average for 10 days, based on the actual volumes recorded and satellite indices, this can trigger a specific action (Figure 9). If the drought advances, breaching other thresholds, additional planned actions can be taken.

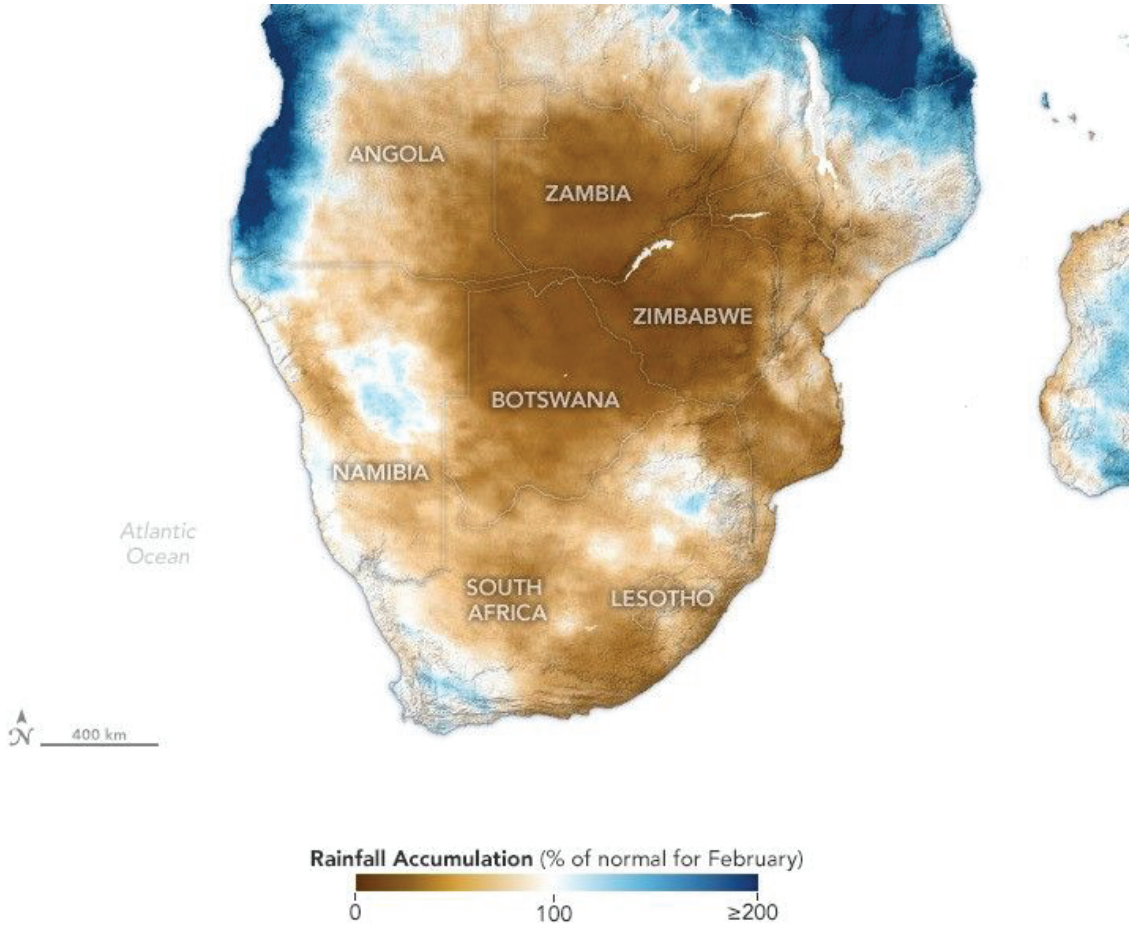


Figure 9. Meteorological drought across southern Africa during the 2023–24 El Niño: Three-month Standardized Precipitation Index (January–March 2024) with drought extent and IPC food security phases.
Source: NASA Earth Observatory images by Wanmei Liang, using data from the Climate Hazards Center, University of California, Santa Barbara.

"By looking at the combination of forecasts, reaching a first trigger, continuing monitoring, reaching a second trigger and so on, institutions and organizations such as the World Food Programme (WFP) and FAO can be prepared, can anticipate, and can integrate Anticipatory Action into their schedules," says Sebastian Grey, Scientific Officer for Agrometeorology at WMO.

Enhancing Africa's resilience to drought

At a time when Africa faces an increasingly complex risk landscape, with public health emergencies caused by both climate extremes and conflict, only 14 out of the 55 African Union (AU) member states have a national drought monitoring system. The AU, through various programs and mechanisms, seeks to improve this situation by driving a paradigm shift from reactive drought management to proactive and prospective approaches that enable countries to forecast, prepare for, and safeguard communities from the worst impacts of drought.

"Central to this paradigm shift are effective early warning systems, proactive and integrated drought management plans and policies, and ecosystem-based approaches, and most importantly, drought risk-informed development," says Viola Otieno, Earth Observation Scientist for Early Warning Systems at the African Union Commission (AUC).

The AUC is tackling the challenge in three ways. The first is through the Africa Multi-Hazard Early Warning and Early Action System (AMHEWAS) program, which aims to drastically increase the availability of, and access to, information on the risk of disasters arising, including from drought (UNDP, n.d.). While early warning system technology has advanced in recent years, turning warnings into effective action remains a challenge. Part of the initiative is establishing situation rooms to coordinate effort across national boundaries, with seven so far developed.

The second is the Great Green Wall initiative, the objective of which is to strengthen communities' resilience to climate and other shocks by restoring 100 million hectares (ha) of degraded land (Figure 10) stretching 8,000 km between Senegal and Djibouti. And the third is through the African Risk Capacity Group, a specialist agency of the AU that provides pre-arranged financing through parametric insurance to help governments improve their capacities to better plan and prepare for, and respond to extreme weather events and natural disasters.



Figure 10. An area of degraded land in the Ferlo region of Senegal.
Photo by G. Gray Tappan

"Last year, for example, Zimbabwe and Zambia received payouts. Zimbabwe received USD 32.8 million in insurance drought and Zambia received USD 9.9 million," says Otieno.

Ensuring social protection systems are shock-responsive

Around the world, the WFP works to ensure that social protection programs are designed not only to alleviate routine poverty but can be rapidly scaled up in times of shocks. The key components of its efforts include early warning systems linked to pre-agreed response triggers, enabling governments to act before drought conditions worsen; flexible pre-arranged financing mechanisms that reduce delays in mobilizing resources when drought gets severe; digital cash transfers and provision of grains and beans that protect livelihoods and maintain access to food and essential services; and institutional support to integrate responsiveness to shocks into national social protection strategies, fostering government ownership and sustainability.

In Sri Lanka, the increased risk of drought and greater climate variability are affecting livelihoods and food security. Here, WFP is supporting the Sri Lankan Government to integrate Anticipatory Action into social protection programs. For example, it works with the disaster management agencies as well as the Department of Meteorology to strengthen early warning capacities and provide more reliable and timely forecasts. It is also engaged in a study with the Government to understand the extent to which the country's long-standing social protection system is responsive to shocks.

"That study is examining what gaps exist and what could be done to make it very responsive. This integrated approach is helping Sri Lanka shift from crisis-driven response to more proactive interventions that safeguard livelihoods before droughts escalate into emergencies," says Rohini Singarayer, OIC – Resilience, Emergency Preparedness, Response and Social Protection at WFP.

"Our Drought Risk and Resilience Assessment, ongoing in several countries, helps us to evaluate what's already there and what's needed regarding drought risk, hazard exposure, vulnerabilities, national capacities, early warning system, and technical capacities. It helps to avoid the duplication of effort, get people to talk and, at the end of the day, prioritize concrete investments.'
Markus Enenkel, Climate Risk Finance Specialist, World Bank.

Strengthening Early Warning for Landslides and Tsunamis

Tsunamis, landslides, and glacial lake outbursts occur in very different contexts—from very low-lying coastal strips to the highest mountain ranges—but they have in common the rapid speed at which they can happen. Each can very quickly cause a disaster, taking many lives and destroying infrastructure. The 2004 Indian Ocean tsunami remains the deadliest such event on record, responsible for around 230,000 deaths (Omer 2025). The worst landslide on record, triggered by a powerful earthquake in 1920 in Haiyuan, China, similarly killed 200,000 people (Verisk 2020). Meanwhile glacial lake outbursts—where water is released when a moraine or ice dam fails—have cumulatively been responsible for more than 12,000 deaths. The risks from all three of these hazards are rising due to climate change, but early warning systems and transboundary collaboration are helping to reduce the risks.

Learning from the 2004 Indian Ocean tsunami

It is now more than 20 years since the deadly 2004 Indian Ocean tsunami. The disaster was triggered by an undersea earthquake near Banda Aceh, Sumatra, Indonesia, but lives were also lost far from Indonesia, in Sri Lanka, Thailand, India, and the east African countries of Tanzania and Somalia. The tsunami highlighted the need for multilateral cooperation to prevent a similar disaster from happening in the future, and the Intergovernmental Oceanographic Commission of UNESCO (UNESCO–IOC) was mandated to establish a warning system in the region.

The starting point was to undertake risk assessment mapping; in the Indian Ocean, the subsea earthquake hazard derives from the Sunda and Makran subduction zones (Akbarpour Jannat et al. 2023). Informed by the risk assessment, sensor networks were established, encompassing seismographic stations to detect earthquakes, buoys that can identify anomalous waves, and coastal tide and sea-level gauges to verify the existence and height of an approaching tsunami. Set up by member states, these transmit data in real time.

Three countries—India, Australia, and Indonesia—are recognized as tsunami service providers, responsible for sharing tsunami information with other nations in the region. This information is received by disaster management centers and meteorological departments and used to disseminate warnings to coastal populations.

> **Meanwhile, to ensure warnings are acted upon, UNESCO–IOC devised the Tsunami Ready programme. This is a community-centered approach that involves developing 12 indicators, ranging from how to receive warnings, to developing evacuation routes, undertaking drills in communities, and talking about tsunamis with schools (UNESCO–IOC).**
>
> **— Srinivasa Kumar Tummala**
> Secretary, Ministry of Earth Sciences, Government of India

Today, this early warning system is fully operational across the Indian ocean region, with others also established and coordinated by UNESCO in the Pacific, Northeast Atlantic and Mediterranean, and Caribbean.

Reducing fatalities from landslides

Implementing an early warning system in Sri Lanka

In Sri Lanka, around 20% of the land is prone to landslides—primarily in the Central Highlands—and 30% of the population live in the at-risk area. There have been many fatalities in the past due to landslides occurring with minimal warning. In 2017, a series of particularly severe events caused by 400 mm of rain

falling in around six hours killed at least 122 people, displaced 400,000 more, and damaged 1,700 homes. Since 2018, however, fatalities have been lower. This follows efforts made to establish an early warning system by the National Building Research Organisation (NBRO), which is responsible for landslide disaster management in Sri Lanka.

In order to first know more about where landslides were likely to occur, and who and what they were likely to affect, NBRO developed digital landslide hazard zonation maps, considering aspects such as the bedrock, soil cover, slope, angle, hydrology, land use management, and landform. It then mapped where vulnerable infrastructure and communities were located before combining these two types of information to produce maps delineating low-, medium- and high-risk landslide areas. Risk mitigation measures were then developed—including the early warning system—to minimize the risk to people and infrastructure.

The early warning system (Figure 11) operates by receiving data from more than 300 automated rain gauges located in potential landslide areas. These measure the precipitation in real time every 10 minutes. If the threshold of 75 mm/day is reached, the NBRO issues an alert; if 100 mm/day is reached, it releases a warning; and if the rainfall exceeds 75 mm/hour or 150 mm/day it indicates that evacuation is needed. "We issue these notices to the Disaster Management Centre (DMC), which disseminates this information to the general public and the relevant stakeholders," says Asiri Karunawardena, former Director General of NBRO.

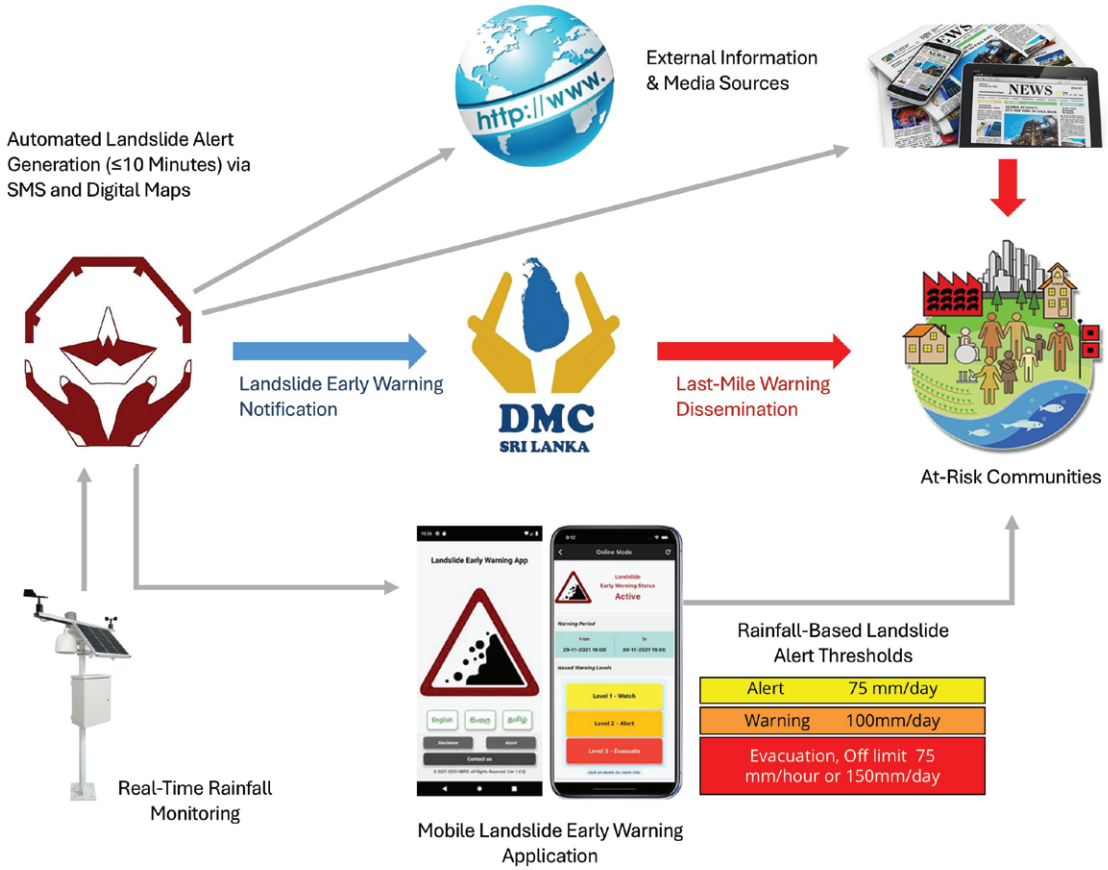


Figure 11. Sri Lanka's landslide early warning system is driven by more than 300 automated rain gauges reporting every 10 minutes; alerts, warnings and evacuation notices are triggered at 75, 100, and 150 mm/day. Inset: NBRO landslide hazard zonation.

Reproduced by IWMI with inputs from National Building Research Institute (NBRI), Sri Lanka

Some site-specific monitoring equipment—such as extensometers to measure movement in rocks—have been installed in critical locations, including hospitals and schools. There have also been efforts aimed at educating specific high-risk communities on how to assess risk, measure rainfall, and develop evacuation routes in their local areas using an accessible map-based digital dashboard. Early warnings—whether locally or nationally produced—are also supplemented by additional risk-reduction measures, including resettling vulnerable families in safer areas, using engineering approaches to stabilize slopes, and developing policies to prevent construction in high risk areas.

> **We must ground our actions in a deep understanding of the physical risk, the social context, and also the institutional landscape. Because if we don't take time for that, there's a risk that our interventions may not be relevant, or could even lead to unintended consequences.**
>
> **— Hari Kumar**
> South Asia Regional Coordinator, GeoHazard International

Handling landslide risk among refugees

Bangladesh has introduced its first landslide early warning dashboard for the district of Cox's Bazar. The dashboard forecasts rainfall and issues alerts to subscribers for precipitation on five consecutive days in the ranges of 95–220 mm, 220–345 mm, and more than 345 mm. It was developed by University College London and Bangladesh Meteorological Department, and is hosted on the Department's website.

Digital maps show the locations likely to be affected and whether they are considered low, medium or high risk. The district has unique challenges as it hosts 1.2 million Rohingya refugees from Myanmar. "We are now giving emphasis to how we communicate and disseminate warnings, as it is difficult for the refugees to move from their camps and the local communities often don't want to evacuate as they don't always have rights to their land and homes," says Bayes Ahmed, Associate Professor, Department of Risk and Disaster Reduction, University College London.

Overcoming silos for better landslide management

When it comes to effectively managing the risk posed by any 'short-fuse' hazardous events, many people need to be involved. In the case of landslides, for example, communication and collaboration is required between geologists, engineers, planners, architects, weather experts, development organizations, funders, and local communities, to name a few. But the reality is that different institutions often work in isolation.

"The engineers don't talk to the architects. Architects don't talk to the geologists. Nobody talks to the planners. And they all work in their own silos. They're all working hard on landslide risk reduction, but they are doing it in isolation. One department may be working on drainage improvements, another on building

regulations, but you know, they're all in their silos. And each of these efforts may be valuable, but they don't align," says Hari Kumar, South Asia Regional Coordinator for GeoHazards International.

After several years of working with authorities in Aizawl, capital city of the mountain state of Mizoram in northeast India, Kumar and his colleagues decided to form the Aizawl Landslide Policy Committee, which brought together a range of stakeholders, including officials from the Central Public Works Department, the Department of Disaster Management, Aizawl Municipal Corporation, and the Public Health Engineering Department, which manages water supply. Challenged to drive down the long term risk from landslides in their city, the group—comprising geologists, engineers, planners, community leaders, university staff, and local government workers—set clear, practical targets and developed a 'roadmap to stability'. They are still working collaboratively and pushing to achieve their targets nearly 10 years on.

"Ultimately, we found that when people come together with a shared understanding of the risk and a common vision for their communities; when they feel that it is for them, their own families, and their own community, then the silos start to break down, and that is when you can get real lasting change," says Kumar.

Tackling glacial lake outbursts in challenging terrain

Glacial lake outburst flooding (GLOF) presents a serious challenge in high altitude settings. It occurs when a lake fed by meltwater from a glacier that is contained by ice, moraine or bedrock is suddenly released. The International Centre for Integrated Mountain Development (ICIMOD) applies scientific expertise and fosters collaboration across the Hindu Kush Himalayas (spanning Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan) to help mitigate and alleviate the impacts of GLOF. The region contains the largest volume of ice outside of the polar regions, which feeds 10 major river systems that support 1.9 billion people.

Among the tools developed by ICIMOD to support better understanding of GLOF is a freely accessible GLOF database, which lists each GLOF event and details the location, triggering factors and any reported impacts, such as fatalities, the number of people displaced, livestock losses, and damage to the settlements and infrastructure, such as hydropower facilities. This is helping experts and practitioners to understand historic and recent events, and the evolution of associated risks. It has also created a methodology for pinpointing 47 potentially hazardous lakes in the region using high resolution satellite imagery (Figure 12).

"In Nepal, one of the lakes identified as high priority is Imja Lake," says Finu Shrestha, Remote Sensing and Geo-information Analyst at ICIMOD in Kathmandu, Nepal. "So, ICIMOD has provided technical expertise to them, such as in hydrodynamic modelling and detailed hazard-risk assessments. This information has been useful to support decision making, from setting up early warning systems to providing awareness and education to vulnerable downstream communities of the lake, and evacuation planning," explains Shrestha.

Despite these gains, Shrestha admits that managing GLOF is very challenging. The rugged terrain, extreme weather, and limited road access in the Hindu Kush region make it difficult to install monitoring equipment. Meanwhile, poor communications networks and power cuts can hinder the dissemination of warnings to people. Such challenges are compounded by the region's fragile geopolitical dynamics, which complicates trust and transparency.



Figure 12. Imja Tsho in Nepal's Everest region, one of the Hindu Kush Himalaya's 47 potentially dangerous glacial lakes. The lake has expanded rapidly behind its moraine dam as the Imja Glacier retreats.
Source: NASA Earth Observatory, EO-1 ALI image acquired 4 October 2010

Overcoming these challenges calls for inclusive governance, regional agreements, formal data sharing protocols, sufficient funding, the establishment of joint monitoring stations in transboundary basins, and the strong involvement of communities and regions in transboundary decision making to mitigate the risks of GLOF.

"ICIMOD has been working closely with partners across the regions to promote collaborative approaches and support harmonized data sharing. These efforts have built trust and also fostered a common interest between the partners to understand the cryosphere, so that they can have more coordinated and timely response to GLOF threats," says Shrestha.

Part 3: The Key to Resilient Communities

Building Resilience through Community-Led Early Warning Systems

Communities live on the frontline of disasters and, as such, are the first responders when an incident occurs. Therefore, for an early warning system to be effective, it must be co-designed by the communities it is aimed at helping. This calls for perspectives from all sectors of society including those who are marginalized, such as women, youth, and those who are illiterate or disabled. A careful balancing act is required to connect such 'ground-up thinking' with the wider authorities and institutions responsible for delivering the early warning system, and further still to link it to national and global strategies. Today, locally- driven early warning systems that leave no one behind are transforming disaster preparedness and response in vulnerable communities.

Community-led early warning system saves lives in the Hindu Kush

Communities who live in the Hindu Kush region face an array of hazards. Spanning landslides, floods, droughts, glacial lake outbursts, and more, the risks from these hazards are being exacerbated by climate change. With the region warming two times faster than the global rate, disasters caused by both too much and too little water are becoming more frequent and occurring with greater intensity than in the past.

Floods have been particularly devastating of late, with several destructive events occurring in 2024 alone. In Bangladesh, flooding killed 71 people and displaced 502,501; in Bhutan, a flash flood damaged homes and disrupted drinking water supplies, forcing evacuations; and in Thame, in the Everest region of Nepal, two glacier lakes burst, extensively damaging a Sherpa village and disrupting infrastructure. Based in Nepal, ICIMOD has developed a community-led flood warning system, which it is implementing in the region and elsewhere to help reduce impacts from future flooding.

Once in operation, a simple device in a river relays information on the water level (Figure 13) to a nominated caretaker's house. On uploading the data, the caretaker verifies if a flood is anticipated. In case it is, the person informs downstream communities and also the local government. The system is built around the Four Pillars of Early Warning, with particular attention placed on engaging the communities who might potentially be affected.

"We work together with the communities. We find out which households have children, people with disabilities or elderly people, and we identify where there is a shelter zone and what rescue routes they can take to it. Ensuring there is equitable access to information and resources is very important," says Neera Shrestha Pradhan, Senior Water and Adaptation Specialist, and Cryosphere and Water Lead, at ICIMOD.



Figure 13. The community-based flood early warning system on the Ratu River: a low-cost water-level sensor on the bridge transmits readings to a caretaker's home, who alerts downstream communities in Nepal and India.
Photo by Mahendra Bahadur Karki/ICIMOD

The ICIMOD-installed system on the Ratu River—which originates in Nepal before crossing into India—is credited with helping 64,000 local inhabitants each monsoon season. Before the system was installed, around two to four people were killed in the Ratu floods every monsoon, but since 2017, deaths from the river have been rare. In 2017 itself, communities received eight hours warning of an impending flood and were able to move to higher ground and safeguard their livestock. Nepal's National Disaster Risk Reduction & Management Authority (NDRRMA) recognized early warning systems as a major factor in preventing casualties during the 2022 monsoon.

> **Eighty percent of implementing an early warning system is working with communities; 20 percent is the technology.**
>
> **— Neera Shrestha Pradhan**
> Senior Water and Adaptation Specialist, and Cryosphere and Water Lead, at ICIMOD

Ensuring community voices are heard

Placing local voices at the heart of risk and resilience planning ensures that communities have ownership of early warning systems rather than simply being observers. This is the approach adopted by the Global Network of Civil Society Organisations for Disaster Reduction (GNDR), whose members work across 132 countries to prevent hazards such as floods, droughts, earthquakes, and infectious diseases. When developing early warning systems, it seeks to gather the lived experiences of at-risk communities and local CSOs and authorities and to identify gaps in understanding capacities to deal with hazards at both local and institutional levels.

The Network is currently working with 10 communities in the Philippines and Indonesia who are affected by volcanic eruptions and typhoons. Early efforts sought to find out about existing indigenous or formal warning systems and barriers to their effective use, such as insufficient institutional capacity, financial constraints, and lack of inclusive decision making structures. After almost a year, the stakeholders reached a consensus on what early action protocols should be. This involved power shifting to local communities and their representatives sitting equally on the same platform with CSOs and the local government.

“While taking this bottom-up approach, there is also a need to analyze at the national level, to find out what policies can enable this kind of an environment and, if there is a gap, how national decision-makers can come together to bring about solutions based on community-level evidence,” says Shivangi Chavda, Head of Programmes at GNDR. “GNDR works to amplify the voices of the local communities, make sure they are not just involved in the consultative process but that they are collaborators, which ensures that this community knowledge directly influences systems, rather than being sidelined in top-down processes,” adds Chavda.

The Network is at pains to include the most marginalized in society in the process of developing early warning systems, believing exclusion to be a structural barrier rather than simply a lack of participation. In its work in the Philippines and Indonesia, it engaged local women’s groups, youth, and persons with disabilities to understand their specific experiences with existing early warning systems or their lack. A GNDR report on local early warning systems in 88 countries found that marginal communities were more often than not passive recipients of early warning information.

“It is very important for us to be advocating for the adaptation of communication channels and formats to local realities including using local languages, oral and visual tools, and trusted community messengers,” says Chavda.

> **There was an earlier understanding that an early warning system was very much a technical thing. But in very recent times, there has been much research that projects an early warning system as more of a societal process.**
>
> **— Deo Raj Gurung**
> formerly Chief Scientist, Aga Khan Agency for Habitat

‘Not for them, with them’

The Sri Lanka Red Cross Society works closely with communities to develop and implement early warning systems. Its experiences have shown that even the most sophisticated system can fail if the local community is not part of the initiative from the outset. The organization has therefore adopted a four-pronged approach to developing early warning systems in a way that is, as Ganga Kariyawasam, Head of Programs, Sri Lanka Red Cross Society, says, ‘not for them but with them’.

The first stage involves co-creating the early warning system with the communities. This means involving local people in hazard mapping, selecting communication channels, and identifying the most trusted local voices to disseminate the alerts (Figure 14). Those chosen might be a school principal, religious leader or youth volunteer. This helps to build ownership of the early warning system. Second, the Society prioritizes local leadership and peer-to-peer learning, which involves training volunteers from within the community who speak the local language, understand the culture, and already have the trust of their neighbors. “When the warning comes from someone you know, you’re more likely to act on it,” says Kariyawasam.

The third aspect is to ensure the system is inclusive and relevant to the everyday lives of the people. In a landslide-prone area, this might call for visual flag alerts and door-to-door campaigns, especially in places where mobile signals are limited or literacy rates are low. And it means ensuring that women, people with disabilities, and other marginalized groups are considered as decision-makers—not beneficiaries—and are involved at the design and planning stages. Trust in the system must be built throughout the community, through regular preparedness drills, community meetings, and seasonal warning campaigns.



Figure 14. Trusted local voices: Sri Lanka Red Cross Society volunteers run a community preparedness drill. When a warning comes from someone you know, you are more likely to act on it.
Photo by Pradeep Liyanage/IWMI

Finally, the Sri Lanka Red Cross Society advocates for celebrating communities' resilience by publicly honoring local responders or showcasing community initiatives at national forums to help communities feel proud and invested in their early warning systems. "The strength of an early warning system is not just in its sirens or software, but in the human connections behind it. When communities feel that the system belongs to them, that their voices matter, they don't just listen to the warning, they become part of the warning," says Kariyawasam.

Achieving the required level of buy-in calls for partnerships. Village communities, grassroots NGOs, and Red Cross volunteers are needed to ensure that the warnings are not only received but understood, trusted, and acted upon. Meanwhile, national agencies such as disaster management centers, meteorological agencies or social protection departments bring technical resources, official mandates, and access to scientific data. And beyond national borders, global networks facilitate access to global good practices—amplifying local voices—and funding mechanisms. "Partnerships are not just value added, they are the foundation of resilience," says Kariyawasam.

Embedding flood warning in schools and communities

A Plan International project in El Salvador sought to develop intercommunity warning systems for flooding. Potentially damaging and life-threatening river floods are expected to occur at least once in the next 10 years across much of the country, and it is also vulnerable to earthquakes, volcanic activity, and droughts. The initial goal was to establish systems in 4 communities in 2 departments, but as neighboring communities expressed interest in the work, the project was expanded to cover 22 communities in 3 departments.

For each community, the work involved installing equipment such as water level meters and sirens, developing response plans and evacuation routes, building or upgrading community shelters, and providing first aid training. At both school and community levels, groups of 20 people were established and split into 4 teams with responsibilities for monitoring and early warning, evacuation security, first aid, and temporary shelters. In an emergency, the teams work in harmony with the monitoring and early warning team alerting the evacuation security team, and messages passing further up the chain as required.

"In the long term, the hope is that the early warning system structure established within the schools is incorporated in the curriculum at the subnational or even national level. So far we have achieved this in another country but not yet in El Salvador," says Manuel von der Mühlen, Global Program Manager, Plan International, Switzerland.

In addition to engaging people within the community, Plan International forged links at the policy level by establishing joint work agreements with the two national agencies responsible for disaster management, namely the Observatory of Hazards and Natural Resources and the General Directorate of Civil Protection. "It was crucial to build a high level of trust between the different parties. With our long-standing presence in the community, we have built this, but it was also important to establish that trust between the government and the communities too," von der Mühlen adds.

> **I think as a next step, we can build a community practice for knowledge sharing among disaster risk reduction practitioners, so that we can learn from simple initiatives in other countries. You can have local differences but at the same time have common learnings and approaches that work at the global level.**

— Manuel von der Mühlen
Global Program Manager, Plan International Switzerland

The need for early warning systems in hydropower

As climate extremes threaten hydropower infrastructure and downstream communities, early warning systems tailored for water-energy security are becoming increasingly important. Integrating weather, hydrological, and dam operation data can support risk-informed decisions and reduce cascading impacts on livelihoods and ecosystems.

Ensuring the hydropower sector is resilient to climate shocks

Hydropower is becoming increasingly important around the world. Globally, it is already responsible for half of renewable power, and will likely play a critical role in the continued transition to low-carbon pathways. It is particularly important for grid management as it can stabilize the grid while integrating high amounts of variable renewable energy, such as wind and solar. However, its future success will depend on the sector's ability to be resilient in the face of climate change.

"In the last one and a half years, we have had many requests from our member countries about how to do specific work around hydropower resilience," says Amit Tripathi, Lead Specialist – Energy Sector Resilience for the Coalition for Disaster Resilient Infrastructure (CDRI). "In India and Nepal, in the last two to three years, repeated extreme weather events have taken a toll on lives, livelihoods, and critical infrastructure, including in the transport and the hydropower sectors. Organizations have lost hundreds and thousands of megawatts of power-generating capacities in the region," adds Tripathi.

The CDRI has 50 country members; many are major hydropower users, and eight partners, including funders of the sector, such as the World Bank and Asian Development Bank. It leads the Community of Practice on Building Hydropower, which has identified the need for modern early warning systems within the hydropower sector and efforts required to support their widespread adoption. The economic case for effective early warning systems alone is compelling, with the WMO reporting an estimated tenfold return on investment on early warning systems (WMO 2023c).

The CDRI has identified a range of actions that are needed to deliver resilience within hydropower. These range from the creation of robust climate databases and impact-based forecasting tailored to hydropower operations and assets, to integrated multi-hazard monitoring and multistakeholder collaboration. Knowledge products and platforms for sharing best practices and data will also be required. Regions may

need a tailored approach; while Africa is hindered by aging infrastructure, funding shortages, and data gaps, the Himalaya and Andes regions face specific risks from glacial lake outbursts and inaccessible terrain.

Integration is key to modernizing hydropower early warning systems

When it comes to operating hydropower plants efficiently and safely, having access to environmental monitoring and operational data, and good communications with meteorological departments and disaster management centers is key. However, many plants still base their warning alerts on historic—rather than real time—data, and frequently the institutions they need to communicate with operate as separate silos. Developing a modern MHEWS can bring benefits to all aspects of hydropower plant operations, simply due to the integration required for the system to work effectively.

Any effective early warning system needs data from monitoring and modelling, to provide information on the status of a hazard or hazards. This will come from a range of sources— from weather stations, satellite observations and simulation models, to probabilistic forecasts, global platforms and citizen science. Developing a modern early warning system provides a way to bring these disparate sources of data together and to have a far more accurate picture of a potentially hazardous situation than trying to use such data sources separately. Within hydropower, it provides a way to view a plant's entire operation through a lens of resilience metrics, robustness, and risk thresholds.

An integrated system can incorporate diverse data, such as maps of river catchments and dam typologies, and figures on storage capacities. These can provide insights into the nature of risks faced by the plant, such as what impacts a failure might have on downstream communities or on energy security as a whole, as well as potentially cascading risks. "It's common to see, for example, floods disrupting energy systems, not because of physical damage to the hydropower dam per se, but because roads connected to the hydropower plant are completely wiped out or disrupted. So, in that case, the energy shock comes from people not being able to access the hydropower plant," says Homero Paltán, Associate Researcher at the School of Geography and the Environment, University of Oxford.

A further benefit accrues from the connection with external institutions that comes from implementing an early warning system. The process of developing and using the system calls for coordination across multiple sectors and institutions including water agencies, dam operators, energy utilities, meteorological services, and disaster agencies. The whole system joins up in monitoring potential hazards, understanding risk thresholds, and disseminating alerts that can initiate action that potentially saves lives and livelihoods. "The necessary integration facilitates a level of coordination that is essential for energy security," says Paltán.

Hydropower giant embraces early warning

In 2021, a rock and ice avalanche in Uttarakhand (Figure 15), India, killed 200 people and badly damaged two hydropower plants (Shugar et al. 2021). In response, the Ministry of Power mandated that early warning systems be put in place to cover vulnerable hydroelectric projects. As an owner of 24 hydro projects and with a total capacity exceeding 7,000 MW, The National Hydroelectric Power Corporation (NHPC Limited) was directed to establish an early warning system and set up a master control room to monitor hydropower early warning systems across the country (NHPC 2022).

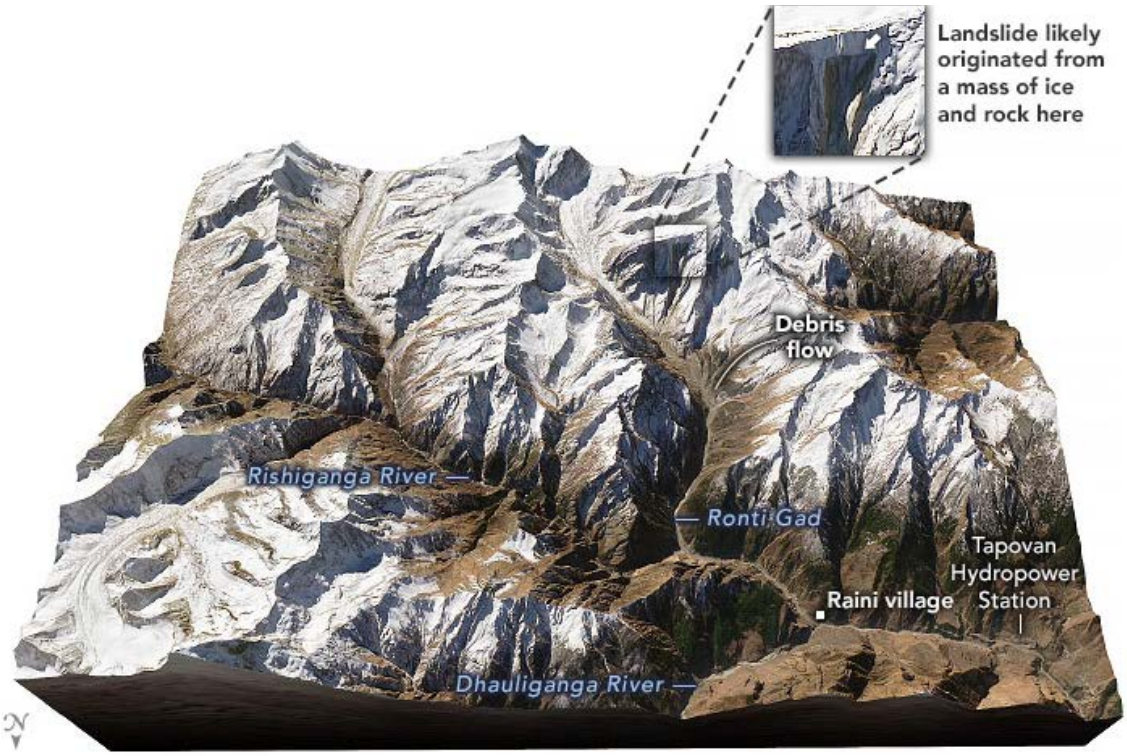


Figure 15. Landsat 8 images before (January 20, 2021) and after (February 21, 2021) the 7 February 2021 rock and ice avalanche in Chamoli, Uttarakhand, which killed some 200 people and destroyed two hydropower plants.
Source: Joshua Stevens, using Landsat data from the U.S. Geological Survey and topographic data from the Shuttle Radar Topography Mission (SRTM).

Before the new system was installed, NHPC Limited mostly relied on data from IMD and the Central Water Commission (CWC) to help it forecast potential hazards, with information disseminated through various WhatsApp groups. Its new cloud-based system is more sophisticated, incorporating upstream water-level sensors and real time inputs from IMD to underpin its alerts. "Based on the sensor data, we are able to predict the discharge at the dam location, with 24/7 monitoring. We have also developed software that automatically generates an alert if particular thresholds are breached," says Manjusha Mishra, General Manager (Civil), NHPC Limited.

The company credits the system with saving lives of its personnel, as well as equipment, during several incidents, including when floods in 2022 and 2024 affected work on the 2000-MW Subansiri Lower Hydroelectric River project.

Building resilience to climate change into hydro planning

In the past 20 years, the Asian Development Bank (ADB) has financed 30 hydropower plant projects. Prior to approval, projects undergo steps to ensure that resilience to climate change is integrated into both the design and operation of schemes. These include assessments of historical data and future climate risks, as well as hydrological and sediment studies. The aim is to make sure that hydropower plants can be resilient while being aligned with sustainability goals, international best practices, and ecological and social requirements.

Take the example of the Tina River Hydropower Development Project in the Solomon Islands. Recently approved by ADB, this is the first large, utility-scale renewable energy project for the Islands. Its design was based on very detailed climate risk assessments, with increased spillway capacity provided in line with forecasts for more intense tropical cyclones and rainfall and a rise in extreme water flow of 25% to 30%. "Monitoring early warning systems were included to cope with flood management in advance," says Jinsun Lim, Climate Change Specialist at ADB.

The Bank recently launched a sustainable large hydropower development technical assistance program, which aims to expand the adoption of advanced digital technologies and innovations in the design and operation of hydropower projects. "It includes automated smart digital technology for data collection, monitoring, early warning systems, forecasting, and operation planning. By providing this kind of technical assistance, capacity building, and knowledge products, we are trying to support developing countries to integrate climate-resilience components successfully," says Lim.

Making early warnings the norm, not the exception

Integrated early warning systems should be the norm for the hydropower sector, not the exception. This is the view of the International Hydropower Association (IHA), a global nonprofit membership organization working in 120 countries. "We see early warning systems as essential for hydropower resilience," says Lei Xie, Energy Policy Manager at the IHA, whose members range from hydropower owners and operators, to developers, designers, suppliers, and consultants. "Floods, cyclones, droughts—these climate risks are growing, and relying on historical data alone is no longer enough. We need dynamic systems that integrate climate forecasts, hydrology, and real time dam data," adds Xie.

At present, having an early warning system is an exception within hydropower. Some operators are using climate forecasts, flood modelling, and community warnings; for example by linking flood modelling with early warning triggers, protecting both dams and communities by enabling timely evacuations. However, many operators still rely on historical data. Moreover, many regions lack reliable hazard data, interoperational platforms, and localized warning dissemination, weakening the impact of any systems that do exist.

To promote wider use of early warning systems, IHA and its sister organization, the Hydropower Sustainability Alliance, have developed a series of international guidelines to provide clear benchmarks for good practices across the sector, covering environmental, societal, governance, and climate resilience dimensions. A key tool is the newly updated *Hydropower Sector Climate Resilience Guide*, which provides guidance on managing climate risks in new and existing projects, including information on project design, due diligence, and finance.

Having international standards can fulfil three roles. First, they set common expectations that resilience to climate change and early warning systems should be incorporated as standard. Second, they can help to unlock finance by linking early warning protocols to investor requirements. And third, they can enable learning by building in feedback and best practices to ensure that guidance keeps pace with emerging risks. "Early warning systems are not extras but core to safety and sustainability. Hydropower can only fully support the clean energy transition if it is climate resilient," says Xie.

Preventing Crises from Escalating

Climate shocks often trigger complex crises involving hunger, displacement, and conflict. Integrated early warning systems can monitor interconnected risks—such as drought, price volatility, and migration—to inform Anticipatory Action. Combining forecasting data with local intelligence and cross-sector coordination, and ensuring that humanitarian, development, and government actors work together, can contain crises before they escalate, helping to build long term resilience at all scales.

How diverse data can help pre-empt crises

Forecasting acute food insecurity

Climate shocks are inevitably complex. In southern Africa, 95% of farmers rely on rainfall to grow crops and more than 60% of the region's people rely on agriculture for their livelihoods. If a drought cuts agricultural production, the market price of staple crops rises, reducing people's access to food. In areas of conflict, such situations can be compounded by the large-scale displacement of people, and, as these people are often farmers, this can reduce food production further. Understanding how these different elements interact and exacerbate each other is vital for preventing climate shocks escalating into major crises.

Established in response to the 1984 famines in East and West Africa, to inform the US Government on the demand for foreign aid, the Famine Early Warning Systems Network (FEWS NET) provides forecasts and analysis of acute food insecurity. Drawing on data from wide-ranging partners that spans agriculture, climate, conflict, hazards, market and trade data, it produces monthly reports that analyze how events may unfold as far ahead as 18 months hence. It specifically seeks to understand who will be affected by acute food insecurity, where, how and when, and what the drivers of the situation are.

"In 2015 there was a drought equally severe as that in 1984.' But by then multiple early warning systems were in place and the international community was monitoring indicators of drought, and we were able to really be ahead of this potential famine. And because of that, resources were allocated that helped the Ethiopian government to be on top of the situation. The US government and governments in Europe and a lot of partners around the world were able to all work together to avert famine in 2015," says Karyn Tabor, Senior Agroclimatiology Advisor for FEWS NET and research scientist at NASA.

Despite positive gains, the past decade has seen an increase in deadly food crises. Since 2012, FEWS NET has used the Integrated Food Security Phase Classification (IPC – which ranks acute food security from 1 [none or minimal] to 5 [catastrophe or famine]), to produce standardized, evidence-based maps to provide early warning of situations potentially needing humanitarian response. Starting with Sudan, it is now also making its various data sources available for external consultation through its website.

"Say there's a conflict event in Sudan," says Tabor, "you can pull in data from the International Organization for Migration to show where people are moving – which, combined with agroclimatology data, can show if they are moving to areas where there may already be drought or crop failure. If they are, this can inform those providing food assistance in those areas. It can help humanitarian planners identify and really pinpoint where people need assistance and where there's increasing need."

Anticipating compound risks

More and more, hazards are not occurring individually but at the same time. Climate variability is increasingly affecting both natural and human systems, putting societies at risk of multiple and interrelated, environmental, socioeconomic, and political crises. At the Alliance of Bioversity International and CIAT, analysts are applying a Compound Risk Framework (CRF) to identify how, in fragile communities, a single trigger can unleash multiple hazards and to highlight buffers that can help to slow down crises.

In Mozambique, the most northern province of Cabo Delgado faces armed insurgency, cyclones, floods, and chronic underdevelopment. Using the framework to analyze 22 years of monthly data revealed that conflict accounted for 36% of the variation in IPC rankings, with floods and cyclones explaining 25%. The researchers identified three mechanisms that could potentially slow down crises: functioning trade and transport corridors, stable crop production, and market connectivity.

“Scenario modelling demonstrated that when both conflict intensity and flood risk surpassed critical thresholds, the likelihood of passing from IPC level two [stressed] and three [crisis] to four [emergency] became higher,” says Grazia Pacillo, Senior Scientist and Co-Lead of the CGIAR FOCUS Climate Security at the Alliance of Bioversity International and CIAT.

There is a need to expand the existing shared evidence base using systems and approaches such as CRF and FEWS NET and others that are available, to provide policy makers and humanitarian development and peace actors with an integrated picture of risk. Developing dual-purpose triggers—essentially layered thresholds that can activate different types of action from the same early warning signal—would also be beneficial.

“For example, if we have a forecast drought plus early market stress, this can trigger livelihood, social protection, and development interventions,” says Pacillo. “However, triggers are only as good as the systems that prompt action to respond to them. Therefore, these early warning systems must be conflict sensitive, and they must be linked to peacebuilding activities. They need to have all of this at the heart of the design,” explains Pacillo.

> **Data sets a baseline to actually look at whether different interventions are working or not working, so you can build loops of evaluation and learning into governance processes that can really bring home the need to work together.**
>
> **— Sanjiv de Silva**
> Senior Regional Researcher, Natural Resource Governance, IWMI

Facilitating use of Anticipatory Action in East Africa's pastoral areas

Anticipatory Action has its roots in work undertaken by the humanitarian sector in 2013–2014 that linked climate data to pre-arranged financing. By using science-based forecasts and pre-agreed triggers and plans, it seeks to prevent hazards from becoming disasters, thereby reducing losses and suffering, and saving lives and livelihoods. In the past decade, Anticipatory Action has moved from being a concept to a core component of humanitarian practice, and driven a shift from reactive to proactive disaster management.

The approach is increasingly seen as vital in fragile and conflict-affected areas to prevent crises compounding already desperate situations. The Jameel Observatory for Food Security Early Action, a partnership led by the University of Edinburgh that is based at the International Livestock Research Institute (ILRI) in Nairobi, Kenya, is currently convening key stakeholders in Anticipatory Action and food security in East Africa, with the hope of enhancing application of the approach in pastoral areas. Currently, a lack of data and less accurate climate modelling means that the Anticipatory Action is harder to apply in these locations than in other more data-rich regions.

"We need scientists and policymakers in the same room so that they can learn from each other," says Nathan Jensen, Research Lead at Jameel Observatory for Food Security Early Action. However, he adds: "But we also have to involve local community members in the collection and interpretation of early warning information, not only so that they believe in it and trust it, but also so that we—as scientists and model developers—can understand where our models are missing critical components of food security and seek to fill those gaps. Crises and shocks are extremely dynamic and nonlinear, which emphasizes the need for continued local engagement—because any model is going to be wrong, we can just only hope to improve it with local insights and to educate the implementers."

Part 4: Harnessing Transformative Technology

Applying the Power of Artificial Intelligence for EW4All

Artificial Intelligence and data-driven decision-support systems are increasingly being used in early warning systems. AI and machine learning have the potential to contribute to all aspects of early warning systems from enhancing forecasting accuracy, to facilitating rapid risk analysis and transcribing alerts into wide-ranging formats and languages to support inclusivity. While challenges remain, real world applications are already demonstrating how tech-enabled insights can empower stakeholders to act before disasters strike.

Building AI into the Four Pillars of EW4All

Artificial Intelligence spans technologies that can detect patterns, act logically, and generate content. As such, it has the potential to ramp up the work of the EW4All across Four Pillars, by helping scientists make sense of complex data faster. Under Pillar 1, it can aid scientists in rapidly assessing weather, vegetation, hazard, and socioeconomic data to better understand disaster risk and inform effective decision making. Under Pillar 2, it can enhance researchers' capacity to detect, monitor, analyze, and forecast hazards. Under Pillar 3, it can help ensure that warnings are disseminated in ways that enable communities to understand and act appropriately. And under Pillar 4, AI can offer new information and communication resources that help people respond to warnings.

Seeking to harness the benefits of AI technologies, the lead agencies of EW4All established the AI for Early Warnings for All Group. The group brings together the Pillar lead organizations, as well as representatives from the public and private sectors, including major global technology companies such as Google and Microsoft. "We identify gaps in early warning and we explore AI-based solutions that really respond to countries' needs. We aim to scale these solutions through country pilots to close the gap and to use AI to strengthen early warning systems," explains Vanessa Gray, Head, Least Developed Countries, SIDS and Emergency Telecommunications at ITU.

Driven by the overarching principle that AI has to solve operational problems, the AI group has four main work strands. The first is to undertake gap analysis to understand what specific issues exist that prevent the provision of effective early warnings—particularly in the countries that are most at risk—and to match the problem with suitable AI technologies and expertise. Issues might include a lack of lead time when a hazard strikes, or that alerts are not reaching people in need. The second is to develop an online catalog of AI tools, models, and applications, tagged by identifiers such as hazard, maturity or Pillar, so that countries and agencies can find peer-reviewed, field-tested solutions to particular problems and engage with the organizers or developers directly. The third is to develop pilot initiatives, bringing together technology providers, governments, and local actors to test and showcase methods and approaches. And the fourth is to mobilize resources to implement and potentially scale up pilot AI projects.

"We're looking to answer questions such as: Can machine learning help to identify at-risk populations faster? Can natural language processing help warnings reach people in their own language? And can new forecasting models run on the limited infrastructure that national meteorological agencies actually have?" says Newton Campbell Jr, Computer Scientist, AI Subject-Matter expert for EW4All, ITU. "We convene scientists, technology, technologists, and disaster managers to make sure that the answer to those questions is 'yes' and that solutions are implementable," adds Campbell.

One of the group's early activities was to run a global hackathon. Aiming to identify AI solutions to fill critical gaps in disaster risk reduction, it attracted around 50 submissions. The finalists included: Bibliotechies, which proposed a decision-centered AI platform designed to support anticipatory flood action, encompassing 'what-if' scenarios; Team Daraja, which outlined an AI-powered early warning system tailored to Sudan, including inclusive communication tools; Team Ignitia, which devised a hyper-local storm alert system for climate vulnerable communities underserved by traditional forecasting; and Team Destaj, which conceptualized a solution combining AI and the Common Alerting Protocol to deliver inclusive and accessible warnings in Bangladesh (ITU, n.d.).

"We're now working with those finalists to start working groups and get them moving towards developing pilot projects. Our aim is simple, just to make AI a reliable component of disaster management, not an experiment running on the sidelines," says Campbell.

Connectivity map ensures alerts reach everyone

In an emergency, mobile phones provide a means to rapidly disseminate warnings to large swathes of a population. However, a large proportion of the world's most vulnerable people live in areas with limited or no mobile coverage (Figure 16). Moreover, when a disaster strikes, such infrastructure is often damaged or destroyed. If governments are to design effective strategies for disseminating alerts to everyone, they need up-to-date information on where connectivity cold spots are located.

As part of the EW4All initiative, ITU, together with Microsoft AI for Good Lab, GSMA, Planet Labs, and the Institute of Health Metrics and Evaluation at the University of Washington, USA, set about developing the Early Warning Connectivity Map (EWCM). They aimed to devise a way to know which people could be reached through available messaging channels; how many people were offline and therefore unable to receive alerts at any one time; and how connectivity levels—and therefore the capacity to deliver warnings—might change before, during, and after a disaster.

Using AI, they combined satellite imagery and advanced analytics to generate high-resolution, time-enabled population density maps. Overlaying this information with mobile network coverage data made it possible to identify unconnected areas and inform decisions on expanding the rural network. Importantly, EWCM could provide a detailed and continuously updated view of connectivity gaps—critical for designing inclusive early warning systems (UNDRR 2025a).

So far, the initiative has results for 33 countries, and is scaling up the effort to cover 50 countries in total. For example, the mapping has shown that 7% of Somalia's population live in 'cold spots' that are beyond the reach of fixed broadband, 2G or 3G networks and are therefore not connected by digital technology.

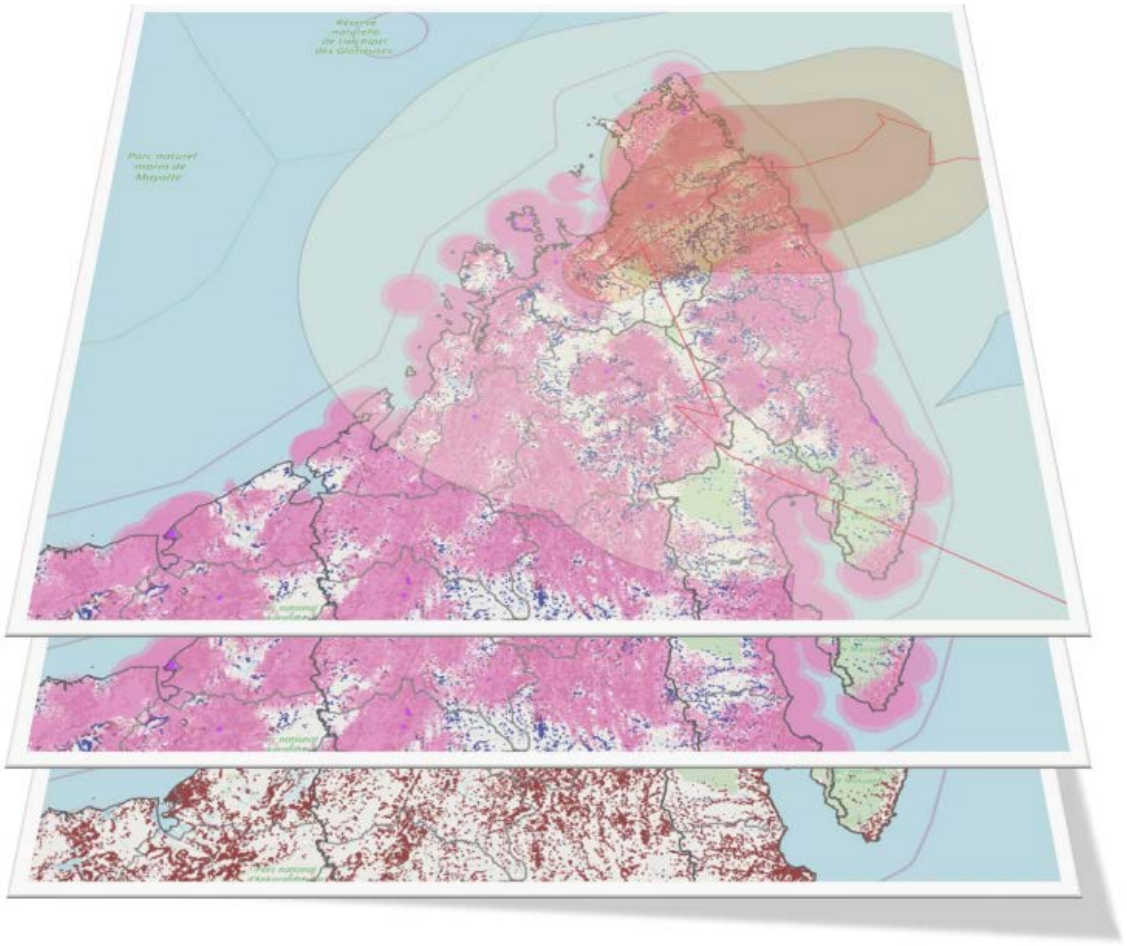


Figure 16. An Early Warning Connectivity Map that combines AI-derived population estimates with mobile network coverage to reveal 'cold spots' beyond the reach of digital alerts, shows that 7% of Somalia's population is in the 'cold spots'.
Source: Early Warning Connectivity Map (EWCM), ITU, and partners

"The map enables governments and partners to identify the populations that are not covered by digital networks, and so to design tailored dissemination strategies and make targeted investments. If there is a large population group that is not covered by digital networks, either we need to find alternative communication strategies or we need to expand networks to these areas, to make sure that no one is left behind," says ITU's Vanessa Gray.

Tested in pilot projects in Fiji, Tonga, and Vanuatu, the approach was subsequently scaled up to include 30 more countries, where the EWCM has strengthened national strategies for last-mile warning coverage and inclusion. "The EWCM shows how AI combined with cross-sectoral partnerships and data can really advance early warning systems," says Gray.

Using AI to build resilience to natural hazards

For impact-based forecasting to be effective, hazard predictions must be coupled with data on exposure and vulnerability, so that practitioners can accurately anticipate consequences on people, crops, and infrastructure. If not, the best forecasts might not translate into early action. However, the overlapping nature of hazards—for example when floods lead to landslides or heatwaves combine with drought—makes analyzing risk highly complex.

The Mediterranean and pan-European forecast and Early Warning Systems against natural hazards (MedEWSa) project is drawing on the latest AI and machine learning technology to help first responders, planners, and policymakers overcome this challenge. Specifically, it is developing a suite of innovative services aimed at helping to improve their knowledge and optimize their response actions.

"MedEWSa is working through eight pilot regions, grouped in twinning pairs, to share experiences and test tools in diverse settings, from Europe to the Mediterranean as well as Africa. This allows learning across very different climates," says Elena Xoplaki, Senior Scientist at the Euro-Mediterranean Centre on Climate Change (CMCC).

Among its achievements so far, the project has developed flood 'now-casting' in the Košice region of Slovakia, with forecasts issued at 5-minute intervals to anticipate flash floods; applied clustering methods to select the best European Centre for Medium-Range Weather Forecasts ensemble members to improve the accuracy of storm surge warnings in Venice, Italy; and built a fire-spread model that accounts for wind, terrain, and vegetation to predict how fires will move and support civil protection planning in Attica, Greece, and is now adapting it for use in Ethiopia.

"It's combining hazard and impact modelling for multi-hazard early warnings across droughts, floods, wildfires, and heat. It is integrating national and international tools into a shared decision-support dissemination system covering the full early warning value chain," adds Xoplaki.

Reaching last-mile communities in Bangladesh

Being highly vulnerable to flooding has helped Bangladesh excel at taking Anticipatory Action. Forecast-based triggers and pre-planning for the provision for aid—such as money from a specially established Disaster Relief Emergency Anticipatory Fund, as well as food and shelter—mean that support can be provided in a timely way before a flooding event becomes a disaster.

AI is increasingly contributing to this effort by helping to determine when to deploy these resources ahead of a crisis, as well as being used for integrated risk forecasting and impact-based modelling. "IFRC is actively harnessing AI to boost Anticipatory Action, pursuing the envelope of this human response to reach the most vulnerable communities more effectively," says Asif Rafsan, Consultant in early warning systems and Anticipatory Action, who was formerly Senior Program Officer at IFRC.

Working collaboratively, the German Red Cross, IFRC, and the Red Cross Red Crescent Climate Centre developed an Anticipation Hub to serve as a global knowledge exchange platform. It acts as a repository for interactive maps, publications, and methodologies, and connects practitioners to promote learning and innovation in Anticipatory Action. It has become a focus for cross-sectional collaboration, including with AI experts, which has helped to drive the development of prototypes for testing in the real world. The Hub reports that Bangladesh has implemented early actions more than any other country (Anticipation Hub, n.d.).

"Natural hazards are growing more and more complex, but with smart systems, good partnerships, and meaningful communication, our responses can be faster, fairer, and more effective."
Elena Xoplaki, Senior Scientist, CMCC

Employing Eyes in the Sky

Earth observation technologies and space-based data have long been critical within disaster risk management, early warning systems, and emergency response. Stakeholders within the sector span international space agencies, national disaster management organizations, academia, the private sector, and international development organizations. In combination with AI and machine learning analysis, space-based technologies, collaborative partnerships, and innovation are driving the transition from reactive response to proactive, data-driven disaster management.

How space tech is vital for humanitarian response

India hails 25 years of satellite flood monitoring

India is highly vulnerable to floods, with the country on high alert for seven or eight months every year. In its efforts to minimize the impacts from flooding, it developed a satellite-based framework for flood monitoring that has now been operational for a quarter of a century. Today, the addition of AI and other complementary technologies are helping to speed up and enhance targeting of the nation's response when floods strike.

The framework's operational process starts with observing rivers and glaciers, using a constellation of Indian Space Research Organisation (ISRO), public and commercial satellites. If flooding is anticipated, satellite imagery is acquired for specific at-risk locations. With speed being critical in an emergency situation, automated, scene-independent algorithms are used to process the acquired data within an hour. This is then analyzed to detect floods. While remote sensing is a mature technology, persistent cloud cover, water in agricultural fields, and mixed pixels can present challenges during interpretation phase.

The final phase involves producing flood maps and statistics, which are disseminated to the National Database for Emergency Management (NDEM). "All information generated in India on disasters is hosted on the National Database for Emergency Management. It is a unique geospatial platform designed to provide real time space-based inputs and forecasting services for all disasters in the country," explains A.V. Suresh Babu, Head of the Flood Mapping and Hazard Assessment Division of India's National Remote Sensing Centre at ISRO.

In addition to managing flood response within its own borders, during April to October 2025, ISRO was the lead for the International Charter: Space and Major Disasters. Involving 17 members' space agencies and 207 satellites, the Charter provides remotely sensed data and works with experts to derive information products that support relief organizations working to respond to major disasters worldwide. During its period as lead country, India activated the Charter 28 times, supporting 23 countries. It requested support for India from the Charter on three occasions, when flash floods and landslides affected the states of Himachal Pradesh, Uttarakhand, and Jammu and Kashmir.

Asia–Pacific's space-based Sentinel

Over the past two decades, Sentinel Asia has responded to more than 500 disasters in the Asia–Pacific region. This initiative, operated on a 'voluntary and best effort' basis and led by the Asia-Pacific Regional Space Agency Forum (APRSAF), shares disaster information in near real time across the region, primarily using internet and digital-mapping technology. Its goals—which include improving the speed and accuracy of disaster preparedness and early warning, minimizing the number of victims and socioeconomic losses

from disasters, and contributing to developing rehabilitation plans—are underpinned by the rapid collection across a wide area of images and other data from earth observing satellites. Sentinel Asia works in close collaboration with the International Charter: Space and Major Disasters.

"We try to manage all phases of a disaster," says Goro Takei, Associate Senior Engineer at the Japan Aerospace Exploration Agency (JAXA), as well as Deputy Executive Secretariat of Sentinel Asia and a board member of the Charter. "This includes the pre-disaster phase—which might involve monitoring, preparing hazard maps, and issuing early warnings—as well as preparedness, such as conducting training and capacity building. However, the biggest activity of Sentinel Asia is the response phase. We respond to requests from the Sentinel Asia members for emergency observation by satellite, then undertake analysis to assess the resulting damage. We also try to cover recovery phases," explains Takei.

Sentinel Asia has 127 member organizations across the region. These include data providers, namely satellite agencies that supply remote sensing imagery; data analyzers, encompassing research institutes and universities, which analyze data and create bespoke information products; and national disaster management entities and international organizations that use the provided data products. If support is needed, a member files a request using the Sentinel Asia management system Optemis. Once the request is approved, Optemis contacts the data providers and analyzers detailing the kinds of data needed. The provided satellite images are then analyzed and relevant products created—such as maps showing flooding extent or building damage—for dissemination to the requisitioner and other Sentinel Asia members.

In the last few years, Sentinel Asia has responded to events including the earthquake that affected the Noto Peninsula of Japan in January 2024 and the super typhoon Yagi, which began in the Philippines but also affected Vietnam, Laos, Thailand, and Myanmar. Responding to the Japan event involved creating maps showing where landslides could have occurred. The government used the maps to direct helicopters which were then able to take detailed photographs to assess the damage to people and infrastructure. The response to super-typhoon Yagi involved responding individually to requests from countries. In the case of Myanmar, the United Arab Emirates' Mohammed Bin Rashid Space Centre supplied satellite images showing the area inundated by flood waters. The WFP used the inundation map, overlaid with population and crop distribution data to estimate the volume of humanitarian aid required.

"AI technology is a very powerful way to rapidly map a disaster. For example, following the Afghanistan earthquake, we did an assessment of damaged building within several hours. We used deep learning to quickly and accurately map damaged buildings."
Xi Li, Professor at Wuhan University.

From reactive to proactive response in Sri Lanka

Satellite technology transforms disaster response

Satellite technology has transformed how Sri Lanka responds to potential and actual disasters. The country frequently experiences a range of hazards, including cyclones, floods, landslides, droughts, and coastal hazards. Managing these—both monitoring and preparation and disaster response—calls for timely, reliable, and wide-ranging information which satellite technology can provide, complementing the nation's ground monitoring systems.

"Satellite data has altered us from reactive response to proactive management. It strengthens scientific decision making, enhances our multi-agency coordination, and builds community trust in early warning, because we have been able to give accurate early warnings to the people," says Sampath Kotuwegoda, Director General of Sri Lanka's Disaster Management Centre.

The DMC regularly uses satellite technology to manage its responses to diverse hazards. For example, if a cyclone is detected in the Bay of Bengal and Arabian Sea, it tracks the storm path, windspeed and rainfall, with support from ISRO and JAXA, providing time to coordinate with local authorities and the military before the cyclone makes landfall. It uses remote sensing for monitoring droughts, too, using tools from the National Aeronautics and Space Administration (NASA) and United States Geological Survey (USGS) to guide water use and plan crops. Flood maps based on Sentinel and Terra SAR-X satellite data have been vital for monitoring communities cut off by damaged infrastructure, managing evacuations, and relief supplies, and deploying response efforts.

Partnerships with the United Nations Platform for Space-based Information for Disaster Management and Emergency Response (UN-SPIDER), the European Space Agency (ESA), the International Charter: Space and Major Disasters, and the World Bank have provided access to satellite technology, as well as technical support and capacity building.

Earth observation tools support early warning goals

Headquartered in Colombo, Sri Lanka, IWMI has worked with remote sensing data for the past two decades. During this time, it has developed considerable expertise in using satellite imagery to map a variety of hazards and to layer this data with population density and vulnerability data to generate risk maps. Having initially undertaken this work at regional level, it now also works at much higher resolutions down to sub-national level. "For example, we look at flood mapping and other components and identify risk hot spots in South Asia (Amarnath et al., 2017). Over time, as our understanding has improved, we have been able to take a much more holistic approach," says Niranga Alahacoon, Regional Researcher in Remote Sensing and Disaster Risk Specialist at IWMI.

Within the field of early warning, IWMI has developed hazard monitoring platforms. These include the South Asia Drought Monitoring System (SADMS) (Figure 17) and the Early Warning, Early Action, Early Finance (AWARE) platform. SADMS links seasonal, subseasonal and seven-day weather forecasts with satellite-based monitoring tools that identify the presence and severity of drought, and district-level agricultural contingency plans for implementing if set trigger thresholds are exceeded. Meanwhile, AWARE disseminates information on climate, market, health, nutrition, and population displacement to promote joined-up efforts by multiple partners at local-to-national scales to enhance preparedness, response, advocacy, and resource mobilization for when climate risks are high.

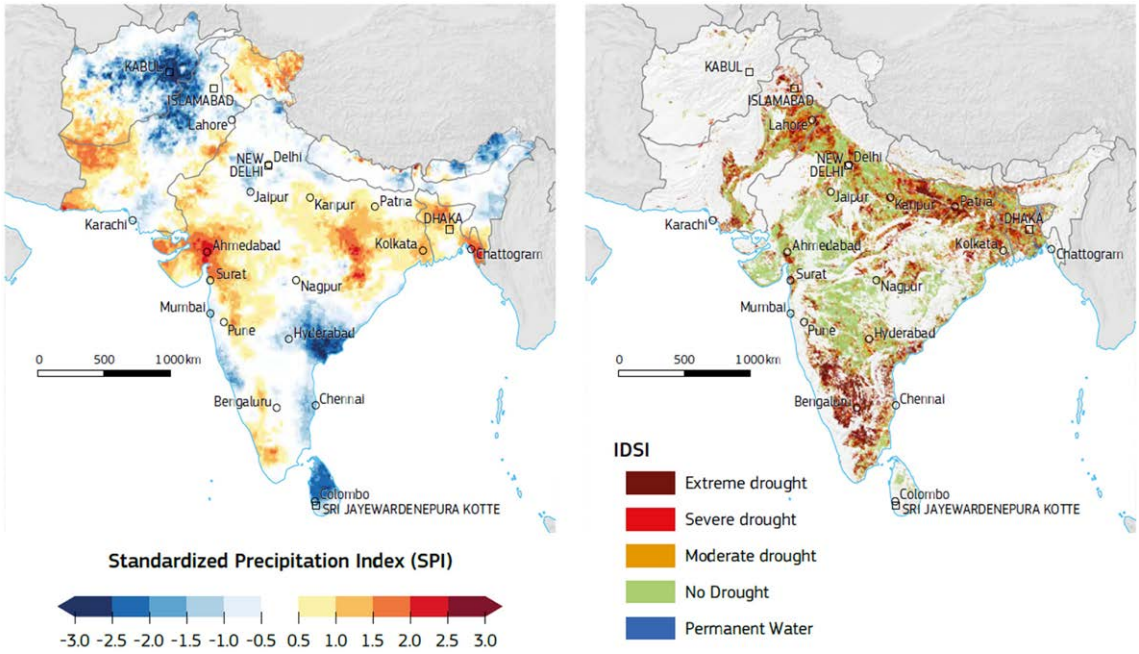


Figure 17. Meteorological (Standardized Precipitation Index) and Agricultural (Integrated Drought Severity Index) drought indexes to represent the South Asia drought in 2026.
Source: IWMI South Asia Drought Monitoring System (dms.iwmi.org) and Toreti et al., 2024)

"Institutionalization, sustainable financing, and making sure platforms incorporating earth observation data are user friendly, are key to ensuring they enter mainstream use," says Alahacoon. "For example, it is important to collaborate with government agencies, as only then will the platform or other product be integrated in managing a disaster situation in the country. When considering the early action and early finance components of AWARE, for example, linking with the government budgetary approaches and other financing agencies is more reliable and supports using the platform to manage the disaster situation," explains Alahacoon.

Commerce can provide disaster support

The major challenge in the immediate aftermath of any disaster is how to rapidly and accurately assess the resulting damage. While optical satellites are invaluable, their sensors' view of the ground can sometimes be obscured by cloud cover, smoke or thunderstorms. The company Synspective seeks to overcome these challenges by providing Synthetic Aperture Radar (SAR) satellite data to government agencies and companies around the world. "We provide a unique all weather, day and night capability at a very high resolution, from 3 meters down to 0.25 meters," says Alvin Hoh, Regional Sales Manager for Synspective.

The radar's ability to see in all conditions, coupled with Synspective's capabilities for rapid analysis were put to good use when the earthquake occurred on Japan's Noto Peninsula in 2024 (Figure 18). The company's experts performed rapid interferometric analysis to detect ground displacement with millimeter accuracy and were able to identify terrain that had undergone significant structural change. "Within hours, we provided detailed maps to the government agencies, highlighting regions likely suffering from landslides and liquefaction, and experiencing infrastructure damage such as compromised roads and bridges. This was critical for planning evacuations and identifying a route to get supplies to people affected by the emergency," says Hoh.

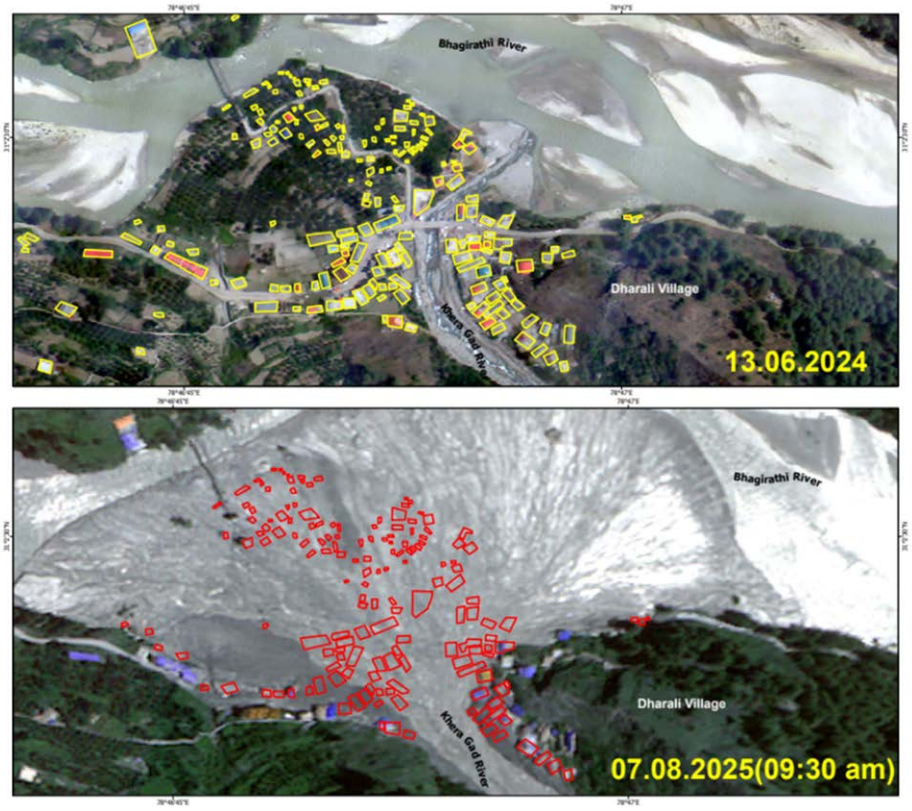


Figure 18. All-weather eyes: Synspective StriX SAR observation of the Noto Peninsula after the January 2024 earthquake, used to map ground change, landslides, and liquefaction within hours.
Source: Synspective, 'Disaster-related observation with StriX' and *Map data*

For humanitarian responses to benefit from the resources and expertise of commercial companies such as Synspective, Hoh believes that they must move from simply being data providers to helping to embed that data within governments' operational workflows and operating processes. "The goal is to make sure our solutions, our analytics, and platforms will be built to be interoperable with their existing systems, so that we can deliver insight in a format that they can immediately use and that is helpful for them, not just raw data. As a commercial company, we need to be seamless, reliable, and empowering partners to governments and also humanitarian agencies, so that we can integrate our latest technology into every corner of disaster preparedness and response," says Hoh.

> **It's very heartening to see that whenever there's a disaster, it's not only the national space agencies that are contributing, but it's also the private sector companies like Synspective who are stepping up and sharing data in the aftermath of the disaster.**
>
> **— Hamid Mehmood**
> Head, UN-SPIDER Beijing Office, United Nations Office for Outer Space Affairs (UNOOSA)

Part 5: Inclusivity, Behavior, and Communication

Embedding Equity and Inclusion in Early Warning Systems

EW4All seeks to reach everybody in an emergency, which includes those who are the most marginalized in society—from Indigenous people, to women and girls, and those living in remote areas. It is therefore critical that marginalized groups are placed center stage when developing the early warning systems designed to help them.

Being AWARE of the need to be inclusive

Early warning systems must have three components to be effective. First, they must be people centered, rather than having an overly technical focus as has traditionally been the case. Second, the warnings must be understood by the people they are intended to help. And third, those people must also know what action they need to take in response. Above all, early warning systems must be for everyone, and include the most vulnerable and marginalized people in society. That spans people living in rural areas, Indigenous people, children, ethnic and linguistic groups, people with disabilities, migrants, sexual minorities, youth and older people, and women and girls in all the above groups.

"We need to have a good understanding of the specific vulnerabilities, requirements, and capacities each of these groups in relation to early warnings. And for them to be able to access warnings and respond, they need to be empowered," says Madhavi Malalgoda Ariyabandu, Senior Expert in Disaster Climate Risk Resilience Development at IWMI. Ariyabandu believes they need to be actively engaged in defining the messages, response mechanisms and required actions, and that efforts to empower them must not only involve increasing their awareness, but also how implementing agencies interact with them—the two-way communication, the engagement—which is a governance issue.

IWMI developed its AWARE early warning, action and response platform to help connect technical and decision-making institutions with humanitarian organizations and other stakeholders in early warning, including communities. The platform incorporates a Gender Equality and Social Inclusion (GESI) strategic framework, which IWMI experts constructed after consulting relevant literature, pinpointing best practices, and conducting local pilot projects to identify marginalized groups and challenges facing them. The framework was designed to address these issues by incorporating approaches such as disaggregating data by sex, age, disability, and other main social divisions; identifying social dynamics preventing participation or access; designing programs to address barriers, constraints and limitations; and ensuring sufficient resources to GESI requirements.

"GESI needs to be addressed from the very beginning, and it needs to remain in all phases throughout the entire process of Anticipatory Action, from risk and vulnerability identification to impact monitoring," says Ariyabandu.

Making women part of the early-warning solution

Under the International Bill of Rights for Women, the 189 signatory states have a legal obligation to ensure that all aspects of disaster risk management—including early warning systems—are inclusive, nondiscriminatory and responsive to the specific needs of women, girls, and marginalized groups. The reality is, however, that the world is still falling short in this regard, not because technology is lacking but because systems are simply not designed for everyone. Seeking to change this status quo, UN Women supports governments to build inclusive systems, undertakes research to generate evidence to inform smarter policies, and develops its own humanitarian programs.

As part of this work, UN Women developed a model questionnaire to support governments to generate individual-level data on women's and men's interactions with the environment, disasters, and natural resources—and which includes a set of questions on early warnings. The questionnaire collects disaggregated sex, age, and disability data on, for example, whether respondents receive early warning messages, the communication channels they trust to receive them, how they respond to hazards after an early warning alert, and how caregiving roles or digital exclusion shapes their capacity to receive and act on early warning messages.

When surveys were undertaken using the questionnaire in Cambodia, only around two in five people (42%) reported receiving early warning information on extreme heat days, for example. While men tended to get early warning information through the internet, women relied more heavily on family, friends, and community members. And when it came to taking precautionary measures, women consistently outpaced men, by taking actions such as preserving drinking water, isolating indoors or moving livestock to safety.

"These surveys are really not just about data, they are also about accountability. They give governments the data and the tools to design early warning systems based on nationally representative data, and these are trusted, accessible, and actionable for all," says Anna Pelkonen, UN Women, Regional Office for Asia and the Pacific.

Data needed to underpin inclusive early warning systems

World Vision Sri Lanka has implemented multiple disaster risk reduction programs over the years. In each case, it has taken a community- or child-centered disaster risk management approach, and tried to develop inclusive early warning systems. However, its experiences indicate that more needs to be done. "Our experience is that the majority of disaster early warning systems are not inclusive enough. There are gaps in the understanding, forecasting, and communication of risk, and in the application of innovative and affordable technologies," says Chandrika Kularathna, Technical Specialist, Disaster Risk Reduction, World Vision, Sri Lanka.

Turning this situation around calls for more data. Specifically, aggregated risk data and other information on women, children, people with disabilities, and other marginalized groups is required. This would enable organizations such as World Vision to better analyze these groups' abilities to receive, understand, and act on warnings. And it would facilitate the design of truly inclusive early warning systems. "These vulnerable groups should not only be recipients, but also active participants in decision making. They should

be represented in village disaster management committees, and be active participants in designing and implementing early warning systems. This will make the systems more relevant, more trusted, and more effective," says Kularathna.

> **How can we call it 'last' mile when it's the people—the women, men, and youths—who are supposed to benefit from the information that we in institutions have? We need to turn around how we think, and say, how do we engage these men, women, and youths, and ask what are the priority areas that they would like to be warned about before we even think about providing early warning.**
>
> **— Everisto Mapedza**
> formerly Senior Researcher, IWMI South Africa.

Helping children play an active role in early warning

Children make up nearly a third of the global population, yet they are often the most affected by disasters. Child-centered systems aim to overcome this disproportionate risk by viewing children as active messengers and problem solvers, empowering them to spot risks that adults do not see, and to co-create practical early actions. For example, in Sri Lanka, Save the Children has worked with children to co-develop evacuation maps and quickly share messages with their families and communities.

The charity has worked with communities across many districts to strengthen local village resource management committees and ensure they are inclusive and connected with the women, children, and youth. The committees then work as a channel for inclusive early warnings. "We have simplified messages in local languages and visual symbols, especially storytelling and pictures or maps, and we use the community-driven communication to ensure early warnings are understandable by marginalized people, plus children and their communities," says Rangana Indrasena, Programme Operations Lead at Save the Children, Sri Lanka.

In one village, Save the Children connected the local children's club with the village resource management committee. The committee was engaged in monitoring the rainfall gauges. So they linked the children into this information source, so they could help to trigger community actions when flood risks were identified. "Often, we see families act faster when early warnings come through local community structures, such as the village resource management committees or women's societies, rather than from official channels. And when children design or adapt messages, especially early warning messages, they are clear and more actionable," says Indrasena.

> **For sub-Saharan Africa, we talk about women having a poverty of time because of the requirements of childcare. Their responsibilities mean that they don't go for meetings where early warnings are being discussed. If you don't understand the specific circumstances of women, you might then not understand why they are being left out—even just in terms of accessing the information itself.**
>
> — **Everisto Mapedza**
> formerly Senior Researcher, IWMI South Africa.

> **The Global System for Mobile Communications Association (GSMA) Mobile Gender Gap Report 2025 notes that 885 million women are still not connected to the mobile internet. And although this number is a significant reduction from earlier times, it is significantly high, and especially high in South Asia and sub-Saharan Africa.**
>
> — **Everisto Mapedza**
> formerly Senior Researcher, IWMI South Africa.

Translating Warnings into Action

The information people have readily available, their mindset, and past experiences can all contribute to how they respond in a crisis. The psychology of early warning is focussed on understanding how to make sure people take appropriate action when they receive a warning.

Understanding responses to weather warnings

If you visit a beach on holiday, you are more likely to be killed by a coconut falling on you than by a shark attack. But after the film Jaws came out 50 years ago, people around the world became too scared to go into the sea. This was because they were relying on the information most available to them when making decisions about sea swimming. It is a good example of where using such heuristics—mental shortcuts—can lead to cognitive bias. This can happen when people receive early warnings about potential hazards.

“We know from research that people who’ve been recently flooded are more likely to take action on receipt of a flood warning,” says Helen Roberts, Socio-meteorologist at the UK Met Office. “This is great news for those with prior experience, who will likely take action, but not so good for those without any experience of being flooded – who are the people we need to particularly focus on when issuing warnings. It’s also really bad news when it comes to unprecedented events, as nobody will have had the experience of the sort of impacts that are potentially on the way,” adds Roberts.

The UK Met Office employs a variety of tactics to encourage people to heed the weather warnings it releases. It has developed a matrix where potential events are positioned according to the likelihood of occurrence (unlikely to very likely) and the level of impact (very low to high). The kind of warning given to the public depends on the forecast hazard’s location on the matrix. Warnings of events that are high impact and very likely tend to be given a ‘loss’ framing. In other words, if you don’t take this action, there is potential for a very bad consequence. Warnings of events that are less likely and of lower impact tend to be given a ‘gain’ framing, suggesting that if you take this action, a good thing will happen as a result.

As Roberts elaborates, “A gain framing might say: ‘People cope better with power cuts when they have prepared for them in advance. It’s easy to do, so consider gathering torches and batteries, a mobile phone power pack. and other essential items.’ This is saying that if you do this relatively easy and straightforward thing, you are going to be more prepared in case of a power outage. We also frame warnings around caring for pets or kin. During heat warnings, we might say: ‘Make sure your elderly relatives drink at least two liters of water per day’. We find that people are more likely to act on behalf of others but then there’s a double win if they then think: ‘I should probably take that advice for myself as well’”.

Roberts is currently undertaking research to find out how likely people were to take action before the Met Office started using behaviorally informed advice statements and afterwards, to see whether there has been a measurable impact from that advice. She’s also studying the value that operational meteorologists’ personal experiences bring to the effectiveness of the National Severe Weather Warnings they issue. Although meteorologists might first consult numerical weather prediction data, they take a whole host of other things into consideration before issuing warnings. These range from specific events that might mean people are more likely to travel, to what the impact of the hazard might be on people, assets, and infrastructure, and any relevant antecedent conditions.

“There’s a lot of intuition and experience that is part of the decision process. That’s why we still have humans in the decision-making process. Otherwise, we would just use raw model data and automate everything,” says Roberts.

Last mile is the weakest link in the early warning value chain

At the international level, progress is being made towards delivering on EW4All. Global mortality levels have declined by 50% in the last two decades or so, and the countries with better early warning systems have at least six times lower mortality. However, the Lloyd’s Register Foundation’s World Risk Poll 2024 (Figure 19), found that 30% of people who had experienced a hazard in the previous five years received no early warning. Significant disparities persisted across regions, education levels, and levels of urban development (Lloyd's Register Foundation 2024).

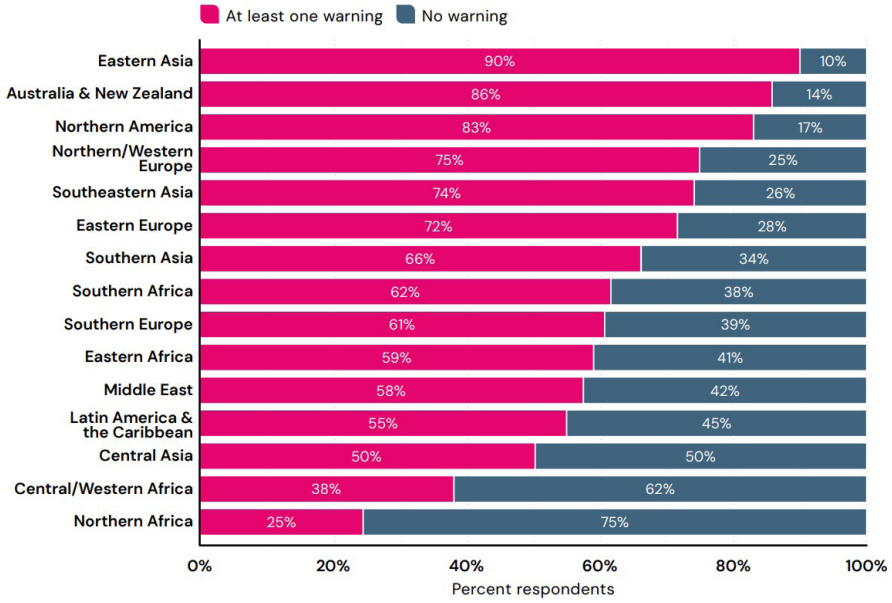


Figure 19. Share of people who received a warning before the last disaster they experienced, by global region (2023 data). Three in ten people worldwide received no warning at all.
Source: Lloyd's Register Foundation 2024

Early warning systems work as a value chain and, as such, are only as effective as the weakest link. Frequently, it is at the community level that the weakest link occurs and the value chain breaks down. "We have done reasonably well in the upstream side of early warning systems—with the collection of risk information, observation and monitoring, and dissemination—but we haven't done as well on the downstream side, which is the backflow of information to the communities," admits Animesh Kumar, Head of Office in Bonn, UNDRR.

Even when communities do receive warnings, they do not always take action to minimize their risk of harm. The UNDRR has identified three behavioral barriers in this regard. Aligning with the findings of the UK Met Office, the first is that people's perception of risk is shaped by what they have experienced in the past and that this induces a cognitive bias that prevents them from responding to the actual threat facing them. As hazardous events become less predictable—for example, with snowstorms occurring in areas that have never experienced them before—this challenge is increasing.

The second barrier relates to the level of trust that people place in the early warning systems themselves. Too many warnings for events that fail to materialize can compromise the trust that people have. On the other hand, simply knowing that an early warning system is in place can lead to a false sense of security. "Sometimes, people feel that if the authorities are there and systems are in place for early warning, they seem protected. But if they don't take action, the whole early warning value chain breaks down there. This is applicable for both sudden-onset events like tsunami, where self-evacuation is the only option, and for slow-onset disasters like drought, which often can be managed just by adapting better," says Kumar.

The third barrier is limitations to collective action. This is particularly relevant in urban areas, where the social capital—the value derived from social networks, relationships, trust, and shared norms—among communities remains very low. The more people have direct access to resources, the less propensity they have to collaborate, and the less likely they are to take community action. The less community action takes place, the more limited the response to early warnings will be. Investments to enhance social capital could therefore help communities act when the early warnings are triggered.

Based on these barriers, UNDRR has developed three key recommendations. First, it is calling for people-centered, locally-led approaches that promote public dialog and use a mix of high-tech, low-tech, no-tech, and traditional knowledge systems to disseminate warnings to overcome the existing digital divide. Second, it recommends an 'all-of-society' approach, with greater stakeholder engagement and data sharing to support collaboration, and increased investment in data. And third, it recommends that countries consider governance when developing MHEWS, rather than simply viewing the task as a project, because "countries with a better governance system have more comprehensive early warning systems," says Kumar.

How people process warnings

People rely on five particular constructs—or formulae—when deciding how to act on receiving a warning. Understanding what these are can help when designing ways to disseminate warnings to communities.

The first relates to how susceptible the person feels they are to the hazard in question, and the second concerns how severe they think the hazard is. For example, in the case of an outbreak of disease, they will weigh up whether catching the disease would have mild, moderate or severe consequences for them. The third relates to potential barriers that a person feels they have to taking action on receiving a warning. These could be physical, social or financial. And the fourth concerns any perceived benefits a person feels they—or their family or community—might gain by acting on a warning. Finally, they will look for clues around them as to whether they should act, based on what their family, colleagues, and peers are doing.

"These individual constructs will be modified or influenced by social constructs, cultural constructs, and also some psychological variables," says Lahiru Kodituwakku, Convener, Expert Committee on Planetary Health, Sri Lanka Medical Association, Sri Lanka. "So, we need to understand a particular community under these constructs when we are developing early warning messages. If we can address the susceptibility, the severity, the barriers, and benefits, also, if we can understand previous experiences of this particular hazard, then we can actually construct our messages in a way that is culturally and socially appropriate," notes Kodituwakku.

A person's psychological outlook can affect how they interpret and react to warnings, and how they respond to a crisis. This is sometimes referred to as the 'fight, flight or freeze' mechanism. At one end of the scale, people become very sensitive and highly fearful and want to be the first to leave the area. At the other, they shut down and are unable to do anything. Children can often mirror their parents' behavior, too, so if their parents are panicking, they likely will be too.

Previous experiences can contribute to how people respond. Repeated exposure to warnings can make some people feel complacent and believe that the hazard will never materialize while others may feel constant unease because an imminent disaster seems ever-present. And how a past warning has presented can affect the level of trust people have in the system going forward. "It's essential that we integrate mental health and psychosocial support into early warning systems. We must involve the community itself—including children and young persons—in building the system and in the messaging, so that they own it," says Jananee Chandramohan, Senior Technical Advisor, Mental Health and Psychosocial Support, Save the Children International.

> **Belief and trust in traditional knowledge and social hierarchies affect how warnings are interpreted. We work with community leaders, sitting with them, listening to them, and then designing the system with them. That's very important to improve perception, so that communities will act on a warning.**

— Senaka Basnayake
Program Lead, Climate Services, Asian Disaster Preparedness Centre (ADPC)

Bridging the Last Mile

Timely warnings mean little if they do not reach the people who need them most. Thirty per cent of people who experienced a hazard in the past five years (Lloyd's Register Foundation 2024) received no form of early warning. Often, the last step in the process is getting the message to the communities most in need is where a warning system fails. However, a variety of innovations encompassing localized alerts, trusted intermediaries, multilingual messaging, and accessible formats are helping close the last-mile gap.

Closing the gap between haves and have-nots

A country's wealth can influence whether or not it has an early warning system for known hazards. The Lloyd's Register Foundation World Risk Poll 2024 shows that in developed countries, between 60% and 80% of people received a warning before the last disaster they experienced, while in developing countries—including many parts of Latin America, sub-Saharan Africa, Central Asia, and the Middle East and North Africa—the percentages are far lower (Lloyd's Register Foundation 2024). However, early warning coverage varies between countries within particular income brackets, so Gross Domestic Product (GDP) is not the only factor influencing whether people do or do not receive warnings.

"Another interesting finding is that where a hazard is less predictable, the percentage of people who receive the early warning is low as compared to when the hazard is predictable," says Karen Woo, Senior Coordinator on early warning systems, ITU. "Across income levels, where the hazard is predictable, the percentage of people who receive early warnings is much higher, especially in high-income, lower-middle income, and upper-middle income countries. Also, low-income countries rely more on local community organization of early warning systems, with greater reliance placed on local government or the police and the Internet or social media as income increases," says Woo.

As the lead of Pillar 3 of EW4All, ITU is particularly concerned with the mechanisms used for communicating and disseminating warnings. Currently, 97.9% of the world population is covered by a mobile network and four out of five people own a mobile phone, which represents a great opportunity to close the gap between those who currently receive early warnings and those who do not. "ITU supports

countries using technologies such as 'cell broadcast' and 'location-based SMS', and standards such as the Common Alerting Protocol, working hand in hand with governments and partner organizations. We also foster communities of practice through the technical expert group on cell broadcast in the AI for Early Warnings for All Sub-Group," says Woo.

Cell broadcast and location-based SMS are types of cellular mobile technologies, both of which are compatible with most devices. Cell broadcast can send located messages to users, including those who are roaming or tourists. No subscription is needed and it is not affected by congestion, but it is a 'blind' technology in that there is no capability for two-way feedback. Location-based SMS requires a subscription and may also require a roaming agreement for use outside of the standard subscription area. Location-based SMS is affected by congestion but allows for two-way feedback. In addition to these, ITU is working to enhance the use of direct-to-device services underpinned by satellite technology.

Using AI to issue context-based alerts

Several challenges hinder the dissemination of digital alerts. These range from uneven coverage and hard-to-reach communities, to public scepticism towards alerts, and the limited use of multilingual and accessible messaging. But these are gaps that AI is showing promise at filling, as the work of private sector company Intersec shows.

A member of ITU, the company is using AI to support critical decision-making in fields including civil protection and telecommunications. Specifically, it takes complex data and turns it into insights that support emergency action. Its technology currently contributes to sending alert messages to 40% of the European Union population. But it is working to promote its technology on all continents to help governments send alerts to citizens.

Based on intelligence gathered from sensors in the field, Intersec's cloud-based applications can help to analyze the situation for a duty manager tasked with issuing an alert in an emergency. They can, for example, contextualize the situation based on intelligence coming from sensors in the field, propose wording for an alert, and translate it into different languages–generating both visual and aural messages–so that everyone can understand how to react to the situation.

"AI can help delineate the zone that the alert should be dispatched to, choose the most appropriate channels to be used—whether that's through mobile network operators, using cell broadcast or location-based SMS, or going beyond digital channels to traditional methods, such as sirens. This is where we see a strong use for AI technology," explains Christophe Nez, Executive Team Member, VP Product, Intersec.

Speaking everyone's language

It sounds like a simple task: to translate an emergency alert into local languages so everyone in a community understands it. However, the reality can be a lot more complex. Not only are affected communities often far more linguistically diverse than is assumed, gender also often compounds exclusion. The global non-profit organization CLEAR Global is trying to overcome such challenges, including by conducting research to enhance understanding of the best language formats in which to provide messaging in different contexts.

"One of the things we've done recently to address this is to create a language-use data platform that compiles data from multiple sources. We are using this as a foundation to work with local partners and communities to develop messaging in appropriate languages and formats, and make evidence-driven decisions behind what language to present messaging in," says Polly Harlow, Senior Project Officer, CLEAR Global.

In Bolivia, the organization worked with Practical Action to better understand the language needs of two Indigenous communities facing climate-related hazards: the Aymara in the highlands and Tacana in the Amazon. They overlaid language data with information on the risks the communities faced, then engaged directly with the communities to understand their communication preferences and to test words that are typically used in Bolivia in early warning messaging.

"As well as there being low connectivity, with many people not reached at all by messaging, we found that technical and abstract terms being used in Spanish often didn't have clear equivalents in local languages. For example, the levels of alert that the national meteorological service was using to disseminate warnings about flood risk simply had no equivalents in the Tacana and Aymara languages," says Harlow.

In response, CLEAR Global worked with partners in the community to co-design new terminology in those languages that reflected the actual risks faced within those communities. Practical Action is now working with local people to integrate those terms into community-led disaster and early warning plans. This includes for dissemination through local radio stations, a channel through which the communities said they would like to receive warning messages.

Building the capability to warn of multiple hazards

When the Indian Ocean tsunami killed around 35,000 people in Sri Lanka in 2004, it spurred the island into action. Within a year, it had started developing an early warning system. Today, its MHEWS covers tsunami, landslides, floods, droughts, cyclones, epidemics, and more. It is coordinated by the Disaster Management Centre, with technical agencies monitoring threats and alerts disseminated via the Disaster and Emergency Warning Network.

For last-mile communication, Sri Lanka draws on 15 warning mechanisms, including SMS messaging, police and military communication systems, VHF and HF radio systems, sirens, warning towers, temple and church bells, and door-to-door announcements. "The time between warning and the hazard coming can be very short. With a tsunami we have only 50 minutes to evacuate people. That's why we developed many mechanisms. However, challenges remain, particularly if a hazard occurs at night," says Pradeep Kodippili, Director (Awareness) DMC, Sri Lanka.

Local knowledge goes a long way

In Bangladesh, 100 million people are exposed to hazards such as floods, heatwaves, and cyclones. There are two main early warning alert systems: Bangladesh Meteorological Department has 274 automated weather stations and a signal-based cyclone early warning system, and the Flood Forecasting and Warning Centre has a suite of water-level monitoring and forecasting stations. Both disseminate warnings to national ministries and departments.

Although Bangladesh has had these early warning systems for a long time, challenges remain in turning warnings into action, particularly at the last mile. These include forecasts being general rather than tailored to specific communities, messages being hard to act on, and communities being ill-prepared for hazards. Poor infrastructure and limited access to technology further hinder effective communication of warnings.

Practical Action is currently working at the community level using four channels to disseminate early warnings: warning voice messages, digital weather boards, 'resilience agents', and a disaster-alert app for the media. Resilience agents have been particularly key to building trust, as they each know their own community well—including what levels of difficulties or vulnerabilities there are—and can easily convey their needs.

"They are trained to use the information or the alerts that they get from different sources—such as from the local government, our voice messaging system or a disaster alert from Bangladesh Meteorological Department—and they disseminate this information to the local people and make them informed," explains Nishat Tasnim, Officer, Knowledge and Influencing, Practical Action, Bangladesh.

Trained in first aid and search and rescue, the resilience agents assist with disseminating early warnings, such as for flooding, by visiting households and advising people on preparedness and responses. They are also helping to champion women's and girls' rights. "The community people have found it very effective. When they get this information they can take early actions, such as relocating their assets to a safe place and cutting their crops early. Once upon a time it was very difficult for community people to get warnings quickly, but now it has been solved through these local resilience agents," says Tasnim.

Part 6: Investing in Preparedness

Nurturing Public-Private Partnerships

Innovative partnerships between governments, development partners, and the private sector have the potential to transform early warning systems. Co-investment, shared-risk approaches, and technology-driven solutions can all help to unlock long-term resilience gains. However, its early days and work is needed to bolster the legislative framework in less well-resourced countries.

The challenge of engaging the private sector in early warning systems

Early warning systems provide a public service and contribute to national security. As such they predominantly need to be run by national institutions and financed by governments. However, public budgets are shrinking and the costs of managing infrastructure are high. Monitoring calls for observation networks; predicting extreme events demands numerical weather forecasting models; understanding risk requires prediction and social data to be analyzed alongside each other; and human effort is needed to promote community ownership. This burden makes the prospect of commercial investment attractive.

Certainly, early warning systems would seem to lend themselves to public-private partnerships. In modern systems, a government meteorological department and disaster authority might work with private sector tech providers and investors, as well as with research institutions and CSOs. However, a challenge lies in the fact that the nations that are most exposed to extreme events—the least developed countries and SIDS—are also the ones with limited institutional capacity and lower private sector penetration.

“If you look across the countries we’re working in, which are the least developed countries and SIDS, the private sector is mostly composed of micro and small enterprises, which are often informal,” says John Harding, Director, Climate Risk and Early Warning Systems (CREWS) Secretariat, WMO. “In some of the countries, this can comprise up to 90% of the businesses. There is low private sector penetration because those countries have underdeveloped financial systems, high interest rates, and limited access to capital. And in the SIDS, tourism is predominant, which often crowds out any kind of diversification of the private sector,” explains Harding.

Engaging such countries more with developing early warning systems calls for a widening of the private sector. CREWS, a multilateral fund that supports vulnerable countries by supporting people to understand the risks they face, monitor hazards, issue warnings, and know how to respond in the case of a climate emergency, has experience in this regard. For example, in Tonga, it worked with a private company to develop a smart weather app that enables the whole population to access weather and climate information and warnings, and to feed back into the system.

“In countries where we have institutions that are built on robust legislation that clearly defines institutional roles and the modalities to engage the private sector—that’s the space in which it’s really possible to

maximize the benefits of the private sector and all the innovation that comes with competition. At CREWS, we try and support the countries we're working in to develop these more robust institutional settings and legislative frameworks as the first step for private sector engagement," says Harding.

Community-led public-private partnerships effective in India

Early warnings are most effective when the systems are 'owned' and operated by local actors. So believes Mihir Bhatt, Director of the All India Disaster Mitigation Institute (AIDMI). This community-based NGO works to bridge the gap between policy, practice, and research in the fields of humanitarian action, disaster risk reduction, and climate change adaptation, as laid out in the National Disaster Management Plan of Government of India of 2019. "The localization of early warning is extremely important," he says.

Over almost four decades, AIDMI has supported local communities across India and other Asian countries in minimizing the impacts of multiple types of disasters. The organization has worked with street vendors, micro-enterprises, small businesses, transportation workers, and other actors to obtain private finance to help translate alerts from the IMD and other institutions into anticipatory and practical action for handling extreme heat, floods, and cyclones.

Local NGOs and small entrepreneurs have co-financed efforts such as display boards, micro-insurance, and social protection including providing shade, ventilation, and access to drinking water during extreme heat. "Such initiatives form community-anchored, public-private early warning partnerships. Government agencies provide the forecasts; private telecoms and insurers provide technology and financial tools; and citizens groups and the affected population themselves ensure last-mile credibility and connectivity," says Bhatt.

> **What we have learned from our own experience is that early warning systems can only translate into resilience when we are able to connect people, finance, and technology.**
>
> **— Ritu Bharadwaj**
> Director, Climate Resilience, Finance and Loss and Damage, International Institute for Environment and Development (IIED)

Highlighting the value in private sector investment

If the private sector is to invest in the early warning space, actors must understand what is in it for them. This means demonstrating the value proposition across the whole value chain. "Private investors will look at an investment as something which delivers economic value, which has a better economic return from them—so we need to demonstrate the value," says Ritu Bharadwaj, Director, Climate Resilience, Finance and Loss and Damage, International Institute for Environment and Development (IIED).

To make the case for private sector investment in early warning, IIED examined 24 social protection initiatives in eight countries. The study estimated the potential losses to those eight countries, given the continued current pattern of disasters, to be USD 21 billion. But it also showed that if an Anticipatory Approach was taken through early warning and early action, mitigating those losses could be achieved with an upfront investment of USD 4 billion.

Apart from highlighting the overall financial gain that can come from investing in Anticipatory Action, IIED believes it is important to pinpoint specific gaps in capacity and to highlight the value that could be gained by an injection of private finance to fill the gaps. To this end, IIED has developed a diagnostic tool called the Anticipatory Social Protection Index for Resilience (ASPIRE). The tool assesses the ability of a country's existing social protection provision to deliver resilience to climate (or other) shocks, and identifies gaps and opportunities in a country's policies, systems, and programs related to social protection.

"Governments probably have the biggest delivery channel and the biggest funding in the space. We need to identify where the gaps are. If we are able to identify those gaps and show the value proposition of investing in those areas, then we probably have a much better chance of drawing in private sector investment and funding from multilateral development banks," says Bharadwaj.

Empowering local companies to maintain flood management systems

Low-lying coastal areas, particularly in least developed countries and SIDS, are bearing the brunt of sea level rise and storm surges. Independent knowledge institute Deltares works to try and ensure that the world's deltas, coastlines, and river areas are safe and will remain habitable into the future. It developed the open source software platform Delft-FEWS to support this effort. Used in 70 countries around the world, primarily for flood forecasting, the tool connects real time weather forecasts and sensor data with hydrological models to provide early warnings and manage water systems.

Deltares works with private sector companies around the world, often on projects to mitigate the impacts of flooding. Recently, it collaborated with partners in Accra, Ghana, on a system to limit the impact of urban flash flooding; in Dar es Salaam to develop a local flood warning system called Community Water Watch (FloodTags 2025); and in Assam, India to strengthen the state's flood management capacity (Deltares, n.d.).

"It's always a matter of educating and training these local private firms so they can maintain the developed early warning system. It's our goal at Deltares to transition knowledge as much as possible to the local private firms or local government organizations, so they can maintain the system themselves and develop it further," says Albrecht Weerts, Data Model Integration Expert and Senior Specialist Hydrology, Deltares.

Collaboration delivers new flood warning system for England

In England, about 5.7 million homes and businesses are at risk from flooding. A flood warning system that had been in place for two decades was outdated, so an upgrade was commissioned. The new system was

developed by collaborative public-private partnership. Stakeholders included the Environment Agency, a non-departmental public body; the UK Met Office; digital innovation company Leidos—which was contracted to develop an early warning system in collaboration with design consultancy Cogworx—and mobile data and location intelligence company Intersec.

Drawing on real time monitoring and forecasts, the system uses digital mapping to pinpoint at-risk homes, businesses, and infrastructure and to send warnings targeted to specific assets rather than just general areas. The service sends approximately 3,000 alerts per year to 2.6 million users, who register and request to receive warnings by text, phone or email. "Earlier, there were legacy, fragmented systems from different sources, which was challenging for the users. Now, it's cloud based and is a lot more modern and unified," says Charlotte Cardona, Marketing and Communications Director at Intersec.

Through its work across 50 countries, Intersec has identified four barriers to the deployment of early warning systems and the involvement of the private sector in such systems. These are: a lack of government mandate; the length of time it can take to obtain donor funding; siloed working leading to fragmented systems; and the lack of incentives for engaging the telecoms sector. "We need to explain that it's beneficial for governments and the private sector, and to explain to the telecoms operators that while supporting early warning systems is a public good, they can also benefit, for example by coordinating their efforts with homeland security or law enforcement agencies," says Cardona.

Financing Before Disaster Strikes

Linking early warnings to financial triggers enables faster, more effective action, and therefore can make a real difference in protecting lives, livelihoods, and economies before disasters unfold.

The cost benefits of disaster finance are clear

A world without disaster risk financing is a bleak one, with limited options for governments. One is to opt for a traditional humanitarian response, often resulting in action that is too little, too late, and carrying a burden of debt. Emergency borrowing is another choice, but the terms are likely to be highly unfavorable. And there is the possibility to reallocate the national budget, affecting other investments or planned projects. Finally, there is the option of doing nothing, with potentially devastating impacts on lives and livelihoods.

Currently, the amount of uncovered disaster losses in Emerging Markets and Developing Economies exceeds 90%. This means there is a huge insurance protection gap. Moreover, the proportion of international development financing allocated to pre-arranged finance is less than 3% (2017–2022 figures). And while 319 million people are benefiting from crisis and disaster risk-financing instruments per year, many millions more are not. These statistics represent wide-ranging opportunities within the disaster finance space.

In a postdisaster scenario, money is potentially needed for relief, recovery, and reconstruction, with the amount of money required increasing with each phase. Spending money pre-emptively, before disaster strikes, can avoid the burgeoning losses further down the line. "If you think in terms of return on investment, the earlier you act, the more efficient your programs can be if you manage to translate

your early warnings into early action," says Markus Enenkel, Climate Risk Finance Specialist at the World Bank. "If you think about an earthquake, for instance, relief is expensive, recovery is more expensive, and reconstruction blows the budget out of the water, because the reconstruction for an earthquake is by far the most long lasting and expensive endeavour," Enenkel explains.

This is where disaster risk financing can come into its own. There is no silver bullet but there is an array of available tools, from small to large scale and from simple to complex. These span: risk layering, where financial instruments such as reserve funds, insurance, and bonds are used to manage disaster costs based on the expected frequency and severity of events; applying evidence-based insights, data, and tools to shift from reactive disaster spending to proactive, pre-arranged financial planning; risk modelling, where science, engineering, and statistics underpin estimates on the financial impacts of disasters; and de-risking investments by using public, philanthropic or multilateral funds to spread risks and make disaster resilience projects more attractive to private capital. Capacity and trust building are vital for all the above.

"If these tools are applied, we can make things more predictable, faster and less stressful. Transparency increases and the fiscal volatility of the government decreases. Additional value comes from increased accountability. We must be very, very explicit that disaster risks can be mitigated; they can be transferred to international markets, but they will never be zero. This means that from the perspective of a government, or subnational decision maker, or a humanitarian partner—whoever you want to focus on—accountability and risk ownership is key," says Enenkel.

Upward trend in pre-arranged financing

In 2024, international pre-arranged financing reached an all-time high of USD 9.4 billion (Figure 20), with growth across all country groupings and types (Scott et al. 2025) This was a key finding of the State of Pre-Arranged Financing for Disasters 2025 report, published by the UK Centre for Disaster Protection (CPD). While it is cause for cautious optimism, the report also notes that low-income countries and fragile and conflict-affected areas still have the smallest share of pre-arranged financing, receiving less than 7% of total pre-arranged finance. And, its findings came before sweeping cuts to donor funding were announced early in 2025.

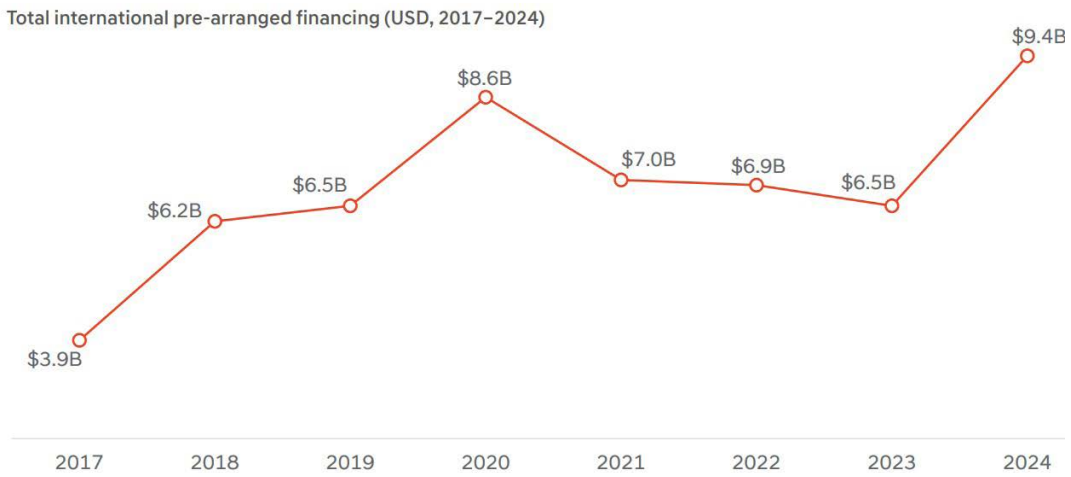


Figure 20. International pre-arranged financing for disasters reached a record USD 9.4 billion in 2024, yet low-income and fragile, conflict-affected countries each received under 7% of the total.
Source: Scott et al. 2025

"It is important to note that most of this financing—74% in 2024—is in the form of loans that are not highly concessional," explains Michèle Plichta, Senior Researcher at CDP. "So that means that they are more expensive to countries than, for example, grants, or concessional loans or subsidized insurance products that are often used with regional risk pools. This is important to bear in mind, especially in a context where a lot of countries face high debt levels and vulnerability, and it also partly explains why we see the lower levels in low-income countries," explains Plichta.

The value of actual payouts—monies released from pre-arranged finance instruments when triggered by disasters—more than doubled in 2024 compared to the previous year. This was largely due to the World Bank's Catastrophe Deferred Drawdown Options. Although a relatively small amount went to low-income countries—due to the available instruments being mostly available to countries with a higher borrowing capacity—there were some notable successes.

For example, when category five Hurricane Melissa struck Jamaica in late 2025—causing widespread damage and loss of life—the government was prepared. Having put in place a comprehensive disaster risk financing strategy, hundreds of millions of dollars of payouts were confirmed within days of the island being declared a disaster area, and money arrived in a matter of days and weeks. "Overall, we are seeing encouraging progress around pre-arranged financing, but it is a rapidly evolving space, and we need to keep encouraging transparency around what is happening," says Plichta.

Learning from the insurance industry

The insurance sector has a trick up its sleeve that could encourage the private sector to invest in pre-disaster action. This is catastrophe risk modelling, which involves simulating thousands of future scenarios to uncover the probability of a specific hazard occurring. Used in combination with site-specific risk engineering—which can help determine resilience measures that can potentially reduce the risk—it provides a robust assessment of anticipated future losses.

"It's very clear that early resilience investment makes economic sense," says Ritu Bharadwaj of IIED, "but despite this, governments, multilateral development banks, and even the private sector are not investing. This is because they still look at early resilience investment, or resilience investment per se, as a cost, rather than something that can lead to returns."

This is where the insurance sector could help by offering risk modelling and future loss assessments as a standalone service to make the business case for resilience investment. To demonstrate the value that could be gained, IIED partnered with Zurich insurance and used the company's Climate Spotlight Tool to calculate the probability of hazards affecting the sector and the potential losses under different scenarios.

The assessment of power plants across Africa, Asia, the Caribbean, the Pacific and Latin America showed that if resilience measures were taken, annualized expected losses could fall from USD 48.6 million to USD 9.8 million, saving some USD 39 million each year. Over 20 years, this amounted to roughly USD 10 billion in avoided losses, with extreme event losses declining by around USD 177 million per year. Scaled to the USD 8.9 trillion global power sector, the study concluded that resilience investments could prevent USD 23 billion in cumulative losses over two decades, a four-to-sixfold return delivered through avoided damage and sustained operation (Bharadwaj and Karthikeyan 2025).

"Using risk analytics and investing in early resilience instead of waiting for a climate impact to become a disaster makes pure economic sense, but that intelligence is not available because we don't use insurance sector risk analytical capabilities in designing these resilience investments, which is something we can do to unlock those investment needs," says Bharadwaj.

Early action insurance benefitting from data innovations

A key part of establishing early finance investments is to determine the triggers that will release the funding. In India, Weather Risk Management Services is providing this service, as well as building data systems to help merge relevant datasets and installing weather stations to collect real time data. Used to underpin early action insurance, its efforts have seen early cash delivered into the hands of beneficiaries or to aggregation organizations in countries including Bangladesh, Fiji, and Zambia.

"In some countries, while there is forecast data available, there are also datasets of past disaster relief data," says Anuj Kumbhat, CEO of Weather Risk Management Services. "These can be used to create both hazard and exposure datasets, and are usually easily available in geocoded form. So, we've also been using these to help create the triggers. We're strengthening the weather infrastructure to improve and localize forecasts. A challenge is that delivering the money to targeted beneficiaries calls for better vulnerability and exposure data, and registries, from the public sector," adds Kumbhat.

Insurers are drawing on new datasets and capacities to build innovative weather insurance offerings. For example, the African Risk Capacity (ARC) Group, supported by reinsurance and technical assistance from reinsurer Munich Re, is providing parametric insurance solutions for drought and flood risks across Africa. "ARC group was a partner in structuring WFP's Sahel Climate Catastrophe Layer, which links the seasonal forecast to pre-arranged funding for food security interventions," explains Mangesh Patankar, Regional Head, Agriculture, Munich Re.

"A lot of innovation is happening, to automate the pay outs, to enhance transparency and to reduce the transactional costs as well as the speed of the settlement. These innovations, collectively, align very well with predictive analytics, allowing us to bring in rapid liquidity, which makes the anticipatory finance more credible, more affordable and more meaningful for the sovereign interest," says Kumbhat.

> **Early action finance should be part of every disaster risk management strategy. That would help an uptake in insurance as well as any early action financing or pre-arranged financing.**
>
> **— Mangesh Patankar**
> Regional Head, Agriculture, Munich Re

Putting Early Warning Center Stage

The four pillars of early warning—knowledge of disaster risk; detecting, observing, monitoring, analyzing and forecasting; communicating and disseminating warnings; and preparedness and capability to respond—were designed to facilitate the development of community-based, inclusive early warning systems that were grounded in local contexts but that could also respond to national and regional needs, and ultimately contribute to achieving the ambitions of EW4All and the Sendai Framework for Disaster Risk Reduction. The following case studies highlight innovations, institutional frameworks, and regional cooperation that are helping to drive risk-informed policy and action across all scales.

Developing regional resilience to hazards

Central Asia, comprising the countries of Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan, experiences diverse natural hazards from earthquakes, mudflows and avalanches to heavy rains, floods, and extreme temperatures. Within the region, which is home to 75 million people, Kazakhstan is leading the way in building resilience to natural hazards by embedding transboundary cooperation into its national disaster risk reduction.

The country enshrined an emergency alert system into law with a set of legal and regulatory acts dating back to 2014. In 2016, it developed a national disaster risk reduction strategy aligned with the Sendai Framework as part of reforms extending to 2030. Identifying shared hazards such as seismically active zones and transboundary river basins, it prioritized regional and international cooperation (UNDRR 2025b).

In partnership with Kyrgyzstan and supported by UNDRR, it established the Centre for Emergency Situations and Disaster Risk Reduction in Almaty to act as a platform for regional coordination. The organization facilitates simulations of emergencies to strengthen readiness and enhance coordination around regional hazards; the exchange of information; and shared risk assessments.

An early warning system for glacial lake outburst floods has been jointly developed by Kazakhstan and Kyrgyzstan for the Tien Shan mountains that span both countries, which disseminates alerts to communities both sides of the border. Meanwhile, working with Uzbekistan, Kazakhstan has integrated disaster risk reduction measures into transboundary river basin management. Its approach to disaster risk reduction exemplifies how national strategies can help to strengthen regional resilience to natural hazards.

Jointly reducing risks from climate change and natural hazards

The Pacific Islands region spans a geographic and cultural area containing tens of thousands of islands across Melanesia, Micronesia, and Polynesia. The Pacific Ocean provides the 14.5 million people who live across the region with food, transport, and livelihoods. But it is ringed by a belt of volcanoes and high seismic activity. The islanders' location makes them vulnerable to tsunamis, earthquakes, and eruptions, as well as weather-related hazards such as cyclones, droughts, and floods. Climate change is adding further challenges by causing the sea level to rise; ocean water to become more acidic, threatening sea life; and rainfall and temperatures to become more extreme (Pacific Resilience Partnership, n.d.)

The Framework for Resilient Development in the Pacific takes an integrated approach to climate change and disaster risk management, with a view to making islanders more resilient to hazards. It aims to build actions to address both these major challenges into all sectors, from health, education, and tourism, to water, energy, and agriculture, and fisheries. The Framework provides high-level voluntary guidance to a variety of stakeholder groups with three major aims: to better manage and reduce risks caused by climate change and natural hazards; cut the carbon footprint of development; and strengthen preparation for, response, and recovery from disasters.

Among its successes, the Framework has streamlined the use of resources by combining climate adaptation with disaster management; created the Pacific Resilience Partnership in 2017 to unite diverse stakeholders and better coordinate action on climate change and natural hazards; and inspired new funding mechanisms. However, as its guidance is voluntary, it is not possible to enforce action, and gaps in baseline data make it difficult to measure progress. Financing can also still be slow to reach grassroot initiatives (Islands Business 2026)

Combining technology, culture, and cooperation

Japan faces high exposure to natural hazards, which encompass earthquakes, tsunamis, typhoons, floods and volcanic eruptions. Of these, earthquakes and tsunamis present the highest threat. Not only do a fifth of the world's earthquakes of magnitude six or greater occur in the country, Japan's 30,000km coastline puts it at high risk of tsunamis from offshore quakes. Powerful typhoons often hit the country in late summer to autumn, and flooding from these and other weather systems is frequent and widespread. The country also has 111 active volcanos. Additional hazards come from mudslides, heavy snowfall and avalanches in Japan's mountainous terrain.

The country benefits from one of the most advanced mobile networks in the world, with 97% of households owning at least one mobile phone. This mature mobile infrastructure forms the basis for Japan's national early warning system, underpinned by the high proportion of urban inhabitants (92%), high smartphone use and widespread digital literacy. Other outlets used to disseminate warnings include television, radio and loudspeakers. Warnings are divided across two integrated satellite systems: 'J-alert' provides urgent warnings requiring immediate action and 'L-alert' operates alongside it providing local information as a hazardous event evolves.

The use of Japan's tech-based early warning system is complemented by a cultural approach that considers disaster risk reduction as a priority for the whole of society. Japanese communities are encouraged to develop action plans, undertake drills and put in place preparedness measures grounded in specific actions by individuals (self help), groups (mutual help) and public help. And disaster risk reduction in Japan is grounded in a legal framework that lays out the responsibilities of national and local authorities, other entities and residents. These elements, supported by institutional cooperation, have helped to make Japan's early warning system one of the most effective in the world (GSMA 2026).

The system's alignment with Sendai Framework goals to 'increase the availability of and access to MHEWS' and to 'enhance disaster preparedness for effective response' have led to measurable progress. Compared to the 1950s–60s, Japan recorded a 97% reduction in deaths and a 21% cut in total economic damages (share of GDP) from natural disasters in 2020 (WEF 2023). It is fitting that the Sendai Framework was adopted in the Japanese city of Sendai, as the nation's approach to early warning exemplifies what the Framework—and EW4All—seek to achieve.

Conclusion

As this report highlights, huge efforts are being made around the world towards achieving the goal of EW4All. These are producing effective early warning systems that are grounded in scientific data, respond to communities' needs, provide warnings that are comprehensible to diverse audiences, and are ultimately saving assets, livelihoods, and lives.

The use of technology such as remote sensing, computer modelling, and AI; targeted action on specific hazards; efforts to adopt community-led and inclusive approaches; analysis of integrated data, such as on weather, food needs, markets, migration, and conflict; a focus on particular sectors such as hydropower; and innovative financing are all playing a part.

However, while the number of countries with life-saving early warning services has more than doubled in 10 years, many millions of people remain unprotected against potentially dangerous natural hazards. If the world is to meet the ambition of EW4All by the close of 2027, a redoubling of effort is required, with support directed to those countries and sectors of society who need it most.

At IWMI, we continue to work towards this goal, through initiatives such as our Drought Action Catalyst, designed to mobilize proven practical action to overcome drought; and our ENSO Outlook tool, which facilitates analysis of the potential impacts of forecast climate shocks on variables from water resources, livestock. and people's health, to migration and financial markets.

Through these and our popular webinars, we aim to motivate government representatives, scientists, social scientists, technology experts, and practitioners across the water, agriculture, meteorology, energy sectors and beyond, to make EW4All a reality. By continuing to forge strong partnerships and collaboration—including with and between actors in the Global South—we will ensure that no one is left behind when the next natural hazard strikes.

References

Adaptation Fund. n.d. "Adaptation Fund". Accessed October 22, 2026. https://www.adaptation-fund.org/.

Akbarpour, Jannat, Mahmood Reza, Ehsan Rastgoftar, and Katsuichiro Goda. 2023. "Improvement to Stochastic Tsunami Hazard Analysis of Megathrust Earthquakes for Western Makran Subduction Zone." *Applied Ocean Research* 141 (December): 103784. https://doi.org/10.1016/j.apor.2023.103784.

Amarnath, G., Alahacoon, N., Smakhtin, V. and Aggarwal, P., 2017. Mapping multiple climate-related hazards in South Asia (Vol. 170). International Water Management Institute (IWMI). https://doi.org/10.5337/2017.207.

Amarnath, Giriraj, Petra Schmitter, Bapon Fakhruddin, Ashish Agrawal, Darshini Ravindranath, and Mohsin Hafeez. 2026. Drought Action Catalyst: A country platform for anticipatory, financed, government-led drought resilience. International Water Management Institute. https://doi.org/10.5337/2026.223.

Anticipation Hub. n.d. 'Who We Are." Accessed October 22, 2026. https://www.anticipation-hub.org/who-we-are/about-us.

Ashrit, Raghavendra, Kuldeep Sharma, Sushant Kumar, Anumeha Dube, Karunasagar, S., Arulalan, T., Ashu Mamgain, Paromita Chakraborty, Sumit Kumar, Abhishek Lodh, Devajyoti Dutta, Imranali Momin, Bushair, M. T., Buddhi J. Prakash, Jayakumar, A., and Rajagopal, E. N. 2020. "Prediction of the August 2018 heavy rainfall events over Kerala with high-resolution NWP models." *Meteorological Applications* 27(2): e1906. https://doi.org/10.1002/met.1906.

Bharadwaj, Ritu, and Karthikeyan, N. 2025. *How to Unlock US$1.3 Trillion in Resilience Finance: Using Risk Assessment to Drive Investment and Impact*. IIED. https://www.iied.org/22683iied.

Deltares. n.d. "The EPIC Response Framework". Accessed October 22, 2026. https://www.deltares.nl/en/expertise/projects/epic-response-framework.

Emerton, Rebecca, Julien Nicolas, Anna Lombardi, and Claudia D. Napoli. 2026. "Global heat stress intensification and its expanding footprint on the human population." *Nat. Clim. Chang.* 16: 989–996. https://doi.org/10.1038/s41558-026-02670-5.

FloodTags. 2025. "Community Water Watch." June 10. https://floodtags.com/success-stories/community-water-watch/.

GEF (Global Environment Facility). n.d. "Who We Are". Accessed October 22, 2026. https://www.thegef.org/who-we-are.

CEMS (Copernicus Emergency Management Service). n.d. 'Global Flood Awareness System. Accessed October 22, 2026. https://global-flood.emergency.copernicus.eu/.

Green Climate Fund. n.d. "The World's Climate Fund for Developing Countries." Accessed October 22, 2026. https://www.greenclimate.fund/node/73640.

GSMA (Global System for Mobile Communications Association). 2026. *Japan's Early Warning System: The Role of Mobile Network Operators*. https://www.gsma.com/solutions-and-impact/connectivity-for-good/mobile-for-development/wp-content/uploads/2026/01/GSMA_Japans-Early-Warning-System-The-Role-of-Mobile-Network-Operators_2026_m4h_web.pdf.

IPCC and WMO, eds. 1992. *Climate Change: The 1990 and 1992 IPCC Assessments, IPCC First Assessment Report Overview and Policymaker Summaries and 1992 IPPC Supplement*. IPCC. https://www.ipcc.ch/report/climate-change-the-ipcc-1990-and-1992-assessments/.

Islands Business. 2026. "Pacific Climate Finance Gaps Threaten Local Resilience." March 24. https://islandsbusiness.com/news-break/pacific-climate-finance-gaps-threaten-local-resilience/.

ITU (International Telecommunication Union). n.d. “AI for Early Warnings for All Innovation Challenge: Bridging Gaps with AI Solutions - Top Four Finalists.” Accessed October 22, 2026. https://www.itu.int:443/en/ITU-D/Emergency-Telecommunications/Pages/Events/2025/AI-for-EW4All-Hackathon-Finalists.aspx.

IWMI (International Water Management Institute). n.d. “Drought Action Catalyst.” Accessed October 22, 2026. https://www.iwmi.org/projects/droughtaction/.

IWMI (International Water Management Institute). 2025. “IWMI Launches Eyes On The Storm - a Global Webinar Series on Advancing Early Warning for All.” *International Water Management Institute (IWMI)(blog)*. March 21. https://www.iwmi.org/news/iwmi-launches-eyes-on-the-storm/.

IWMI (International Water Management Institute). 2026. Positioning the Drought Action Catalyst for Drought Resilience: A Strategic Framework. International Water Management Institute (IWMI). https://hdl.handle.net/10568/184955.

Lloyd’s Register Foundation. 2024. ‘World Risk Poll 2024 Report: Resilience in a Changing World’. June 19. https://www.lrfoundation.org.uk/publications/resilience-in-a-changing-world.

NASA Earth Observatory. 2010. Imja Tsho, Nepal. https://science.nasa.gov/earth/earth-observatory/imja-tsho-nepal-46405/.

NASA Earth Observatory. 2014. Flooding on the Zambezi River. https://science.nasa.gov/earth/earth-observatory/flooding-on-the-zambezi-river-83667/.

NASA Earth Observatory. 2021. A Deadly Debris Flow in India. https://science.nasa.gov/earth/earth-observatory/a-deadly-debris-flow-in-india-147973/.

NASA Earth Observatory. 2024. Severe Drought in Southern Africa. https://science.nasa.gov/earth/earth-observatory/severe-drought-in-southern-africa-152711/.

NHPC (National Hydroelectric Power Corporation). 2022. *NHPC Launches Cloud-Based Early Warning System for Hydroelectric Projects*, August 10. https://www.renewableenergyworld.com/hydro-power/technology-equipment/nhpc-launches-cloud-based-early-warning-system-for-hydroelectric-projects/.

Omer, Sevil. 2025. “2004 Indian Ocean Earthquake and Tsunami: Facts and FAQs.” *World Vision*, July 25. https://www.worldvision.org/disaster-relief-news-stories/2004-indian-ocean-earthquake-tsunami-facts.

Pacific Resilience Partnership. n.d. *Framework for Resilient Development in the Pacific*. Accessed October 22, 2026. https://pacificresiliencepartnership.org/framework-resilient-development-pacific/.

Pannell, Alfie. 2025. “Colombia Marks 40 Years since Deadliest Volcano Eruption in a Century.” *Latin America Reports*, November 13. https://latinamericareports.com/colombia-marks-40-years-since-deadliest-volcano-eruption-in-a-century/12893/.

Prabhu, Shravan, Keerthana Anthikat Suresh, Srishti Mandal, Divyanshu Sharma, and Vishwas Chitale. 2025. *How Extreme Heat Is Impacting India – Assessing District-level Heat Risk*. https://www.ceew.in/sites/default/files/ceew-how-extreme-heat-is-impacting-india-final-web-file.pdf.

Scott, Zoë, Darshni Nagaria, and Michèle Plichta. 2025. ‘The State of Pre-Arranged Financing for Disasters 2025’. Centre for Disaster Protection. https://www.disasterprotection.org/publications-centre/pafreport25.

Shugar, D. H., M. Jacquemart, D. Shean, et al. 2021. “A Massive Rock and Ice Avalanche Caused the 2021 Disaster at Chamoli, Indian Himalaya.” *Science* 373 (6552): 300–306. https://doi.org/10.1126/science.abh4455.

South Asia Drought Managment System. n.d. https://dms.iwmi.org/drought-management-system?Country=southasia.

Synspective, 'Disaster-related observation with StriX'. 2024, Noto Peninsula Earthquake. https://www.synspective.com/news/disaster-related-observation-with-strix/.

Systematic Observations Financing Facility. n.d. 'The Systematic Observations Financing Facility, SOFF'. Accessed October 22, 2026. https://www.un-soff.org/.

Toreti, A., Tsagai, D., Maurer, T., Cremonese, E., Rossi, L., Werth, M., De Moel, H., Sabino Siemons, A., Acosta Navarro, J., Essernfelder, A.H. and Volpi, D., 2024. World drought atlas. https://www.unccd.int/resources/publications/world-drought-atlas

Tsegai, Daniel, Patrick Augenstein, and Zhuojing Huang. 2023. Global Drought Snapshot 2023: *The Need for Proactive Action*. UNCCD. https://www.unccd.int/sites/default/files/2023-12/Global%20drought%20snapshot%202023.pdf.

UNDP (United Nations Development Programme). n.d. 'Africa Multi-Hazard Early Warning and Early Action System'. Accessed October 22, 2026. https://www.undp.org/africa/publications/africa-multi-hazard-early-warning-and-early-action-system.

UNDRR (United Nations Office for Disaster Risk Reduction). 2015. 'Sendai Framework for Disaster Risk Reduction 2015-2030'. June 29. https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030.

UNDRR. 2025a. 'Global Status of Multi-Hazard Early Warning Systems (MHEWS) 2025'. November 10. https://www.undrr.org/reports/global-status-mhews-2025.

UNDRR. 2025b. 'Pioneering Regional Resilience: Kazakhstan's Model for Transboundary Disaster Risk Reduction'. May 30. https://www.undrr.org/resource/case-study/pioneering-regional-resilience-kazakhstans-model-transboundary-disaster-risk.

UNDRR. 2025c. 'AI Helps Identify Mobile Connectivity "Cold Spots" for Inclusive MHEWS'. November 11. https://www.undrr.org/resource/case-study/ai-helps-identify-mobile-connectivity-cold-spots-inclusive-mhews.

UNESCO-IOC 2025. 'Tsunami Ready'. Tsunami Programme. February 7. https://tsunami.ioc.unesco.org/en/tsunami-ready.

UNOOSA (United Nations Office for Outer Space Affairs). n.d. 'Early Warning Systems'. UN-SPIDER Knowledge Portal. Accessed October 22, 2026. https://un-spider.org/risks-and-disasters/early-warning-systems#no-back.

Verisk. 2020. "The 1920 Haiyuan Earthquake: One of the 20th Century's Deadliest." (blog). December 17. https://www.verisk.com/blog/the-1920-haiyuan-earthquake-one-of-the-20th-centurys-deadliest/.

WEF (World Economic Forum). 2023. "Japan's Pioneering Early Warning System: Offers Blueprint for Climate Adaptation." https://www.weforum.org/stories/forum-in-focus/japans-early-warning-systems-blueprint-climate-adaptation-efforts/.

Wikipedia. 2026. '1976 Tangshan earthquake'. October 21. https://en.wikipedia.org/w/index.php?title=1976_Tangshan_earthquake&oldid=1381356098.

WMO (World Meteorological Organization). 2020. "'World's Deadliest Tropical Cyclone Was 50 Years Ago." Press release. November 12. https://wmo.int/media/news/worlds-deadliest-tropical-cyclone-was-50-years-ago.

WMO. 2023a. "Climate Risk and Early Warning Systems (CREWS)." World Meteorological Organization, March 23. https://wmo.int/activities/climate-risk-and-early-warning-systems-crews.

WMO. 2023b. "Early Warnings For All Initiative Scaled up into Action on the Ground." Press release. March 22. https://wmo.int/news/media-centre/early-warnings-all-initiative-scaled-action-ground.

WMO. 2023c. "Early Warnings for All Officially Becomes WMO's Top Priority." Press release. June 1. https://wmo.int/news/media-centre/early-warnings-all-officially-becomes-wmos-top-priority.

Annex 1. List of Experts Consulted During the Eyes on the Storm Webinar Series

1. Albrecht Weerts, Data Model Integration Expert and Senior Specialist Hydrology, Deltares.
2. Ajith Wijemannage, Director General, Department of Meteorology, Sri Lanka.
3. Alok Sikka, former Country Representative for India and Bangladesh, International Water Management Institute (IWMI).
4. Alvin Hoh, Regional Sales Manager. Synspective.
5. Anasrasia Wahome, Research Team Leader, Alliance of Bioversity International and CIAT.
6. Amit Tripathi, Lead Specialist – Energy Sector Resilience, Coalition for Disaster Resilient Infrastructure (CDRI).
7. Animesh Kumar, Head of Office in Bonn, United Nations Office for Disaster Risk Reduction (UNDRR).
8. Anna Pelkonen, UN Women Regional Office for Asia and the Pacific.
9. Anuj Kumbhat, CEO, Weather Risk Management Services.
10. Asif Rafsan, Senior Program Officer, International Federation of Red Cross and Red Crescent Societies (IFRC).
11. Asiri Karunawardena, Former Director General, National Building Research Organisation (NBRO), Sri Lanka.
12. Bayes Ahmed, Associate Professor, Department of Risk and Disaster Reduction, University College London.
13. Chandrika Kularathna, Technical Specialist, Disaster Risk Reduction, World Vision, Sri Lanka.
14. Christophe Nez, Executive Team Member, VP Product, Intersec.
15. Charlotte Wirion, Founder and CTO, WEO-Water.
16. Charlotte Cardona, Director, Marketing and Communications, Intersec.
17. David Farrell, Principal Scientist, Caribbean Institute of Meteorology and Hydrology.
18. Daniel Tsegai, Programme Officer, United Nations Convention to Combat Desertification (UNCCD).
19. Deepa Joshi, Gender, Youth and Inclusion Lead Specialist, IWMI.
20. Deo Raj Gurung, Chief Scientist, Aga Khan Agency for Habitat.
21. Douglas Lubaba, Acting Water Resources Operations Manager, Water Resources Management Authority, Zambia.
22. Ramesh Tripathi, Project Officer, World Meteorological Organization (WMO).
23. Elena Xoplaki, Senior Scientist, Euro-Mediterranean Centre on Climate Change (CMCC).
24. Erica Allis, Chief, Partner Engagement and Coordination Division (Disaster Risk Reduction), WMO.
25. Everisto Mapedza, former Senior Researcher, IWMI, South Africa.
26. Finu Shrestha, Remote Sensing and Geo-information Analyst, International Centre for Integrated Mountain Development (ICIMOD), Nepal
27. Fulco Ludwig, Former Strategic Program Director, IWMI.
28. Ganga Kariyawasam, Head of Programs, Sri Lanka Red Cross Society.
29. Giriraj Amarnath, Research Group Leader, Water Data for Climate Resilience (WDCR), IWMI.
30. Goro Takei, Board Member, International Disaster Charter, JAXA.

31. Grazia Pacillo, Senior Scientist and Co-Lead of the CGIAR Climate Security Team, Alliance of Bioversity International and CIAT.
32. Grey Nearing, Research Scientist, Google.
33. Hamid Mehmood, Head, United Nations Platform for Space-based Information for Disaster Management and Emergency Response (UN-SPIDER), United Nations Office for Outer Space Affairs (UNOOSA).
34. Hari Kumar, South Asia Regional Coordinator, GeoHazard International.
35. Helen Roberts, Socio-Meteorologist, UK Met Office.
36. Hosni Ghedira, Director of Research Engagements, Mohamed bin Zayed University of Artifical Intelligence (MBZUAI).
37. Homero Paltan Lopez, Associate Researcher, University of Oxford.
38. Jananee Chandramohan, Psychologist, Save The Children, Sri Lanka.
39. Jinsun Lim, Climate Change Specialist, Asian Development Bank (ADB).
40. Johan Gely, Asia Director for Research Impact, IWMI.
41. Johan Stander, Senior Director of Services, WMO.
42. John Harding, Director, Climate Risk and Early Warning Systems (CREWS) Secretariat, WMO.
43. John Nairn, Senior Advisor, WMO.
44. Jonathan Stone, Manager, Climate, Environment and Resilience, IFRC.
45. Joanne Robbins, Science Manager, UK Met Office.
46. Juliette Murphy, CEO & Co-founder, FloodMapp.
47. Karen Woo, Senior Coordinator on early warning systems, International Telecommunications Union (ITU).
48. Karyn Tabor, Senior Agroclimatology Advisor for FEWS NET and research scientist, NASA.
49. Kenneth Sinachikupo, Meteorologist, Zambia Meteorological Department.
50. Kolli Rao, President & Senior Advisor, Aon India Reinsurance Solutions.
51. Lahiru Kodituwakku, Convener, Expert Committee on Planetary Health, Sri Lanka Medical Association, Sri Lanka.
52. Lei Xie, Energy Policy Manager, International Hydropower Association (IHA).
53. Loretta Hieber Girardet, Chief, Risk Knowledge, Monitoring and Capacity Development, UNDRR.
54. Luca Brocca, Director of Research, National Research Council's Research Institute for Geo-Hydrological Protection, Italy.
55. Madhavi Malalgoda Ariyabandu, former Senior Expert Consultant in Disaster Climate Risk Resilience Development, IWMI.
56. Mangesh Patankar, Regional Head, Agriculture, Munich Re.
57. Manjusha Mishra, General Manager (Civil), NHPC Limited.
58. Manuel von der Mühlen, Global Program Manager, Plan International, Switzerland.
59. Mariangel Gracia Andarcia, Research Group Leader, Water Futures Data and Analytics, IWMI.
60. Mark Smith, Director General, IWMI.
61. Markus Enenkel, Climate Risk Finance Specialist, World Bank.
62. Michèle Plichta, Senior Researcher, Centre for Disaster Protection (CDP).
63. Miguel-Angel Fernandez-Torres, Assistant Professor, Universidad, Cartos III de Madrid.
64. Mihir Bhatt, Director, All India Disaster Mitigation Institute (AIDMI).
65. Muehlen Manuel von der, Global Program Manager, Plan International, Switzerland.

66. Nathan Jensen, Research Lead, Jameel Observatory for Food Security Early Action.
67. Newton Campbell Jr., Computer Scientist, AI Subject-Matter Expert for EW4All, ITU.
68. Niranga Alahacoon, Regional Researcher in Remote Sensing and Disaster Risk Specialist, IWMI.
69. Nishat Tasnim, Officer, Knowledge and Influencing, Practical Action, Bangladesh.
70. Polly Harlow, Senior Project Officer, CLEAR Global.
71. Pradeep Kodippili, Director (Awareness), Disaster Management Centre (DMC).
72. Rachael McDonnell, Deputy Director General, IWMI.
73. Raghavendra Ashrit, Scientist, National Centre for Medium Range Weather Forecasting (NCMRWF), India.
74. Ramesh Tripathi, Project Manager, WMO.
75. Rangana Indrasena, Programme Operations Lead, Save the Children, Sri Lanka.
76. Ritu Bharadwaj, Director, Climate Resilience, Finance and Loss and Damage, International Institute for Environment and Development (IIED).
77. Rohini Singarayer, OIC – Resilience, Emergency Preparedness, Response and Social Protection, World Food Programme (WFP).
78. Rui Kotani, Disaster Risk Reduction Coordinator, Group Earth Observations (GEO).
79. Safi Ahsan Rizvi, Advisor (Mitigation), The National Disaster Management Authority, India
80. Sally Jane Edwards, Coordinator, Health and the Environment, World Health Organization (WHO).
81. Sampath Kotuwegoda, Director General, DMC, Sri Lanka.
82. Sanjay Srivastava, Former Chief Disaster Risk Reduction, United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP).
83. Sanjiv De Silva, Senior Regional Researcher, Natural Resource Governance, IWMI.
84. Sandra Ruckstuhl, Research Group Leader – Fragility, Conflict, Livelihoods and Water, IWMI.
85. S. C. Bhan, Consultant, Ministry of Agriculture & Farmers Welfare, India.
86. Sebastian Grey, Scientific Officer for Agrometeorology, WMO.
87. Senaka Basnayake, Program Lead, Climate Services, Asian Disaster Preparedness Centre (ADPC).
88. Shivangi Chavda, Head of Programmes, Global Network of Civil Society Organisations for Disaster Reduction (GNDR).
89. Srinivasa Kumar Tummala, former Head, UNESCO Intergovernmental Oceanographic Commission (UNESCO-IOC) Secretariat for the IOTWMS UNESCO and presently Secretary, Ministry of Earth Sciences, India.
90. Stefania Grimaldi, Hydrological Forecaster and Scientist, European Centre for Medium-Range Weather Forecasts (ECMWF).
91. Suresh Babu, Head, Flood Mapping and Hazard Assessment Division, National Remote Sensing Centre at ISRO, India
92. Thea Turkington, Deputy Principal Research Scientist, Centre for Climate Research, Singapore.
93. Tamuka Mangadzire, Field Scientist, Famine Early Warning Systems Network (FEWS NET), Southern Africa.
94. Vanessa Gray, Head of Climate and Emergency Telecommunications within the Telecommunication Development Bureau, International Telecommunication Union's (ITU).
95. Viola Akoth Otieno, Earth Observation Scientist for Early Warning Systems, African Union Commission.
96. Vishwas Chitale, Senior Programme Lead – Climate Resilience, Council for Energy, Environment and Water.
97. Xi Li, Professor, Wuhan University.



IWMI
International Water Management Institute

CGIAR RESEARCH CENTER

Headquarters
127 Sunil Mawatha, Pelawatta, Battaramulla, Sri Lanka

Mailing address
P. O. Box 2075, Colombo, Sri Lanka

Telephone +94 11 2880000

Fax +94 11 2786854

Email iwmi@cgiar.org

Website www.iwmi.org

ISBN 978-92-95131-10-1 (PRINT)
ISBN 978-92-95131-11-8 (PDF)

Published: November 2026

International Water Management Institute (IWMI)

The International Water Management Institute (IWMI) is an international, research-for-development organization that works with governments, civil society and the private sector to solve water problems in developing countries and scale up solutions. Through partnership, IWMI combines research on the sustainable use of water and land resources, knowledge services and products with capacity strengthening, dialogue and policy analysis to support implementation of water management solutions for agriculture, ecosystems, climate change and inclusive economic growth. Headquartered in Colombo, Sri Lanka, IWMI is a CGIAR Research Center with offices in 16 countries and a global network of scientists operating in more than 55 countries.