WAYANAD LANDSLIDES 2024: EARLY WARNING SYSTEM

CHANGING THE LAST MILE TO THE FIRST MILE

August 2025

WAYANAD LANDSLIDES 2024: EARLY WARNING SYSTEM

CHANGING THE LAST MILE TO THE FIRST MILE

A Joint Report by

India-Japan Center on Climate and Culture
Indian Institute of Management (IIM) Kozhikode

Center for Climate Resilience and Disaster Management
National Institute of Technology (NIT) Calicut

Centre for Technology Alternatives for Rural Areas
Indian Institute of Technology (IIT) Bombay

India Japan Laboratory,
Keio University, Japan

August 2025

About this report:

This report is a collaborative attempt of four universities to look at the issues and challenges of early warning system during Wayanad landslide of 2024. A joint field investigation was undertaken in January 2025, followed by interviews with local communities and stakeholders at different intervals. Most of the data collection was done by the graduate students from four universities. We acknowledge the strong support from the district administration as well as local communities.

Team members:

India-Japan Center on Climate and Culture, Indian Institute of Management (IIM) Kozhikode
Salmanul Faris K
Sanjay Krishnan C
Anupam Das

Center for Climate Resilience and Disaster Management, National Institute of Technology (NIT) Calicut
Krishnadas Sasidharan Nair
Mohammed Firoz C

Centre for Technology Alternatives for Rural Areas, Indian Institute of Technology (IIT) Bombay
Shashank Kumar Anshu
Parmeshwar D. Udmale

India Japan Lab, Keio University
Seira Mary Cherian
Tomo Kawane
Rajib Shaw

AUGUST 2025

Please refer to this publication as follows:
Salmanul Faris K, Sanjay Krishnan C, Anupam Das, Krishnadas Sasidharan Nair, Mohammed Firoz C, Shashank Kumar Anshu, Parmeshwar D. Udmale, Seira Mary Cherian, Tomo Kawane, Rajib Shaw (2025): Wayanad Landslides 2024: Early Warning System: Changing the last mile to the first mile, 87 pages, Kozhikode, India

भारत के राजदूत
AMBASSADOR OF INDIA

सत्यमेव जयते

भारत का राजदूतावास
Embassy of India
2-2-11 Kudan Minami, Chiyoda-ku
Tokyo 1020074

FOREWORD

It gives me immense satisfaction to write forward for the report, “Wayanad Landslides 2024: Early Warning System – Changing the Last Mile to the First Mile.” which I believe enhance our capabilities to handle natural disaster. This collaborative effort by the three Indian institutes namely the Indian Institute of Technology Bombay, Indian Institute of Management Kozhikode and the National Institute of Technology Calicut along with the Indo-Japan Laboratory at Keio University Japan reflects the strength of India-Japan partnerships in diverse sectors.

The unfortunate landslide that struck Wayanad, Kerala in July 2024 was a stark reminder of our growing vulnerability in the face of extreme weather events. More than a natural disaster, it was a call to rethink how we anticipate, prepare for, and respond to such crises. This study thus addresses the issue by placing people and communities at the heart of disaster preparedness and calling for early warning systems that are not just technically sound, but socially meaningful.

By bridging scientific research, technological innovation, policy insight, and community voices, this study demonstrates how international and interdisciplinary collaboration can lead to on ground, community centric implementable solutions. It advocates a powerful shift: from viewing communities as the "last mile" in disaster response to recognizing them as the "first mile" of resilience and early action.

India and Japan two great countries have a longstanding relationship rooted in our cultural exchange, technological cooperation, and mutual respect. As we celebrate the Year 2025-26 as “India-Japan Year of Science Technology and Innovation Exchange”, the outcome of the initiatives undertaken by the Indian and the Japanese academic and research institutions is a classic example depicting how the partnership can deliver meaningful impact at the community level and add value to this special year.

I extend my appreciation and gratitude to the teams involved for their commitment and insight, and I pay tribute to the people of Wayanad for their resilience. Their experiences remind us that effective disaster management must be one of the most priority aspect in the coming years

Let me wish that this report be a guiding example of how countries like India and Japan can co-create knowledge for a safer, more resilient future.

(Sibi George)

Tokyo
9 July 2025

Telephone: +81-3-3265-5036; Fax: +81-3-3262-2301; E-mail: amb.tokyo@mea.gov.in; amboffice.tokyo@mea.gov.in

PREFACE

In the early hours of July 30, 2024, the district of Wayanad in Kerala was shaken by a catastrophic landslide triggered by unprecedented rainfall. While the physical scars left by the disaster were visible in uprooted trees, washed-out homes, and fractured terrain, the invisible cracks it exposed in our systems of preparedness and warning were far more telling. This report emerged from a shared realization across our institutions — that the final and most critical step in disaster response, the “last mile,” must be reimagined as the “first mile” of community engagement, resilience, and action.

This joint effort by the **India-Japan Center on Climate and Culture at IIM Kozhikode**, the **Center for Climate Resilience and Disaster Management at NIT Calicut**, the **Centre for Technology Alternatives for Rural Areas at IIT Bombay**, and the **India Japan Laboratory at Keio University** is the product of field visits, interviews, data collection, and deep inter-institutional dialogue. Together with the support of the local administrators, we set out not just to assess the disaster’s aftermath, but to understand the human, cultural, institutional, and technological dynamics that shape disaster risk and response.

This report underscores the vital role of early warning systems as both technological instruments and social processes. It blends community narratives, policy analysis, and cutting-edge technological reviews to chart a path forward — one that bridges scientific precision with grassroots wisdom, and institutional protocols with local realities. Our collective recommendation is simple, yet profound - for an early warning to be truly effective, it must not just beep from a device — it must ring within the hearts and homes of those most at risk.

We hope this report will be of value to policymakers, practitioners, students, and citizens who seek to build more resilient, inclusive, and culturally rooted approaches to disaster preparedness. Above all, we dedicate this work to the people of Wayanad, whose courage, stories, and knowledge inspire us to rethink not only how we respond to disasters but also how we live with risk in an era of climate uncertainty.

Anupam Das
Mohammed Firoz C
Parmeshwar D. Udmale
Rajib Shaw

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

01

Introduction:

Wayanad landslide, 2024

Chapter 1: Introduction: Wayanad Landslide, 2024

On July 30, 2024, at approximately 2:00 AM, a catastrophic landslide struck the Wayanad district of Kerala, India. Triggered by 409 mm of rainfall in just 24 hours, the event unfolded in the early hours, catching many residents off guard as they slept.

The rainfall saturated the already weakened soil and reactivated an old landslide zone on steep slopes (25°–40°), with loose overburden and fractured rock. The landslide originated in a forested area near the Iruvanipuzha River and swept through villages like Chooralmala and Mundakkai, releasing a destructive debris flow up to 8 km long.

The Key factors included:

- Steep terrain and high elevation drop (~1 km)
- Decayed forest root systems and deforestation (62% forest loss since 1950)
- Soil piping, water infiltration through decayed root pathways
- Climate change, particularly warming of the Arabian Sea, in turn, intensifying rainfall.

Table 1 Casualties and Damages. Source: (Das, 2024)

Category	**Impact**
Deaths	Over 400 people
Injured	More than 200
Missing	Over 200
Houses destroyed	1,555 totally/severely damaged; 452 partially
Property damage	₹281 crore (~$33.5 million USD)
Farmland loss	310 hectares
Displaced individuals	2,500+ in state-run camps, 6,759 overall

The disaster has been a wake-up call for Kerala, highlighting the need for proactive measures to balance development with environmental sustainability. The Wayanad landslide in Kerala has posed significant challenges while also opening up opportunities for resilience and sustainable development.

Challenges

Human casualties: The landslide of July 2024 led to the loss of over 400 lives.

Widespread Destruction of Infrastructure: Homes Roads and Public utilities were destroyed

Economic Setbacks: Wayanad, predominantly an agrarian society, suffered the heavy loss of important commercial crops such as coffee, tea, and spices, directly impacting the sources of livelihood for the local population.

Decline in Tourism Industry: Wayanad is known for its eco-tourism, but post the disaster, the region saw a drop in the number of visitors because of safety concerns, impacting the local economy dependent on tourism.

- Environmental Degradation: Deforestation, quarrying, and construction have weakened slopes, making the region more vulnerable to future landslides.
- Inadequate Warning Systems: Despite warnings from local leaders, the lack of an integrated disaster alert system led to delayed responses.

Opportunities

- *Improved Disaster Preparedness*: The government is working on installing an X-Band Doppler Weather Radar in Wayanad to enhance early warning systems.
- *Sustainable Land Management*: Afforestation, slope stabilization, and better drainage systems can help mitigate future landslides.
- *Economic Recovery Plans:* Investments in rebuilding infrastructure and supporting affected farmers can help restore livelihoods.
- *Eco-Friendly Tourism Initiatives:* Revamping tourism with sustainable practices can attract visitors while preserving the environment.
- *Community Resilience Programs:* Educating locals on disaster preparedness and sustainable farming can strengthen long-term resilience.

This report focuses on the early warning challenges during the Wayanad disaster.

02

Overview of Early Warning Systems (EWS) and Their Critical Challenges.

Chapter 2: Overview of Early Warning Systems (EWS) and Their Critical Challenges.

2.1 Introduction

Early warning systems, as integrated systems, are designed to provide timely and actionable warnings of impending hazards such as cyclones, floods, droughts, heatwaves or wildfires. They build resilience and safeguard lives and livelihoods against increased climate change impacts while reducing loss of life and injury, minimizing economic losses, and protecting critical infrastructure (UNDP 2025). Limited financial resources and institutional capacity, data gaps and uncertainties, communications barriers and complex and evolving climate risks are acknowledged as major challenges (UNDP 2025). The United Nations International Strategy for Disaster Reduction (UNISDR 2012) defines an early warning system to be 'The set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss'. As this definition and most other available disaster risk reduction literature implies, EWS is a social process that aims to address the need to avoid harm due to hazards (Kelman and Glantz, 2014). Rather than just the technical aspects that detects a hazard event and sends the event details to the authorities for decision-making, EWS is a system that comprises of these decision-making authorities and the process of decision-making before and after the hazard event. They span various domains, including climate-related disasters, financial crises, and health emergencies.

According to the United Nations Global Survey of Early Warning Systems 2006, early warning is the integration of four main elements.

1. *Risk Knowledge*: Assessment of risks provides essential information to set priorities for mitigation and prevention strategies and to design early warning systems.
2. *Monitoring and Predicting*: Predictive and monitoring systems offer timely assessments of the possible risks to economies, communities, and the environment.
3. *Disseminating Information*: Communication networks are essential for transmitting warning signals to potentially impacted areas to notify local and regional governmental organizations. The messages need to be dependable, synthetic, and easy for the public and authorities to understand.
4. *Response*: Effective early warning necessitates coordination, sound governance, and appropriate action plans. Education and public awareness campaigns are

also essential components of disaster mitigation.

Climate Change and Regional Challenges of Early Warning Systems (EWS) in Asia

1. *Regional Cooperation in South Asia*: The state of regional cooperation among the South Asian countries is affected by inconsistent data sharing and coordination.
2. *Disaster Monitoring*: Asian nations, especially landlocked developing countries (LLDCs) struggle with outdated or insufficient infrastructure.
3. *Outdated Technological Application*: Timely warnings are delayed due to the fact that many regions rely on traditional methods, though advanced forecasting tools exist.
4. Funding Constraints: A Significant amount of investment is required to scale up EWS applications, yet the limitations of finance are the cause of delay in accelerating widespread adaptation of technology and implementation of suitable EXS applications.
5. *Difficulty in Risk Prediction due to Geographical Complexities*: Countries with diverse climate hazards, such as Nepal (from floods to glacial lake outbursts), find it difficult to prepare comprehensive risk mapping.
6. *Lack of Awareness or Access to Warning Systems*: vulnerable communities are not aware of and do not have access to EWS, which is detrimental to creating an atmosphere where local participation is the utmost priority and key factor for saving lives.
7. *Coordination of Disaster Management Frameworks at National and Regional Levels*: Policy on EWS should be prioritized and bureaucratic hurdles need to be removed.
8. *Cross-Border Disaster Management: Transboundary cooperation is weak among multiple countries*
9. *Integrating Traditional Knowledge Systems into Modern EWS: Missing valuable insights good for DRR*

Over the past five years, academic research has highlighted both the advancement of EMS and the persistent challenges of EWS. This study seeks to envisage the framework for establishing sustainable collaborations among key regional stakeholders with sustained efforts from governments, international organizations, civil society, and the private sector.

2.2 Landslide Early Warning System (LEWS)

Early LEWSs began to emerge in the 1970s and the first operational regional LEWS was started in Hong Kong in 1977, using empirical thresholds of historical rainfall and landslide data. Following the 1990s, the development of LEWSs gained momentum globally, supported by international disaster risk reduction initiatives such as the UNIDNDR, Hyogo, and Sendai frameworks, leading to systems being implemented in countries like Italy, the United States, Taiwan, and Norway. Over time, they have integrated soil water balance models, distributed slope stability models, meteorological forecasts, satellite and radar rainfall data (Fausto et. al., 2020).

In the past few decades the observed technology trends can be broadly categorized into three areas: data acquisition methods, analytical and predictive algorithms, and timely dissemination of warning information.

Data Acquisition and Remote Sensing Technologies

The real-time monitoring using ground-based sensors include Micro-electro-mechanical systems (MEMS), Tilt sensors, Moisture content sensors, Extensometers and inclinometers. In many regions, the combination of satellite remote sensing and ground-based sensor networks provides a holistic picture of evolving slope conditions. For instance, advanced Internet of Things (IoT) platforms facilitate wireless data collection and ensure that continuous monitoring is both scalable and cost-effective. This integration is pivotal in achieving high temporal resolution in data collection and improving warnings' reliability (Abraham et.al., 2020)

Satellite-based Remote Sensing, InSAR and related techniques, has significantly advanced landslide forecasting. The technology allows for early detection of slopes prone to collapse, with demonstrated success in both spatial and temporal prediction of large landslides. These are very valuable in regions where deploying ground-based sensors is challenging (Moretto et.al., 2021).

A study showed an advanced landslide early warning system that integrates 5G communication and IoT technologies to enable high-speed, real-time geohazard monitoring. The system collects data from on-site sensors measuring rainfall, ground cracks, surface deformation, and pore water pressure using GNSS-based and mechanical sensors, which are then transmitted using a dual-mode 5G and BeiDou/GPRS network. A key innovation is its use of automated data processing, dynamic visualization, and a four-level warning system based on the slope deformation–time curve's tangent angle. This system was successfully deployed in Youxi County, Fujian Province, China, where it provided continuous monitoring of slow-creeping terrace slopes and demonstrated the feasibility of fully automated early warning platforms. The approach marks a shift from traditional manual methods to automated, scalable, and energy-efficient systems capable of supporting decision-making in disaster-prone areas. (Li et.al., 2021)

Analytical and Predictive Technologies

Modern landslide warning systems are increasingly adopting machine learning (ML) techniques to analyze large data sets recorded from multiple sensor sources. ML techniques have been employed to create probabilistic models that account for the nonlinear and dynamic nature of landslide processes. A significant challenge in landslide prediction is the incompleteness of landslide inventories, particularly the lack of precise timing information. To address this, researchers have developed probabilistic ML models that can operate effectively even with incomplete datasets.

Information Dissemination and Public Communication

The ultimate goal of any early-warning system is to provide timely and accurate warnings to the public and relevant authorities. Globally, there is a growing emphasis on integrating warning systems with public information networks such as:

- Television and radio broadcasts
- Internet-based platforms
- Mobile alert systems

These dissemination mechanisms ensure that the warnings reach a wider audience in a prompt manner. In many cases, warnings are designed to accompany real-time data updates on public meteorological websites, enabling risk managers to take preemptive actions before a landslide occurs.

The Various Types of Early Warning Systems:

- Conventional Early Warning Systems: Threshold-based systems.

  Challenges are highly dependent on manual observation, slower response time, less accuracy with complex terrain or weather variability.

- Edge Computing-Based Systems: Instead of sending all sensor data to the cloud, edge devices (local computers) process the data near the sensor location itself.

- Machine Learning models: Predictive models based on historical and real-time data. Train on large datasets (rainfall, slope data, historical landslides) to learn patterns and predict future landslides.

- Deep Learning (DL) Models: Automatic feature extraction and high-accuracy classification. Deep neural networks automatically learn important features from large and complex datasets like satellite images.

- Community-based: Like the LandAware Initiative, a global network promoting real-world, community-focused LEWS, where local knowledge, experiences, and innovations are shared to improve the practical design and management of warning systems. There could be Infrastructure challenges like a lack of reliable mobile networks in remote or hilly areas (Krishna et.al., 2024)

2.2.1 India: Landslide Early Warning System

India, with its complex topography and climatic variability, is particularly vulnerable to landslides. India's early adoption is also limited to basic monitoring, mostly using rain gauges, empirical rainfall thresholds and mostly retrospective analysis with manual data interpretation. Currently, adopting a multi-domain LEWS framework integrating IoT, geophysical sensors, AI/ML models, and participatory tools for real-time risk assessment, monitoring, and communication. Two case studies, Munnar in the Western Ghats and Chandmari in the Eastern Himalayas, demonstrate the successful deployment of Amrita's IoT-based LEWS, tailored to different types of landslides and regional conditions. These systems use Deep Earth Probes (DEPs), geophysical sensors, meteorological data, and ML models for early detection and communication of landslide risks. The systems successfully detect diverse landslide types like debris flows, rockslides, mudslides, and creep movements. Amrita LEWS is an advanced, AI-enabled IoT solution developed by Amrita Vishwa Vidyapeetham's Amrita Center for Wireless Networks & Applications (AmritaWNA) in India. It is designed to monitor, detect, and provide early warnings for landslides. Following devastating landslides in July 2024, Amrita LEWS is being deployed in Wayanad to enhance disaster preparedness and community safety.

However, there are challenges such as high deployment costs, data scarcity, terrain-specific complexities, unreliable communication in remote areas, and limited coordination among stakeholders. Despite these hurdles, the development of scalable, adaptive, and community-engaged LEWS offers a promising path toward disaster resilience in India. (Ramesh et.al., 2023).

System Integration and Communication

Integrated within the broader IoT framework, individual sensor nodes communicate wirelessly to a central data logger, which in turn uploads data to an internet-based database. This seamless linkage ensures that real-time updates are available to decision-makers and local authorities, enabling swift remedial actions when necessary. The study conducted between 2017 and 2019 in the Darjeeling region involved real-time, continuous monitoring of active slopes. Data collected from six distinct sensor units were integrated into a centralized IoT network. Found to reduce False Alarms and be better in cost effectiveness and scalability, which is particularly important given the size and diverse topography of the Himalayan region. (Abraham et.al., 2020).

2.2.2 Japan: Landslide Early Warning System

Japan has long been at the forefront of disaster risk reduction efforts. The nation's approach to landslide prevention, particularly following the catastrophic landslide incidents of the early 2000s, leverages sophisticated data analytics and machine learning techniques.

Japan's nationwide landslide early warning system was launched in 2005, predicts potential landslides using key rainfall indices, primarily a 60-minute cumulative rainfall and a soil–water index within 5-km grid cells for localized analysis. The system employs Radial Basis Function Networks (RBFN) to set adaptive thresholds based on non-disaster rainfall data, compensating for limited precise historical landslide records. Since March 2007, warnings have been integrated into public channels such as TV, radio, and the internet, improving timely evacuations and reducing disaster impacts (Osanai et. al., 2010).

But technical and Operational Challenges, despite the technological sophistication of Japan's system, still remain:

- Data Limitations: The lack of high-precision historical records for landslide events forces the system to rely on surrogate data. This reliance on rainfall parameters, though effective, can sometimes lead to uncertainty in predicting exactly when and where a landslide might occur.
- Dependency on Meteorological Data: The system's heavy reliance on rainfall indices means that any anomalies in meteorological observations could potentially affect the accuracy of warnings.
- Continuous System Calibration: Given the changing climatic patterns and land use conditions, the thresholds and the machine learning models require continuous recalibration to maintain effectiveness.

2.2.3 Distinctive Regional Features

- Japanese Approach: Japan's adoption of grid-based analysis combined with RBFN demonstrates an early and systematic application of ML directly to meteorological proxies. This approach addresses data scarcity by using non-disaster rainfall data to determine risk thresholds.
- Indian Strategy: In regions like the Darjeeling Himalayas, the utilization of low-cost IoT sensors and real-time field monitoring represents a pragmatic and scalable way to overcome the constraints of diverse geomorphological conditions and rapid urbanization influences.
- Global Perspectives: The global context encapsulates both high-tech, expensive systems (e.g., satellite remote sensing) and more cost-effective, distributed

sensor networks (e.g., IoT-based approaches), reflecting a spectrum that varies depending on local resource availability and infrastructure maturity.

2.3 Overall Challenges

- Data Scarcity and Quality: A recurring issue is the limited availability of precise, high-resolution historical data on landslide events. In Japan, for example, the absence of detailed records means that predictive models must rely heavily on surrogate indicators such as rainfall indices. In India, inconsistency in long-term monitoring data can lead to challenges in calibrating sensor thresholds correctly.
- False Alarms: High false alarm rates can undermine public trust in warning systems. Both global and regional initiatives have had to innovate methods to reduce spurious alerts.
- Cost and Scalability: Advanced remote sensing and high-precision in-situ sensor networks, while technologically superior, often come with prohibitive deployment and maintenance costs. Achieving a balance between cost-effectiveness and technological sophistication is a major challenge faced by policymakers worldwide.
- Local Heterogeneity: Regional variations in terrain, soil composition, land use, and climate conditions demand tailored models. A system that works in Japan's relatively consistent landscape may not directly translate to the heterogeneous conditions found in the Himalayan regions of India.
- Lack of standardization hinders interoperability and credibility.
- Lead Time Issues: There's limited data on the time between warning issuance and landslide occurrence, which affects response strategies.
- Barriers to Adoption:
    - High cost and maintenance
    - Need for trained personnel

03

Cases from India and Japan

Chapter 3: Cases from India and Japan

3.1 Global landslide overview

Globally, between 2004 to 2016, over 55,000 lives were lost due to landslides (Sim et al. 2022) and annual economic losses were estimated at around 20 million USD (Capobianco et. al., 2025). And in recent years, global landslide activity has been increasing exponentially due to climate change, urban expansion and environmental degradation. In July 2024 alone, there were 95 landslide events globally, resulting in over 1167 deaths (Petley, 2024). The large increase in average precipitation is the primary trigger for the landslides. Along with this, the rising temperature is causing the glaciers and permafrost to melt, which in turn destabilises the slopes. According to the study conducted by Wang et. al. in 2023, where a global landslide risk assessment model was developed to explore the spatial and temporal variations in future landslide risk across the globe, it was found that the average annual frequency of landslides triggered by extreme precipitation is projected to increase by 7% in the next 30 years (2031–2060) and 10% in the 30 years (2066–2095) after that. Asia and Africa are expected to have the largest increase in cases, 13% and 20%, respectively. According to the UNDRR global status report 2024, 108 countries have reported the existence of multi-hazard early warning systems as an effort to reduce the global disaster mortality and for better preparedness.

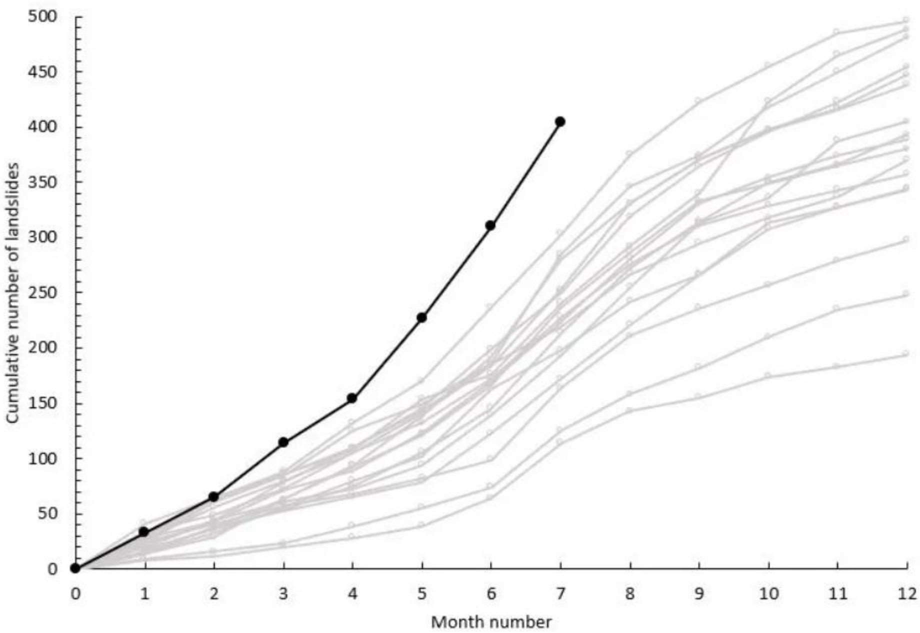

Figure 3-1 The cumulative number of landslides in 2024 (black line), by month, compared with previous years (in grey). Source: (Petley, 2024)

3.2 Wayanad Landslide, 2024

On July 30, 2024, at approximately 2:00 AM, a catastrophic landslide struck the Wayanad district of Kerala, India. Triggered by 409 mm of rainfall in just 24 hours, the event unfolded in the early hours, catching many residents off guard as they slept.

The rainfall saturated the already weakened soil and reactivated an old landslide zone on steep slopes (25°–40°), with loose overburden and fractured rock. The landslide originated in a forested area near the Iruvanipuzha River and swept through villages like Chooralmala and Mundakkai, releasing a destructive debris flow up to 8 km long.

The Key factors included:

- Steep terrain and high elevation drop (~1 km)
- Decayed forest root systems and deforestation (62% forest loss since 1950)
- Soil piping, water infiltration through decayed root pathways
- Climate change, particularly warming of the Arabian Sea, in turn, intensifying rainfall.

Table 3-1 Casualties and Damages. Source: (Das, 2024)

Category	Impact
Deaths	Over 400 people
Injured	More than 200
Missing	Over 200
Houses destroyed	1,555 totally/severely damaged; 452 partially
Property damage	₹281 crore (~$33.5 million USD)
Farmland loss	310 hectares
Displaced individuals	2,500+ in state-run camps, 6,759 overall

The disaster has been a wake-up call for Kerala, highlighting the need for proactive measures to balance development with environmental sustainability. The Wayanad landslide in Kerala has posed significant challenges while also opening up opportunities for resilience and sustainable development.

Challenges

Human casualties: The landslide of July 2024 led to the loss of over 400 lives.

Widespread Destruction of Infrastructure: Homes Roads and Public utilities were destroyed

Economic Setbacks: Wayanand, predominantly an agrarian society, suffered the heavy loss of important commercial crops such as coffee, tea, and spices, directly impacting the sources of livelihood for the local population.

Decline in Tourism Industry: Wayanand is known for its eco-tourism, but post the disaster, the region saw a drop in the number of visitors because of safety concerns, impacting the local economy dependent on tourism.

- Environmental Degradation: Deforestation, quarrying, and construction have weakened slopes, making the region more vulnerable to future landslides.
- Inadequate Warning Systems: Despite warnings from local leaders, the lack of an integrated disaster alert system led to delayed responses.

Opportunities

- *Improved Disaster Preparedness*: The government is working on installing an X-Band Doppler Weather Radar in Wayanad to enhance early warning systems.
- *Sustainable Land Management*: Afforestation, slope stabilization, and better drainage systems can help mitigate future landslides.
- *Economic Recovery Plans:* Investments in rebuilding infrastructure and supporting affected farmers can help restore livelihoods.
- *Eco-Friendly Tourism Initiatives:* Revamping tourism with sustainable practices can attract visitors while preserving the environment.
- *Community Resilience Programs:* Educating locals on disaster preparedness and sustainable farming can strengthen long-term resilience.

3.3 Sikkim Glacial Lake Outburst Flood (GLOF), 2023

On the night of October 3, 2023, a massive section of frozen lateral moraine collapsed into the South Lhonak Lake triggered by heavy rains in northern Sikkim. This sudden displacement generated a towering 20-meter-high wave within the lake and breached the moraine dam, resulting in a sudden and catastrophic drainage of water downstream at a peak discharge rate of 48,500 cubic meters/sec, gushing through the Teesta River valley.

As the floodwater surged downstream:

- They eroded an estimated ~270 million cubic meters of sediment
- Triggered 45 secondary landslides
- Caused the displacement of ~66.5 million cubic meters of sediment within a 5 km stretch (between 40–45 km downstream of the lake).

Table 3-2 Casualties and Damages. Source: (Sattar et.al.., 2025)

Category	**Impact**
Deaths	55 people
Missing	74 people
Buildings Damaged/Inundated/Destroyed	More than 25,900
Bridges Lost	31
Agricultural Land Affected	~270 km^2
Major Infrastructure Loss	Teesta III Hydropower Dam destroyed

3.4 Hiroshima Landslide, 2014

Hiroshima is a city located in western part of Japan, with high development in the mountain areas. The city and prefecture were affected by a major typhoon and rainfall induced landslides in 1999. This was a landmark event, which created the zonation law of Japan in year 2000. The Act on Sediment Disaster Countermeasures for Sediment Disaster Prone Areas [Act number 57 of 2000], which came into effect in 2000, mandates that prefectures designate areas at risk of sediment disasters (Yellow Zone) and areas where a sediment disaster would completely destroy normal wooden buildings (Red Zone). The same area was again affected in 2014. It was exacerbated by extreme precipitation events. During the early morning hours of August 20, 2014, in Hiroshima City, A high-intensity/short-duration rainfall labeled Typhoon-12 dumped 287 mm of rain, 2.6 times the seasonal average, over a few hours. This triggered 166 landslides, including 107 debris flows and 59 shallow slides, especially in the Asa-Kita and Asa-Minami wards.

Table 3-3 Casualties and Damages

Category	Impact
Fatalities	74 people died
Elderly victims	41% of casualties were aged over 65
Homes destroyed	133
Homes damaged	296
Debris flows recorded	107
Shallow landslides	59
Rescue & response	Over 500 personnel, including army units, deployed for rescue efforts

Triggering Factors:

- JMA (Japan Meteorological Agency) issued forecasts, but Hiroshima City Council hesitated to act decisively.
- No operational early warning system for landslides existed at the time.
- Incomplete debris-control dams in the worst-hit wards reduced protection.
- Narrow streets and mountainous terrain made evacuation difficult, even if warnings had come earlier (Ray-Bennett and Shiroshita 2019).

Early Warning System in City of Hiroshima was refined after past disasters, including the 2014 Hiroshima landslides triggered by torrential rainfall and led to significant damage and loss of life. Climate-driven hazards such as landslides cause grave damage to the life of the local population. Asia is the most disaster-prone continent, accounting for **41.75%** of global events. This suggests that Japan, including Hiroshima, remains highly vulnerable to landslides and other climate-driven hazards.

Way Forward:

Hiroshima has an early warning system in place to help residents prepare for potential landslides and other natural disasters. The city issues evacuation orders based on different warning levels, ensuring people know when to take action.

For example:

- **Warning Level 3**: Senior citizens and those needing extra time should evacuate immediately.
- **Warning Level 4**: All residents in hazard areas should evacuate immediately.
- **Warning Level 5**: A disaster is in progress—take immediate action for safety.

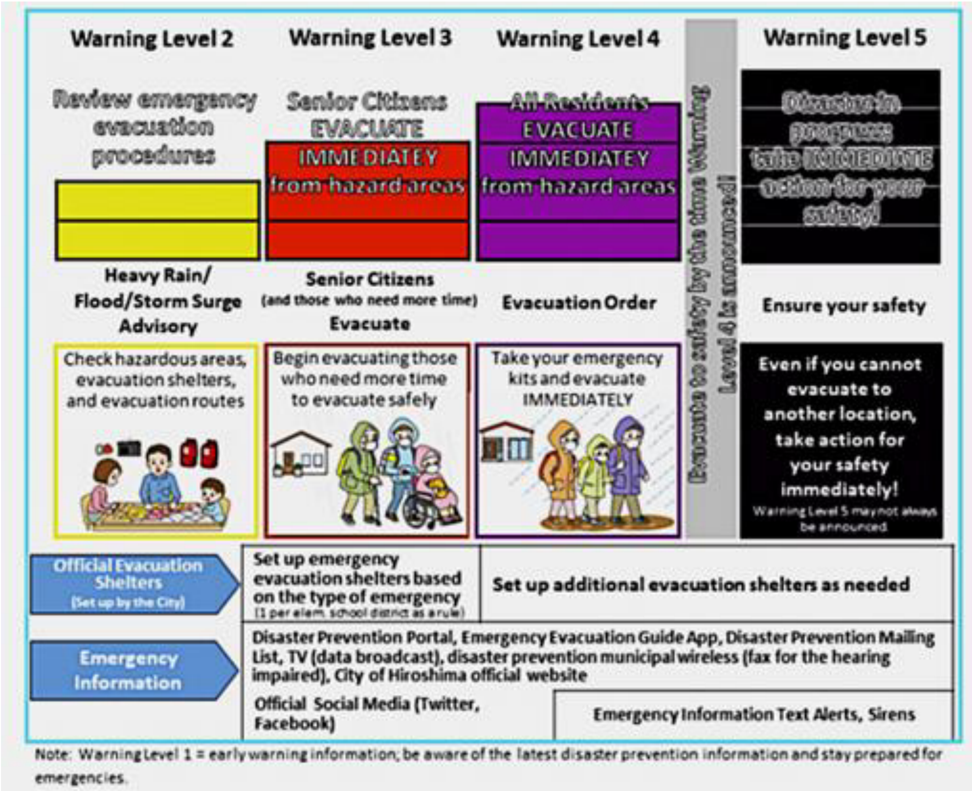

Figure 3-2 Warning Levels in City of Hiroshima. Source: (City of Hiroshima Official Website,2025)

3.5 Atami Landslide, 2021

A significant debris flow happened in the Aizome River in the Izusan region of Atami, Shizuoka Prefecture, Japan, early on July 3, 2021, primarily triggered by over 432.5 mm of continuous rainfall over four days, typical of Japan's rainy season. However, the disaster was intensified by a secondary cause, an illegally constructed landfill containing around 56,000 m^3 of unstable backfill soil at the landslide's origin. Despite being aware that the landfill exceeded legal height limits (permitted: 15 m; actual: 50 m), local authorities failed to take preventive action, marking a significant administrative oversight. The area affected by the mudslide was approximately 1 km in length and 120 m in width. Beyond the physical distructions, the tourism industry in Atami was also severely impacted which was still recovering from Covid 19. This had further economical and psychological toll on the residents too.

Table 3-4 Casualties and Damages. Source: (Poudel et al., 2024)

Impact	Details
Total Deaths	27 (including 1 missing person)
% Elderly Victims (60+ years)	~60%
Damaged Houses	128 total (as of October 1, 2021)
Infrastructure Disruptions	Power outages, water supply cut-offs
Displaced People	600 initially; 144 in temporary housing (as of March 2022)

Triggering Factors

- The area experienced rainfall exceeding its average for July in just 3 days leading to the landslide.
- A real estate company had deposited 54,000 cubic meters of soil in a valley illegally.
- The authorities lack of management and inaction regarding this unauthorized landfill even when records state they knew since 2009.

Way Forward

- Voluntary Disaster Prevention Activities in Practice and evacuation drills for sediment disasters were conducted in the Izusan district by Shizuoka prefecture.
- In 2023, Japan implemented a new law to regulate soil mounds for protection from landslides. New regulated zones that pose a risk were established.

3.6 Findings and Recommendations

It is important to work out how early warning could help the public make up their mind to evacuate or stay back.

Challenge	Description
Limited prediction tools	Especially in remote regions, real-time monitoring systems are rare or underfunded.

Topography and terrain	Hilly or mountainous regions are hard to monitor and evacuate.
Data gaps	Lack of high-resolution, ground-based data (e.g., soil moisture, slope stability).
Last-mile communication	Warnings may not reach the affected people on time, especially in rural areas.
Urban expansion	Settlements often encroach into known hazard zones due to a lack of enforcement.
Community awareness	People are often unaware of how to respond, even if they receive a warning.
Climate variability	Sudden increased intensity of rainfall and melting glaciers make prediction harder.

Recommendations

- Seamless info-sharing among meteorological agencies, disaster management offices, and local municipalities.
- Open-source data should be utilised to build efficient early warning systems.
- Collaborations with innovations and new approaches could be possible with startups
- The disasters showcased that mere digital alerts of disasters by SMS and app through individual gadgets could not be sufficient to alert the local population.
- Community bonding and networking would help the concerned local population to practice practical evacuation drills.
- Coordinating with local administrations, educational institutions and door-to-door volunteer alerts with announcements could save lives.
- The principles of disaster communication need to be disseminated among the journalists.

04

Governance and Institutional Structures for Community-Based Early Warning Systems

Chapter 4: Governance and Institutional Structures for Community-Based Early Warning Systems

4.1 Introduction: Onset of Disaster Management in Kerala

Kerala's remarkable achievements in human development are juxtaposed with its vulnerability to natural disasters, creating a complex scenario for the state's 33 million residents. As of 2025, Kerala maintains its position at the forefront of human development in India, ranking fifth among all states and union territories with an HDI of 0.796. This impressive standing is attributed to the state's exceptional performance in key areas such as education, healthcare, and social welfare. Kerala's literacy rate of 93.91% is the highest in India, and its life expectancy of 74.9 years surpasses the national average (*Memorandum_Meppadi Landslide*, n.d.). The state has consistently topped the NITI Aayog's Sustainable Development Goals Index, showcasing its commitment to holistic development. However, Kerala's geographical location and high population density of 860 people/km^2 (as of 2011) make it particularly susceptible to natural hazards. The state is classified as a multi-hazard prone area, with all 14 districts exposed to multiple hazards simultaneously. Climate change has exacerbated the frequency and intensity of extreme weather events, further increasing the state's vulnerability (*Memorandum_Meppadi Landslide*, n.d.). While Kerala's achievements in human development are commendable, addressing these vulnerabilities becomes crucial to ensure the long-term resilience and sustainability of the state.

In a groundbreaking initiative, Kerala became the first state in India to implement comprehensive local disaster management plans across all its Grama Panchayats[1] and urban Local Self-Government Institutions (LSGIs) in 2019-20. This proactive measure, known as "Nammal Namukkay" (We for Us), was launched under the Rebuild Kerala Development Programme to mainstream disaster risk reduction in local development plans (*Local Self Government DM Plans - Kerala State Disaster Management Authority*, 2020). The disaster management plans, tailored to each LSGI, encompass crucial components such as the LSG's profile, hazard and vulnerability assessment, capacity and resource mapping, response strategies, and plans for preparedness, mitigation, and community resilience (*LSGI of Kerela Prepared DM Plans_KSDMA*, n.d.). The major highlight of the initiative is the directive for the Local Self Government Institutions to include disaster management and mitigation projects in their annual plans, by considering the vulnerabilities to natural disasters specific to their area and their capacities to address them.

[1] ***Gram Panchayat** is a basic governing institution in Indian villages. It is a political institution, acting as the cabinet of a village or group of villages. The gram panchayat is headed by an elected President and Vice President, assisted by a secretary who serves as the administrative head of the panchayat.*

Kerala's comprehensive disaster management framework integrates both localized planning and state-wide strategic updates through its evolving Orange Book[2] system, that has been evolved and developed from the extensive 2016 State Disaster Management Plan (*Kerala State Disaster Management Plan 2016*, n.d.) that has identified 39 distinct hazards – ranging from hydro-meteorological risks like floods and landslides to anthropogenic threats such as industrial accidents and transportation disasters. The Orange Book has been an operational backbone of the system, undergoing mandatory updates in the month of May, before monsoons, considering the learnings from the recent disasters that has affected the state. The document lists Kerala's preparedness towards disasters through its comprehensive contents that establish monsoon forecasts, refine early warning protocols, functioning of Response Teams at all tiers, and allocation of emergency funds with compliance to Disaster Management Act's financial regulations (*Orange-Book-of-Disaster-Management-1-2020*, n.d.). With these details being addressed and implemented, the Orange Book also directs its focus to the macro-level policy frameworks like the Sendai Agreement that calls for micro-level implementation needs, particularly for the ever-growing urban centers. The annual updates of the Orange Books also ensures that civil defense protocols, and inter-agency coordination mechanisms remain aligned, in case of frequent disasters that are impacting the state (*Kerala State Disaster Management Plan 2016*, n.d.), while mandatory district-level reviews enforce accountability across 14 disaster-prone districts.

4.1.1 Legislative Framework and Institutional Structure of Warning Systems in Kerala Disaster Management

Kerala's institutional disaster governance framework functions as a multi-tiered structure, that has been established under Disaster Management Act of 2005, with the Kerala State Disaster Management Authority (KSDMA) heading the cause since its inception in 2007 (*About KSDMA - Kerala State Disaster Management Authority*, 2018). KSDMA is chaired by the Chief Minister and operationally led by the Chief Secretary of the State as the Chief Executive Officer. The apex body coordinates with fourteen District Disaster Management Authorities (DDMAs) established in 2008 across all districts in the state as per the policy (*KSDMA-Policy-2010*, n.d.). The State Executive Committee (SEC) is formed as the functional body, chaired by the Chief Secretary, along with other senior bureaucrats including the Principal Secretary for Disaster Management, who also serves the role of State Relief Commissioner and executive manager of Kerala State Emergency Operations Centre (*State Relief Commissioner - Kerala State Disaster Management Authority*, 2018), as directed in the act. This model ensures that the disaster management protocols are applicable at all levels of administration. It works through three main approaches. Firstly, the policies are developed and implemented under the

[2] *The **Orange Book** prepared by the Kerala State Disaster Management Authority features standard operating procedures and the actions to be taken in the event of any natural disaster.*

guidance of the State Executive Committee (SEC), based on national and state disaster plans. Second, local District Disaster Management Authorities (DDMAs) adapt these plans to local conditions, based on their vulnerabilities to different disasters, by following the guidelines set by the SDMA. Third, various government departments work together through Disaster Management Cells, which helps improve coordination across departments (*KSDMA-Policy-2010*, n.d.).

To ensure a fast and coordinated response during disasters, Kerala has built a strong and well managed emergency management system. At the core of this system, there is a State Emergency Operations Centre (SEOC), located at the State Headquarters in Thiruvananthapuram. The SEOC plays a crucial role in bringing together different agencies to respond to the different disasters of all scales across the state. The center is staffed by experts from various fields, who have practical experience in dealing with emergencies. It plays a crucial role in connecting state departments, central government bodies, and district administrations to make disaster response and recovery more efficient. To make it more efficient, the Emergency Operations Centers (EOCs) are established in every district headquarters. These district-level centers follow the national and state emergency communication plan, to ensure smooth coordination between state and local authorities. At the taluk[3] level, control rooms are managed by the Land Revenue Department. These centers are activated based on Standard Operating Procedures (SOPs) as mentioned in Kerala's disaster management handbook. They provide quick and localized responses when emergencies occur. This three-level system—state, district, and taluk—is designed to reduce delays in disaster response. It also improves recovery by encouraging collaboration between state and central agencies and by making use of specialized skills and resources.

To further localize the system, the State Disaster Management Policy 2010 requires all key departments to set up dedicated control rooms during disaster events. This aids in maintaining continuous communication and coordination across different levels of government and operations. The two major departments that carry on this responsibility are the Department of Revenue and the Department of Home. These control rooms set by the departments function 24/7 and are headed by the Commissioner of Land Revenue and the Director General of Police, respectively. The Control Rooms are equipped to take quick decisions and help allocate resources based on the needs. In 2020, Local Self-Government Institutions (LSGIs) were also advised to establish their own control rooms during the monsoon season to improve disaster response at the local level. Similarly, departments managing necessities, such as the Kerala State Electricity Board (KSEB) and

[3] *The administrative divisions below the district are called **Taluks.** It is an administrative delineation for taxation purposes, typically comprising a number of villages.*

the Water Department, were asked to operate their own control rooms to handle emergencies like power failures and water-related issues.

Also, the (*Kerala State Disaster Management Plan 2016*, n.d.) assigns specific roles to different nodal departments for managing different types of disasters. These roles address all the major stages of disaster - preparedness, response, recovery, and mitigation, for all the specific disasters that are prone to occur in the state. In the case of landslides, which we shall be focusing specifically in this chapter based on the events that occurred in Wayanad, Local Self-Government Institutions (LSGIs) are given the responsibility for preparedness and mitigation stages of the disaster. Their tasks include taking preventive actions to reduce risks and impacts of landslide and also to strengthen the community resilience through local-level initiatives. Furthermore, when a landslide occurs, the Department of Land Revenue takes charge of response and recovery efforts. The role includes managing emergency relief, coordinating rescue operations, and supporting affected communities during and after the event(*Orange-Book-of-Disaster-Management-1-2020*, n.d.).

4.1.2 Functions of Emergency Operation Centers

The Emergency Operations Centers (EOCs), as discussed in the previous sections, plays a central role in Kerala's disaster management system. Set up under the Disaster Management Act of 2005, these centers are designed to function flexibly across all phases of disaster management, by following specific protocols suited to each stage of the specific disaster. During the periods when there is no threat to disasters, the EOCs focus on maintaining and updating information from past events and the procedures followed. They act as knowledge centers, where data from previous disaster events and procedures are well documented and updated. At the same time, they monitor and analyze hydro-meteorological data received from agencies such as the India Meteorological Department (IMD) and the Indian National Centre for Ocean Information Services (INCOIS), helping the state stay alert and ready for potential hazards (*EOC_Kerala*, n.d.). The EOCs are also equipped with advanced technology that supports them to take effective decisions. They use modern Information and Communication Technology (ICT) tools such as GIS-based mapping, satellite communication, and automated alert systems (GoI, n.d.). During emergencies, the Emergency Operations Centers (EOCs) transform to active command hubs that support quick and coordinated decision-making. Different departments take on specific roles based on clearly defined responsibilities, as discussed in the previous sections. The Command section in the center guides overall strategy and policy decisions, whereas the Operations team coordinates actions on the ground. The Planning unit gathers and analyzes information to support the decisions taken, the Logistics ensures that resources are properly distributed, and the Finance section keeps track of spending and ensures it follows proper guidelines. This way of functioning helps the State EOC work smoothly with the 14

District EOCs across the state, ensuring good coordination across all levels, throughout the event. Once the emergency concludes, the center ensures to record all actions taken and prepare detailed incident reports. These reports will be reviewed by the State Executive Committee, which utilizes the findings to improve disaster planning and included the necessary inferences in the annual updates of the Orange Book protocols and the local disaster management plans, helping to strengthen future preparedness (*EOC_Guidelines_Oct_2024*, n.d.).

4.1.3 Stakeholders and Institutional Functions in Disaster Warning Systems

The role for each player involved in the Emergency Operations Centers at different times of the year are clearly mentioned in the Orange books issued every year (*Orange-Book-of-Disaster-Management-1-2020*, n.d.).The emergency response process starts as soon as it becomes clear that a disaster is imminent and continues until the situation is officially declared over. This process is activated when an authenticated early warning or information about the disaster's onset is received. Once an alert is issued, the District Collector or the State Relief Commissioner assumes the role of Incident Commander for managing either local or state-level disaster responses. Emergency Operations Centers (EOCs) work around the clock in an Emergency Time Mode, with various communication modes used to establish immediate access to the affected sites.

Information flow is carefully managed, with early warnings being cross-checked and verified by the State Emergency Operations Center (SEOC) before being shared with the public. Disasters are categorized into levels (L0 to L3), depending on their scale and the capacity of local authorities to manage them. For less severe events, the response is typically handled at the district or state level. However, if the situation worsens, central forces may be called upon for assistance. The SEOC plays a pivotal role, being staffed by senior officers and supported by private and volunteer organizations. It adapts as the situation evolves, ensuring all departments and agencies are working in harmony. At the ground level, the District Responsible Officer (DRO) leads the operations, with the District Emergency Operations Center (DEOC) supporting the coordination. The senior-most uniformed officer on-site assumes the role of the Onsite Incident Commander (OIC), making critical decisions in collaboration with the DRO. As the disaster's severity increases, state and national resources are mobilized, and central forces are involved if necessary. Coordination with neighboring states becomes vital when the disaster's impact extends beyond Kerala, ensuring a more extensive, unified response.

Local departments are expected to have their disaster management plans in place and, when necessary, seek support from the state or national resources. The SEOC is also responsible for maintaining communication with other states and national agencies to keep the response well-coordinated and informed.

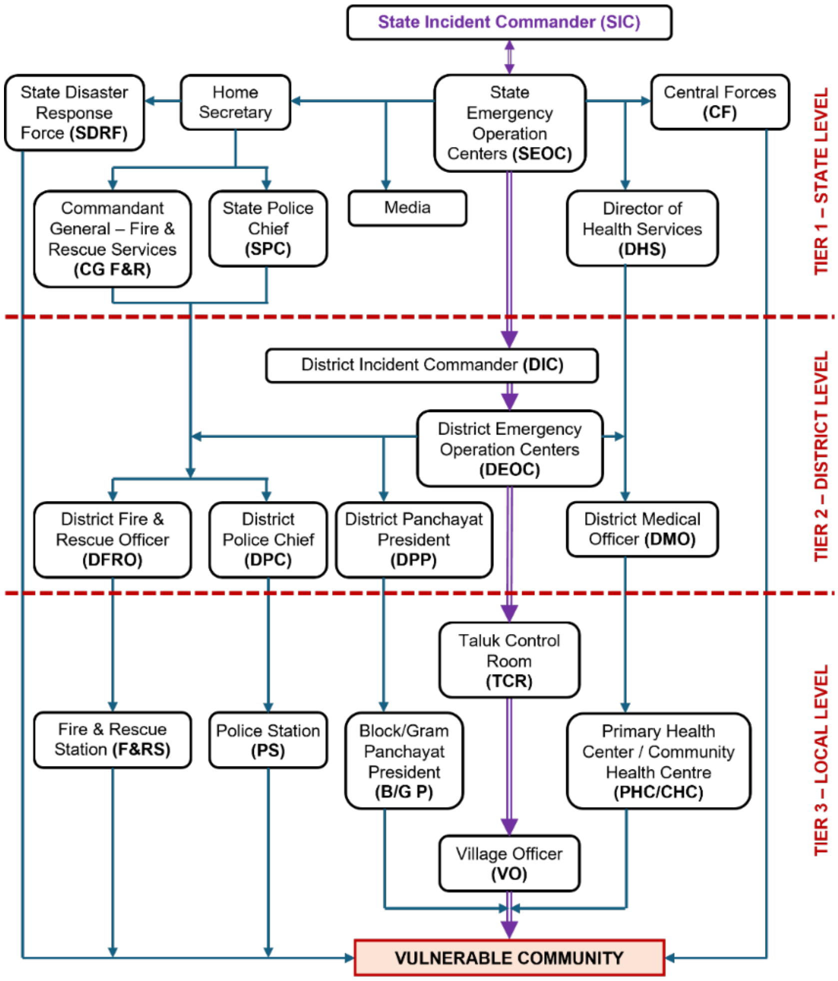

Figure 4-1 Disaster Warning system across Tiers. Source: Orange Book

4.1.4 Consolidating the Warning System in Kerala

As outlined by the Kerala State Disaster Management Authority (KSDMA) in various reports, including the Orange Book, the roles and responsibilities of nodal agencies in the state are clearly defined as discussed in the previous sections. These agencies are expected to act promptly during a disaster, following the guidelines set out for different disaster types, based on their scale and intensity. Furthermore, these agencies are required to stay active throughout the year, gathering data and conducting studies to improve disaster management strategies for the future. The guidelines are specific not only in terms of disaster response but also in the phases of disaster management, including Mitigation, Preparedness, Response, and Rehabilitation.

Although Kerala has devised a strong and detailed institutional framework for disaster management as we have discussed, one key aspect remains to be addressed in all the discussions - the active participation of local communities in the warning system and other stages. Kerala's diverse geography and cultural landscape give rise to a wide range of communities dwelling in the state, each having deep sense and valuable local knowledge about their surroundings. This knowledge, however, is often felt to be overlooked in formal disaster planning. With their understanding of specific risks in their areas, local communities have the capability to contribute to identifying early warning signs and responding quickly during disasters. It can potentially improve the overall effectiveness of disaster response, especially at the early stages. In the context of Kerala, its social structure is complex, with significant differences in vulnerability to disasters, access to resources, and levels of preparedness across various groups. Thereby, despite the potential, it is not a straightforward task to incorporate these communities in the system, due to the diversity and scale. This calls for more customized strategies that address the unique characteristics, needs, and challenges of each community, thereby ensuring that no group is left behind in disaster preparedness and response efforts.

Based on the inferences as discussed, the following sections shall focus on how social causation leads to vulnerabilities and how these social and institutional vulnerabilities have defined the exposure of risk for these different communities, based on these differences. The goal will be to bridge the gap between institutional frameworks and communities, thereby creating a more inclusive and effective warning system. This shall involve both immediate and long-term strategies, to make sure that community involvement is not only encouraged but integrated into the broader disaster management process.

4.2 Vulnerabilities and Stratified Risks

As per (Wisner et al., 2004), disasters are often depicted as the result of natural forces, with terms like "natural disaster" framing them as unavoidable events. However, this viewpoint often fails to consider the influence of social systems, human behavior, and institutional shortcomings in creating and worsening vulnerability during the event of a disaster. The idea of social causation gives a broader and deeper understanding of disaster risk, where it shows how social inequalities and divisions within society shape people’s exposure to hazards. According to this perspective, vulnerability is not just the result of physical location or environmental factors, but something that are further closely linked to political, economic, and social conditions. In this sense, disasters are not purely natural events, but outcome of long-standing and ongoing social processes that influence how risks are distributed. This understanding calls for addressing the root causes of vulnerability, not just physical threats.

The allocation of resources and who controls them plays a major role in where disaster risks are concentrated. For instance, floodplains often provide low-cost land for farming or housing. But while affordable, these areas are also among the most vulnerable to natural hazards like floods. People from marginalized communities, who often lack the means to access safer or better land, frequently end up living in such high-risk zones which increases their exposure to danger during disasters. This depicts how social stratifications increase the exposure to risk, based on their choices. Those with better social or economic status are more likely to live in secure areas with strong infrastructure and good disaster planning. In contrast, poorer or socially excluded groups are pushed to live in unsafe conditions with fewer protections. This inequality creates different levels of vulnerability within society. This further justifies the point that disaster risk is not just about geography or nature, it is also deeply shaped by social systems.

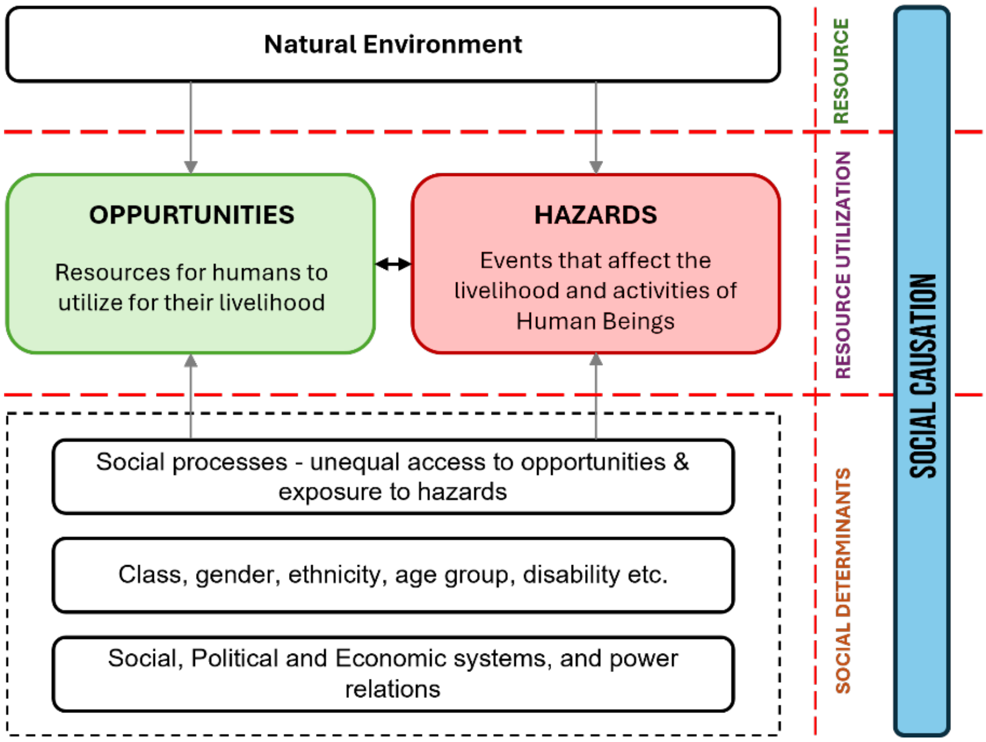

Figure 4-2 The Evolution of Social Causation. Source: Authors

From these observations, it can be inferred that vulnerability is rooted in systemic social issues, such as poverty and inequity, which are historically embedded in power relations. These social conditions thereby perpetuate inequalities, with some groups more exposed to risks while others enjoy better protection, developing the imbalance. Understanding disaster risk, therefore, requires examining both the natural hazards and the social, political, and economic systems that determine who is most at risk and why.

4.2.1 The Pressure and Release (PAR) Model

The Pressure and Release (PAR) Model, discussed by (Wisner et al., 2004), explains how disasters are not just caused by natural events but are shaped by deeper social factors that exists in the society. Instead of viewing disasters as isolated events, the model shows how they are developed over time due to social and economic vulnerabilities. These vulnerabilities are not unforeseen, but a result of historical and structural issues that affect certain groups more than others, due to the social stratifications. According to the PAR Model, disaster happens when two forces meet: the pressure created by long-standing vulnerabilities, such as poverty, inequality, weak governance, or lack of access to resources and on the other side, the pressure due to impact of a natural hazard. The "pressure" part of the model explains how these risks grow gradually through social processes, while the "release" side focuses on how we can reduce them. This includes steps like improving infrastructure to address the immediate unsafe conditions, and also strengthening community preparedness, and addressing the root causes of inequality, that are indirectly impacting the exposure to risk.

4.2.1.1 Analysis of Risk – Pressure Side of the Model

The Pressure side of the model is defined through three interrelated components: Root Causes, Dynamic Pressures, and Unsafe Conditions. Root Causes refer to the deep-seated, systemic issues such as historical inequalities and institutionalized discrimination that distribute resources and opportunities unevenly, as we have discussed with the social stratifications in the earlier sections. These causes are often distant to the vulnerability – spatially and temporally, yet they define the conditions under which vulnerability is inculcated. Dynamic Pressures, in turn, act as a bridge that connects the root causes to localized vulnerabilities, such as lack of local institutions, poor governance and decision making. Finally, Unsafe Conditions represent the most visible manifestations of vulnerability at the ground level such as dangerous settlements, risky livelihoods, inadequate infrastructure, and limited access to services. These three layers of the Pressure side intricately interact to heighten disaster risk, making social vulnerabilities deeply stratified across different groups in society.

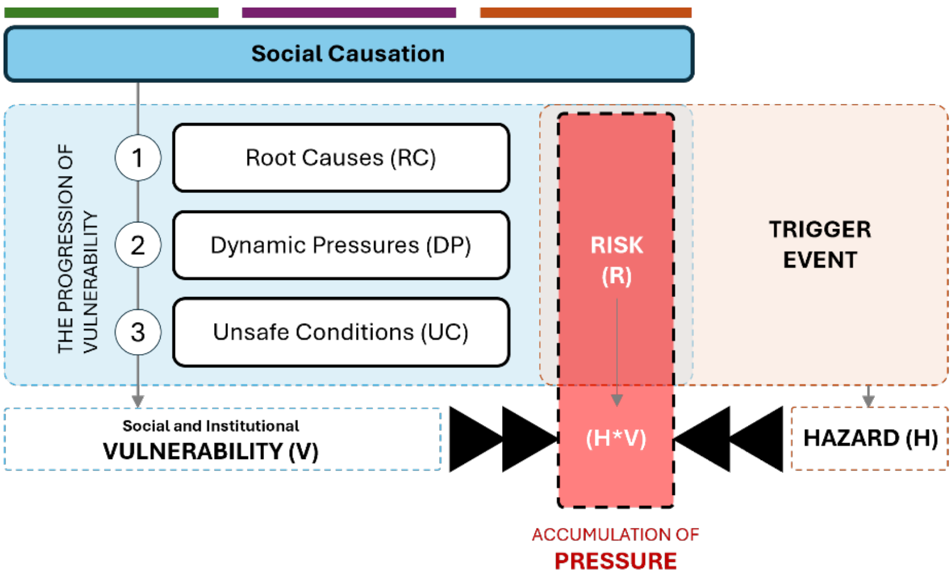

Figure 4-3 Analysis of Risk- Pressure Side. Source: Authors

This layered understanding of vulnerability also directly aligns with the definition of institutional vulnerability, which reflects the extent to which institutions undermine a system's capacity to withstand, cope and recover from natural hazards. Root Causes can thus be seen as reflections of long-standing social inequities, deeply rooted in systemic imbalances. Dynamic Pressures capture the institutional gaps that perpetuate these inequities, highlighting the failures in governance, capacity-building, and timely action. Unsafe Conditions emphasize the localized risks that emerge precisely because of the absence or ineffectiveness of interventions at the ground level. As (Paul, 2011) explains, institutional vulnerability is not about the fragility of institutions themselves, but about the ways they increase societal vulnerability by failing to act effectively. Thereby, the interplay between the three factors — root causes, dynamic pressures, and unsafe conditions, also reveals how deeply institutional vulnerability is embedded within societal structures.

4.2.1.2 Analysis of Risk – Release Side of the Model

On the Release side of the PAR model, the focus shifts towards creating enabling conditions to reverse the build-up of vulnerabilities. From our understandings, it can be noted that recognizing and reducing social and institutional vulnerability through inclusive governance, accountability, and trust-building at the community level is not just necessary — it is foundational for building a resilient society where vulnerabilities are not only addressed but gradually dismantled from their roots. Institutional vulnerability, which arises from the interaction of root causes, dynamic pressures, and unsafe conditions, can be countered through sustained, people-centered efforts.

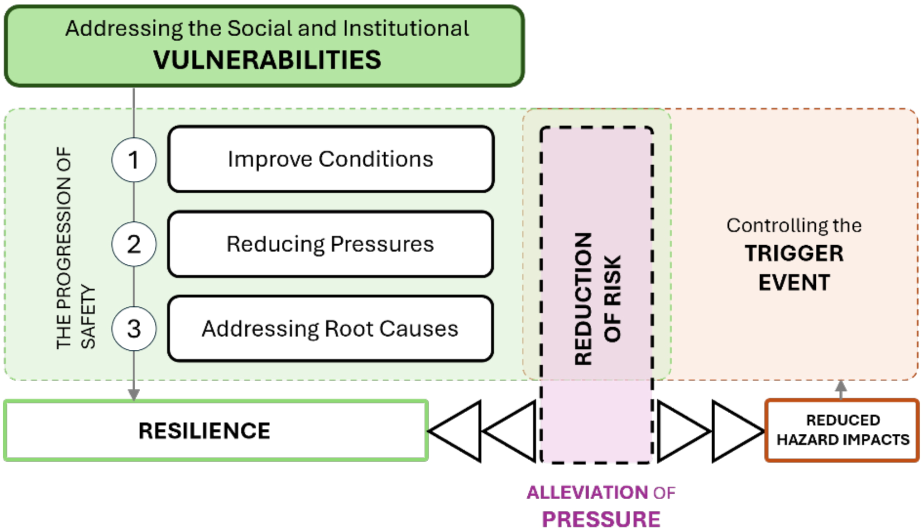

Figure 4-4 Analysis of Risk- Release Side. Source: Authors

While the Pressure side of the PAR Model reflects top-down forces that create vulnerability, the Release side calls for a bottom-up approach. It depicts that the interventions must begin at the local level, addressing the real and immediate risks that people face in their everyday lives. When communities are actively involved in identifying problems and shaping decisions, interventions become more effective and relevant, thereby depicting the potential area where the communities can involve effectively in disaster management. This grassroots participation not only helps reduce immediate dangers but also builds stronger, more responsive institutions, as it supports participation and embraces the diversity in the communities. Over time, such efforts can push back against the deeper social and structural inequalities that lie at the root of vulnerability. In this way, tackling unsafe conditions from the ground up becomes a pathway to long-term, systemic change.

4.2.1.3 Combining the Pressure and Release Sides of the Model

The Pressure and Release sides of the PAR Model together provide a complete picture of how disasters unfold. Vulnerability is something that develops over time through ongoing social, economic, and political processes. This shows that reducing disaster risk is not a one-time action but a continuous process. To truly reduce vulnerability, it must be tackled from both ends of the problem. This involves addressing the deep-rooted causes and the dynamic pressures that weaken communities, while also building up local strengths, safety measures, and support systems. The model shows how these two sides are closely connected.

The diagram (Figure 4-5) illustrates the aforementioned dynamic relationship between vulnerability, risk, and disaster within the framework of the Pressure and Release (PAR) Model. At the core, the neutral zone separating the "Pressure" and "Release" sides is the disaster event itself. The extent and severity of the disaster’s impact are not merely the result of the triggering event but are deeply influenced by the degree to which vulnerabilities have been addressed and resilience has been built over time. Residual risk represents the remaining disaster risk — a gap between the accumulated pressures arising from unresolved social and institutional vulnerabilities, compounded by hazards, and the counteracting force of resilience achieved through targeted interventions. Significantly, the disaster event does not mark the end of this cycle. Instead, each disaster offers critical data that can be analyzed to further reduce future hazard impacts and strengthen systemic responses. Hence, this process forms a continuous system where feedback loops refine preparedness and mitigation strategies. The overall efficiency of this system, however, is heavily dependent on the nature and effectiveness of interventions. Community participation emerges as a cornerstone in this regard, as it enables the incorporation of local knowledge, lived experiences, and context-specific insights into vulnerability reduction measures. It is through such grounded and inclusive interventions that the root causes of vulnerabilities, stemming from broader patterns of social causation, can be most effectively addressed.

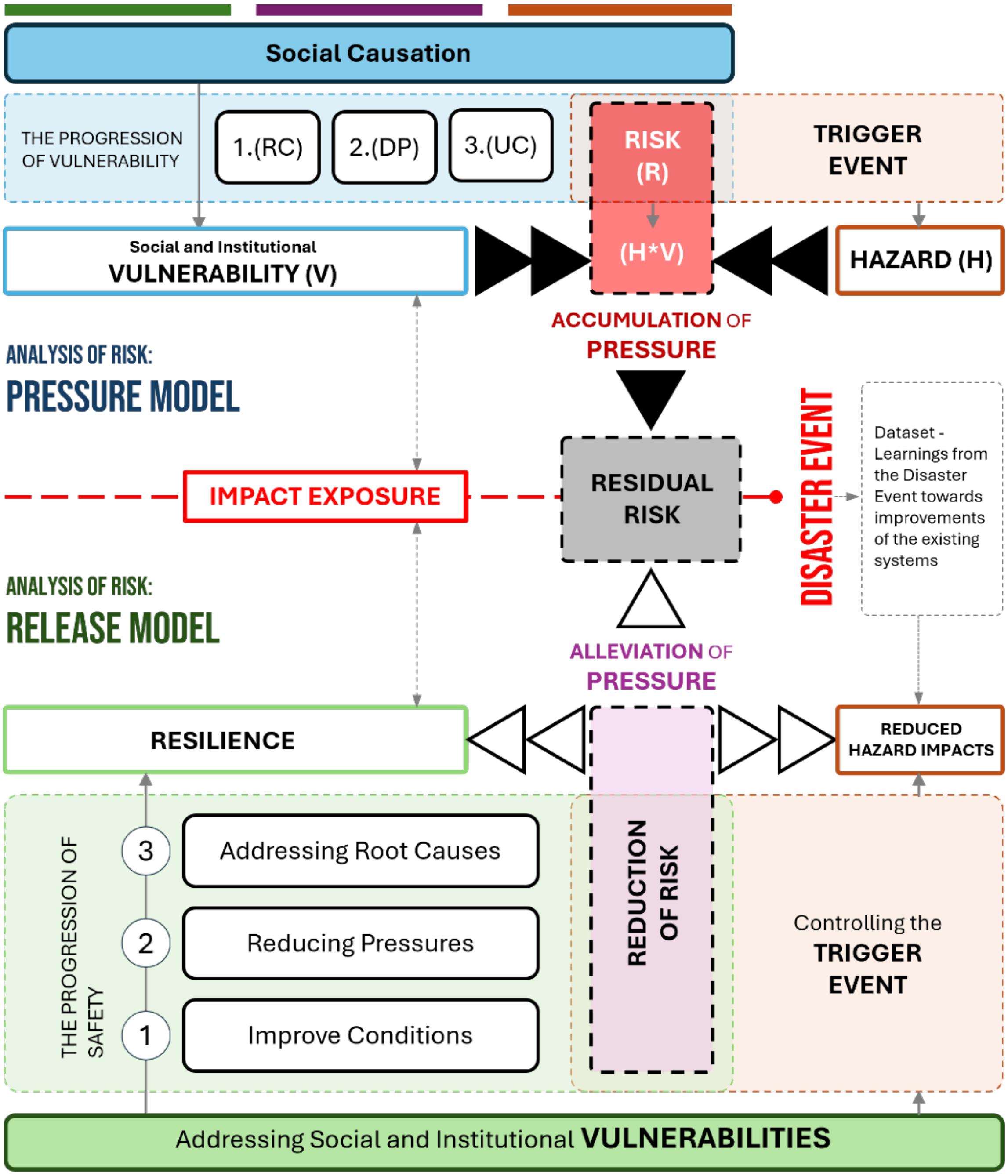

Figure 4-5 Pressure and Release Model- Risk Evaluation. Source: Authors

Therefore, public participation can play a vital role in aiding to transform the deep-rooted social and institutional weaknesses that increase disaster risk. By involving the public in decision making framework, it begins to break down the social and institutional barriers that often leave some groups more vulnerable than others. One key area where participation can be reliable is in building strong Early Warning Systems. The communities can be a part of every step of warning system—starting from identifying hazards, shaping how warnings are designed and shared, and finally in deciding how to respond. As (Papathoma-Köhle et al., 2021) emphasize, institutions play crucial roles throughout all phases of the disaster cycle — mitigation, preparedness, response, and recovery — yet institutional vulnerability is often overlooked. By incorporating public participation within the Warning Systems framework, the institutional vulnerability can be extensively addressed as it brings down the degree of stratifications in the system. Moreover, through meaningful participation, communities can also become active stakeholders rather than passive recipients of information.

To deepen this understanding, it is possible to turn to the case study of the 2024 Wayanad landslide. Through this, we shall explore how social and institutional vulnerabilities, rooted in long-standing social causations, have shaped the experiences of stakeholders across different layers of society. Building on these insights, we will also examine how integrating community voices into institutional frameworks can strengthen resilience and better prepare them for future risks.

4.3 Overview of Wayanad Landslides 2024

Wayanad district in Kerala, is located at the southern tip of the Deccan Plateau and is part of the ecologically rich Western Ghats. Its landscape is mostly made up of elevated plateaus, but it also includes a mix of valleys, ridges, small hills, and mountain peaks. This varied and uneven terrain, especially along the borders which it shares with Malappuram and Kozhikode districts, makes the region highly prone to landslides and other consequent disasters. Landslides have become a recurring hazard in the district, often leading to the loss of lives, destruction of property, and serious damage to agriculture and infrastructure. Studies by the Centre for Earth Science Studies (CESS) have highlighted the Wayanad-Kozhikode border as one of the most landslide-affected zones in the state of Kerala (*Wayanad Preliminary Assessment Report Aug 2024*, n.d.).

On July 30, 2024, Wayanad district in Kerala was struck by a devastating series of landslides, set off by prolonged and heavy rainfall. The disaster began in the early morning hours with a major slope failure near Mundakkai, followed by three more collapses over the next three hours. These incidents took place between 1:30 a.m. and 4:00 a.m., catching many residents off guard as they slept, with heavy debris of boulders, uprooted trees rushing toward Chooralmala. The landslides impact altered the Iruvazhinji River's path, causing severe flooding along its banks that inundated homes, religious buildings, and schools. Satellite evaluations by the National Remote Sensing Centre and Indian Space Research Organization (ISRO) showed the landslide covered about 86,000 square meters, starting at an elevation of 1,550 meters above Mean Sea Level and stretching over eight kilometers. The analysis indicated the reactivation of an ancient landslide zone, with the displaced material significantly widening the Iruvaniphuza River channel, leading to bank erosion and additional structural damage. This event mirrors previous geohazards in the area, particularly the disasters of 2018 and

2019, highlighting the ongoing susceptibility of these regions to landslide disasters. (*Memorandum_Meppadi Landslide*, n.d.)

Figure 4-6 Before and After the Wayanad Landslides 2024. Sources: Planet Labs, Maxar Technologies, Google

In the days leading up to the catastrophic landslide on July 30, 2024, residents of Chooralmala and Meppadi recounted experiencing continuous heavy rainfall on July 27, 28, and 29. Despite the intensifying rains, there were no significant alerts issued by the India Meteorological Department (IMD), nor was there effective communication from higher authorities regarding potential risks of landslides or flooding. Anyhow, the disaster response underscored significant advancements in institutional disaster management frameworks, characterized by the integration of structured governance protocols and community-led initiatives. Following early warnings relayed by local residents, the Meppadi Panchayat administration initiated preemptive evacuation measures, starting with the validation of rainfall data and on-site assessments in Punchirimattam, where initial slope instabilities were observed. The operational strategy adhered to the Orange Book's standardized protocols, integrating vertical command structures—evidenced by the District Panchayat's coordination of Revenue, Police, and Fire and Rescue Services—with horizontal collaborations across Grama Panchayat representatives, ensuring multi-departmental synergy, during the time of the disaster.

4.3.1 Stakeholders Interviews and Data Synthesis

As part of the Wayanad Landslide 2024 case study, informal and non-structured interviews were conducted with 25 disaster-affected individuals in the region. Participants were randomly selected from three of the worst-hit wards of the disaster affected region of the district, ensuring representation across different social and occupational groups.

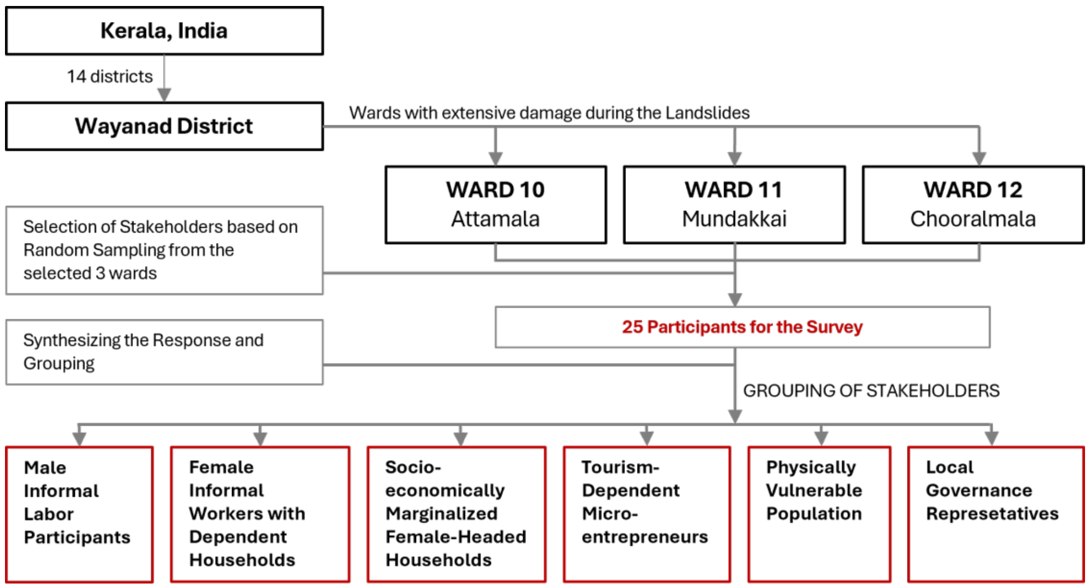

Figure 4-7 Survey Design

The interviews explored personal experiences before, during, and after the landslides. These informal conversations depicted how social stratification influenced both vulnerability of the people and the recovery phase after the disaster. Based on the people with whom the interviews were conducted, they could be categorized into broadly 6 groups. Male informal laborers, primarily daily wage workers, who described sudden income loss that destabilized their households and their own lives. Female informal workers with caregiving responsibilities shared how the disaster intensified their dual burdens, often without any other help. Marginalized female-headed households explained how exclusion from formal aid mechanisms and societal norms left them further behind. Tourism-dependent microentrepreneurs and small business owners reported major livelihood disruptions due to the halt in tourist activity in the region. Physically vulnerable individuals accounted for the difficulties of evacuation and recovery, complicated by health or mobility issues. Local elected representatives, such as ward members and the panchayat president, acknowledged institutional constraints and coordination challenges that limited the effectiveness of the official response, during the time of disaster and in the recovery stage. Collectively, these narratives show how social positioning shaped each group's experience of the disaster and its aftermath. Table 4-1 consolidates these responses and categorizes them under the components of PAR model, to derive a Vulnerability Matrix.

The vulnerabilities observed among the Male Informal Labor Participants, Tourism-Dependent Microentrepreneurs, Female Informal Workers with Dependent Households, Socioeconomically Marginalized Female-Headed Households, and Physically Vulnerable Populations can be categorized under Social Vulnerabilities. These challenges arise from a mix of unstable jobs, financial insecurity, caregiving burdens, social discrimination, and poor access to essential services. These issues do not exist in isolation but are interconnected, reflecting deeper structural inequalities and daily struggles that increase the disaster risk. To effectively tackle them, a reactive response is not enough, but it calls for sustained, people-focused planning that looks beyond immediate relief.

Table 4-1 The Vulnerability Matrix. Source: Authors

VULNERABILITY MATRIX		Categorization of Respondents	Root Causes	Dynamic Pressures	Unsafe Conditions
SOCIAL VULNERABILITES	Socio-economic Vulnerable Categories	Male Informal Labor Participants	• Lack of stable jobs • Economic inequality	• Daily wage reliance • No social safety nets	• Hazardous work • Income loss after disasters
		Female Informal Workers with Dependent Households	• Gender disparity • Limited asset control	• Limited crisis mobility • Caregiving burdens	• Lack of job opportunities post disaster
		Socioeconomically Marginalized Female-Headed Households	• Loss of partner – Social stigma • Financial instability	• Lack of kinship networks for mutual aid	• Lack of job opportunities post disaster
		Tourism-Dependent Microentrepreneurs	• Dependence of limited seasonal tourism	• Capital Intensive • Debt Exposure	• Asset loss • Market crash
	Special Vulnerable Category	Physically Vulnerable Population	• Inadequate support for healthcare	• Social stigma • Limited involvement in community	• Evacuation and aid challenges
INSTITUTIONAL VULNERABILITIES	Administrative Stakeholders	Local Governance Representatives	• Top-Down decision making • Limited input taken from grassroot level	• Slow bureaucratic process • Limited resources	• Conflict between departments of Governments • Lack of Communication at different tiers.

As inferred from the PAR Model and its Risk Evaluation, a bottom-up strategy that strengthens people's participation in decision-making can systematically tackle the unsafe conditions, dynamic pressures, and root causes that lead to vulnerability. Similarly, incorporating these vulnerable groups into the decision-making process shall aid in both long term and short-term interventions that shall improve their effectiveness. Addressing the unsafe conditions of these groups with inputs from these communities shall aid in focused allocation of resources, which can be an effective short-term intervention, whereas a well-defined system with such inputs being considered for decision making shall bring positive changes in long term, that can address the root causes, that are caused by the social stratifications in society.

In contrast, the vulnerabilities identified by the Local Governance Representatives reveal a distinct but equally critical dimension: Institutional Vulnerability, which is unwantedly emphasized by the rigid hierarchical decision-making, bureaucratic lethargy and resource limitations. As mentioned earlier, (Papathoma-Köhle et al., 2021) highlights that institutions play a decisive role across all phases of the disaster cycle—mitigation, preparedness, response, and rehabilitation, yet institutional vulnerability remains least discussed in most of the cases, which is a major reason to which the dynamic pressures are accumulated as per the PAR model. With the high chances of institutional failures during disaster events, these vulnerabilities must be addressed as a matter of urgent response and policy action. Thereby it makes it a need to have targeted interventions to reduce unsafe conditions, particularly by minimizing administrative frictions that delay or distort relief efforts. Political leaderships can be given mandated to focus on restructuring flexible hierarchical governance in ways that allow grassroots inputs to meaningfully influence decision-making and also to have a committed effort to involve communities throughout the disaster phases is essential—not merely as beneficiaries but as co-governors.

4.4 Discussions

The Pressure and Release (PAR) model has been instrumental in showing how disaster vulnerability grows from root causes, dynamic pressures, and unsafe living conditions. As this study progressed, it became increasingly clear that involving communities meaningfully is not just good practice, but a necessity. Survey responses gathered from various vulnerable groups also show the different concerns and how focused interventions could be the way forward. The findings points to one key lesson- building resilience requires tackling two sides - reducing social vulnerability from the ground level while improving institutions through reforms that make community participation central to governance. Interventions must prioritize reducing unsafe conditions by minimizing administrative frictions and delays that compromise effective response.

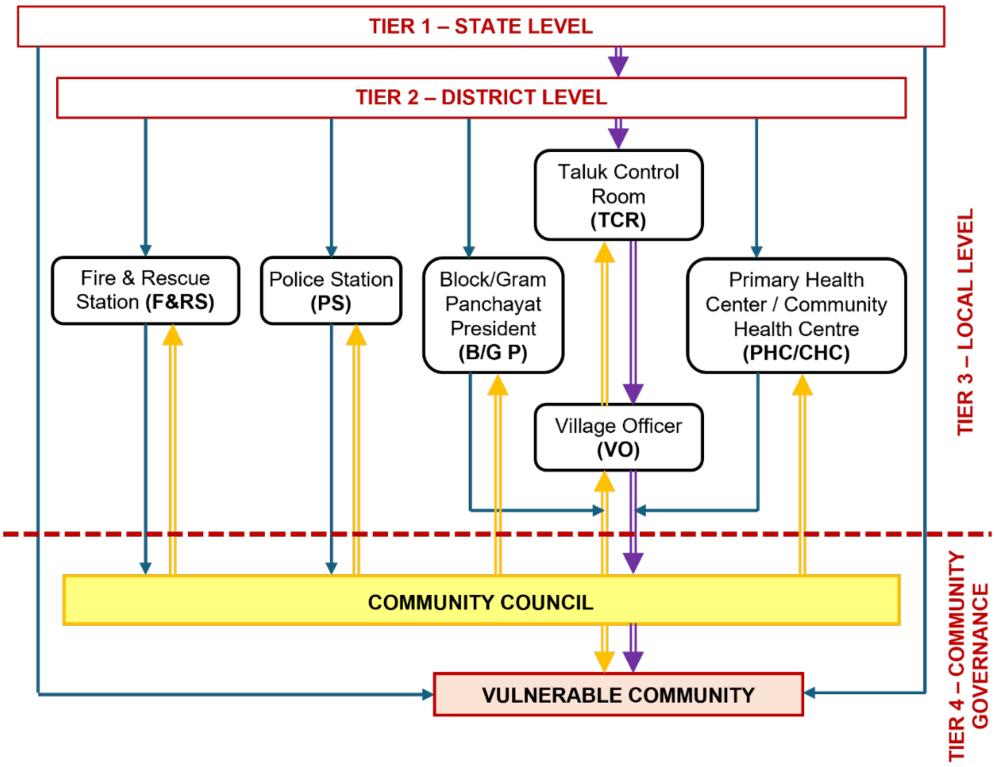

Figure 4-8 Re-assessing the Disaster Warning System. Source: Authors

In this context, involving communities in early warning systems is not just helpful, it becomes a necessity. It helps to fix many of the gaps as we have discussed initially in the centralized systems, where lack of reach to diverse communities across the state often reduces the effectiveness of alerts. When local networks are part of the warning process, alerts become more accurate, better timed and contextualized, and more likely to be trusted by those at risk. Local knowledge helps shape messages that make sense to the people receiving them, while strong community ties ensure that information travels quickly and action is taken. These social connections turn early warnings from distant, technical messages into meaningful, shared responses — making the system stronger, faster, and more reliable when it matters most.

Henceforth, the establishment of a fourth tier of community governance within the disaster response system presents a promising, actionable pathway forward (Figure 4-8). Communities, empowered as active participants in mitigation, preparedness, response, and rehabilitation, would be positioned to transform vulnerabilities into capacities. Critically, through this fourth tier, safer conditions can be progressively achieved, as communities possess the most intimate knowledge of ground-level realities and needs, which can be shared with the formal nodal departments. Their involvement would ensure that risk reduction measures are not only appropriate but also sustainable. Over time, as community governance becomes institutionalized within disaster management frameworks, dynamic pressures, such as lack of mobility, absence of social safety nets, and financial precarity would begin to ease. Eventually, in the long term, it can be expected that the root causes of vulnerability, including systemic inequalities and governance gaps could be addressed. This would not only enhance the overall efficiency of early warning systems but also build a deeply rooted, community-driven resilience that withstands future hazards and reduces the residual risks.

4.4.1 Theoretical Implications

The conceptualization of a fourth tier of community governance, such as the proposed Community Council, offers significant theoretical contributions to the understanding of participatory disaster management and local governance reform. Its emergence challenges the traditional top-down models by placing organized community leadership at the center of disaster resilience efforts. This fourth tier serves not only as an extension of governance but as a corrective mechanism to bridge the often cited disconnect between institutional structures and grassroots realities.

Theoretically, the concept of a fourth tier (Figure 4-8) in governance plays a crucial role in addressing institutional gaps. As discussed earlier, challenges like delayed responses, potential lack of inter-department coordination during disasters, and lack of local involvement often make disaster impacts worse. By incorporating structured community input across all phases, starting from early warnings to post-disaster recovery stage, it can help overcome these limitations that exist. Functioning as a support system to the existing framework, this fourth tier can provide timely and accurate local data to administrative bodies, cutting down on confusion and helping authorities respond more effectively during crises, to the diverse communities that reside across the state.

4.5 Conclusions

This study explored how disaster management is currently practiced in Kerala, with a particular focus on how the role of communities can be enhanced for improved resilience and early warning systems. While Kerala has advanced considerably in using technology and data to issue early warnings and for the efficient functioning of the institutions, a major shortcoming still exists- the lack of real community involvement in any stage of decision making or phases of disaster. Also, the existing systems primarily operate from the top down, because of which they often miss locally observed warning signs and have little provisions in place to build trust or participation at the community level.

Using the Pressure and Release (PAR) Model as a guiding framework, the study examined how disaster risks are shaped by overlapping social and institutional vulnerabilities. Factors such as economic instability, gendered roles, and social marginalization, along with institutional vulnerabilities were found to intensify exposure to hazards. Interviews with individuals impacted by the 2024 Wayanad landslide echoed these patterns. Their accounts repeatedly pointed to a lack of meaningful community involvement, a gap that continues to weaken both disaster preparedness and response efforts across the region, as initially identified after the synthesis of institutional framework that exists in the state.

In this context, the establishment of a fourth tier of community governance becomes a necessary step forward. Integrating community leaders directly into disaster management frameworks at the grassroot levels are expected to close critical gaps, particularly in the warning systems. This approach ensures that decisions reflect the ground realities and are inclusive, timely and contextualized. When this local knowledge is acknowledged in governance processes, it is expected to bring a deeper understanding of on-the-ground changes, enabling quicker and more context-specific responses during emergencies.

Ultimately, by embedding communities within all phases of disaster management as a much-scrutinized long term process, the fourth tier is expected to help in addressing root causes, reducing dynamic pressures, and creating safer conditions. It shall strengthen institutional systems from within, fostering a governance model that is resilient, inclusive, and responsive to the lived realities of its most vulnerable populations.

4.5.1 Limitation and Way Forward

A key limitation of this study lies in the limited discussion on fiscal arrangements and resource allocation for the proposed fourth tier of community governance. Although the importance of community involvement is strongly justified and emphasized, with the support of the PAR model and the interviews conducted, the research does not delve into how funds, staffing, or institutional support would be allocated to make this tier functional and incorporated into the already functioning framework of the State. For the fourth tier to be effective across all the phases of disaster, it requires a clearly defined framework that addresses budgeting, governance roles, and procedural clarity. Future studies should focus on developing these aspects to enhance the model's feasibility and long-term relevance.

05

Cultural and Community Dimension of Early Warning System

Chapter 5: Cultural and Community Dimension of EWS

5.1 Introduction

Early Warning Systems (EWS) are now a vital part of disaster risk reduction efforts around the world. Driven by international initiatives like the Hyogo Framework for Action (UNISDR, 2005) and the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015), there have been major advances in hazard monitoring, data systems, and communication technologies (Zia & Wagner, 2015). Yet, global experience shows that even the most technically sound systems do not always prevent loss of life or damage to livelihoods. In many cases, warnings are issued promptly, but people still fail to act. This persistent gap between warning and response highlights the need to examine more closely the factors that influence how warnings are received, understood, and acted upon.

This chapter focuses on one often neglected dimension of that gap: the role of culture, memory, and community in shaping risk response. It argues that early warning is not merely a technical exercise in hazard detection and message dissemination, but a social process that unfolds within particular histories, relationships, and everyday routines. People's decisions to evacuate or stay, to believe or doubt, are shaped as much by trust, lived experience, and social networks as they are by the accuracy of alerts.

To explore this further, the chapter draws on a qualitative case study of the 2024 landslide in Wayanad district, Kerala, India. Though specific to one location, the case reflects a broader challenge relevant across many geographies: how culturally embedded understandings of risk, place, and safety shape the effectiveness of formal early warning systems. Despite rainfall alerts and local efforts, the Wayanad event led to severe casualties and widespread displacement, raising questions not just about technical failure but about disconnects between systems and social life.

The aim of this chapter is not to criticise early warning systems for what they are, but to explore how they can be made more effective, especially in rural, high-risk, and marginalised areas. It proposes that EWS must move beyond the "last mile" logic of reaching people, and begin instead with how people live, perceive risk, and relate to institutions. In doing so, the chapter contributes to a broader discussion in this report: how to make early warning more local, more trusted, and more effective, by embedding it in the everyday cultures and communities it seeks to protect.

5.2 Understanding Early Warning as a Social Process

Early warning is often imagined as a linear sequence: detect the hazard, issue the alert, and expect a timely response. But in practice, this chain is rarely straightforward. People's decisions to act—or not—depend not only on the content of the message, but on how it is received, interpreted, and weighed against everyday realities. Warning is not just about *when* people are informed, but *how* they come to believe that the message is real, urgent, and relevant to them (Tierney, 2019; Kelman & Glantz, 2014).

In many disaster-prone settings, especially in rural or socially embedded communities, risk is not experienced through abstract probabilities. It is understood through local signals, community memory, trust in familiar figures, and collective norms of behaviour. As Bankoff (2003) notes, what is perceived as dangerous in one context may be seen as ordinary in another, depending on lived experience and cultural framing. This makes it clear that early warning is not only a technical or logistical task, but a social process, negotiated within particular geographies, histories, and relationships (Hamza & Månsson, 2020; Hermans et al., 2022).

This chapter draws on four interrelated concepts to guide its analysis: *relational risk calculus*, *culturally embedded risk rationality*, *place-based attunement*, and *social trust and communication*[4].

- Relational risk calculus: People's judgments about danger are shaped not just by what they are told, but by how warnings fit into their social and emotional obligations—such as caring for children, protecting assets, or preserving dignity in the face of uncertainty. These decisions often reflect a deeply situated logic, not a lack of awareness.
- Culturally embedded risk rationality: How communities evaluate threats depends on what they've seen before, how they remember previous events, and what explanations circulate within local narratives. Warnings that fail to align with this embedded rationality may be dismissed, downplayed, or folded into routine behaviour.
- Place-based attunement: In many regions, people develop intuitive awareness of environmental shifts, observing patterns in rain, wind, animal behaviour, or soil movement. This embodied knowledge forms a kind of informal, continuous monitoring system that is not officially recognised but remains highly trusted.

---

[4] *While these specific terms—such as relational risk calculus, culturally embedded risk rationality, and place-based attunement—are not directly used in the literature (i.e., Hamza & Månsson, 2020; Hermans et al., 2022; Kelman & Glantz, 2014), they emerged through the analysis of field interviews and contextual readings of the Wayanad case. They are used here to frame community-level decision-making and risk interpretation in ways that build on, and remain grounded in, prior scholarship.*

- Social trust and communication: Whether a warning is acted upon depends heavily on who delivers it and how it is conveyed. Studies show that locally embedded figures[5]—such as teachers, ward members[6], or religious leaders, often hold more sway than formal institutional channels (Kelman & Glantz, 2014; Hermans et al., 2022).

Recognising early warning as a social process does not diminish the value of technology. Rather, it highlights the need for design approaches that are not only technically sound but culturally legible and socially anchored. When systems fail to engage with how people actually interpret and respond to risk, their warnings, however accurate, may be met with hesitation or silence.

5.3 Case Study: The 2024 Wayanad Landslide

In the early hours of July 30, 2024, a severe landslide struck Meppadi Panchayat in Wayanad district, Kerala, India. Triggered by prolonged heavy rainfall, the landslide engulfed three wards—Mundakkai, Attamala, and Chooralmala[7]—burying homes, schools, and shops under debris. The scale of destruction was extraordinary: over 400 people lost their lives, more than 150 were missing, and entire communities were displaced (Das, 2024; Gopinath et al., 2024)[8]. Despite rainfall alerts being issued in the preceding days, many residents insist they received no actionable warning. This disjuncture between the issuance of alerts and community response highlights critical limitations in the design and delivery of existing early warning systems.

The terrain of the affected region is complex—marked by steep slopes, dense forest, and tea plantations. These geographical conditions, combined with historical patterns of settlement, contributed both to the vulnerability of the area and to the social cohesion of its population. Many families living in these wards are descendants of plantation workers

---

[5] *Embedded figures refer to individuals or actors who are organically situated within the everyday life of a community, such as teachers, ward members, or local volunteers. Their trustworthiness stems not from formal authority but from their continuous presence, social familiarity, and relational ties within the community, making them crucial conduits for early warning communication and local mobilisation.*

[6] *In India's Panchayati raj system, a ward member (also known as a ward councillor) is an elected representative responsible for a designated electoral division (ward) within a panchayat. A panchayat is the lowest tier of rural self-governance, responsible for planning, service delivery, and local decision-making at the village or cluster level. Ward members serve as the primary link between local residents and the governance system, playing key roles in public service delivery, local dispute resolution, and disaster communication.*

[7] *Mundakkai, Attamala, and Chooralmala are administrative wards under Meppadi Panchayat in Wayanad district, Kerala*

[8] *Das (2024) presents a detailed table documenting the casualties and infrastructure damages caused by the Wayanad landslide. Both Das and Gopinath et al. (2024) also provide comprehensive background on the geological and environmental factors contributing to the disaster, including rainfall intensity, slope vulnerability, and land-use conditions. These sources are recommended for readers seeking further technical detail.*

brought to the region during the colonial period. They reside in quarters known as *paadis*, and their shared history of labour and marginalisation has fostered a close-knit community with strong internal bonds[9].

This background is vital for understanding how risk was perceived in the days leading up to the landslide. While rainfall was heavy, residents reported that it was not unusual for the season. There were no visible signs—like ground fissures or overflowing rivers—that typically signalled danger. In the absence of such cues, and with no clear or urgent communication from authorities, many residents felt little reason to evacuate. As one resident noted,

"*We didn't think this rain was anything different. The river was calm. No one came to tell us to leave.*"

On the institutional side, panchayat leaders did raise concerns with the district administration. Yet, no red alert had been issued in the locality at the time of the disaster. This reflects a broader challenge in early warning governance: the gap between local observation and formal decision-making, and the limited authority of grassroots leaders to escalate alerts. One ward representative recounted,

"*We went around telling people to be careful, but we had no official power to make them leave. And they didn't believe it was that serious.*"

This case study is informed by a phased field inquiry conducted between February and April 2025. In the initial phase, our team attempted to understand the community crisis first-hand. While we were not granted permission to enter the epicentre of the landslide, conversations with locals helped us identify an alternate route to assess the physical impact of the disaster. Based on that assessment, four members of the research team revisited the area to engage with panchayat leaders and school staff. Although this round of fieldwork did not include residents directly affected by the event, it offered critical insight into the role of local institutions. A subsequent visit in April, facilitated by a local auto driver, enabled follow-up interviews with survivors and families directly impacted by the landslide. These conversations helped deepen our understanding of how the warning was experienced—or, in many cases, not experienced—by the affected population.

The Wayanad case illustrates how warnings can fail—not because they were absent, but because they were not embedded in the community's interpretive framework. Where formal systems prioritised rainfall thresholds and administrative protocols, local

[9] *Paadis are long rows of modest, barrack-style housing originally built to accommodate plantation labourers in tea and cardamom estates across Kerala's highlands. These structures continue to shape patterns of settlement and community interaction in plantation regions like Wayanad. For a representative image, see: https://www.alamy.com/stock-photo-tea-plantation-workers-housing-on-hillside-munnar-western-ghats-kerala-47793719.html*

residents relied on familiarity, informal knowledge, and relational trust to assess risk. In such a setting, warnings delivered through SMS or TV broadcasts lacked the immediacy and credibility required to prompt evacuation.

This event, while devastating, offers critical insight into the social life of early warning. It underscores the importance of understanding how communities interpret threats, who they trust, and what local indicators trigger action. These lessons are not unique to Wayanad. Across rural and hazard-prone areas in India and beyond, similar patterns of disconnect between systems and society continue to emerge. This highlights the need for early warning systems to be grounded in the lived experiences and everyday practices of the communities they serve.

5.4 Community, Culture, and Risk Perception

In Wayanad, as in many rural and disaster-prone regions, risk is not interpreted through technical alerts alone. It is shaped by habit, history, and sensory familiarity with the environment. Most residents said that the rainfall before the landslide, although heavy, did not seem unusual to them. Without visual cues like flooding or landslide cracks, the event did not feel threatening.

"Heavy rains and small landslides in the forest—that's not new for us. The mud would just flow through the river, and by next day, everything would be back to normal. We never thought it would be something this serious," explained a long-time resident from one of the affected wards.

This everyday relationship with rain is central to understanding why formal alerts did not translate into action. A schoolteacher with deep ties to the area shared,

"As teachers here, we could look at the sky and predict the strength of the rain. When the clouds turned darker, we'd close the school early, making sure the students reached home safely before the downpour hit."

Despite being familiar with the rhythm of monsoons, there was no intuitive recognition that this particular episode posed catastrophic danger.

Many residents, even those who lost family, echoed a sense of disbelief at what unfolded. One old man who survived the disaster told us,

"I lost seven people from my family... I used to bring them to my house whenever it rained heavily. This time also, I begged them to come. But they said, 'It's okay here, nothing will happen.' And then... this happened. Nobody warned us. Nobody told us anything."

This quote reflects the depth of attachment to both place and routine, and how, in the absence of urgent, believable signals, people chose to stay.

The notion of warning itself—what counts as one, and whether it should be trusted, was also contested. One resident recounted,

"It just felt like any other rain, and nobody came to say we should leave."

Others noted that when warnings were given, they lacked institutional authority. A local elected representative explained,

"We tried warning people to stay alert, but without an official notice, no one really paid attention. For them, we're just neighbours, not experts."

These accounts reveal the gap between institutional systems of risk and community logics of response. People listened, but they didn't believe. They saw water, but no warning. In this setting, risk was interpreted not through meteorological reports but through a lens of shared memory, embodied knowledge, and relational trust. When they came, the warnings were simply out of sync with how people recognised threats in their daily lives. These layered interpretations of risk—shaped by routine, memory, trust, and local cues—point to a more grounded understanding of how warnings are processed in everyday life. A summary of key insights drawn from the Wayanad case is presented in Table 5-1 below.

Table 5-1 Community Interpretations of Risk During the 2024 Wayanad Landslide. Source: Authors

Theme	***Insight***	***Supporting Quote***
Familiarity with Risk	*Seasonal rainfall and minor landslides were seen as normal, making the threat feel routine.*	*"Heavy rains and small landslides in the forest—that's not new for us."*
Intuitive Weather Interpretation	*Local teachers and elders often relied on embodied knowledge to gauge rainfall, which failed to signal danger in this case.*	*"We could look at the sky and predict the strength of the rain. But nobody could sense what was coming."*
Disbelief in Absence of Visible Cues	*Without cracks or rising rivers, many did not perceive risk—even when rainfall alerts were issued.*	*"We didn't think this rain was anything different. The river was calm. No one came to tell us to leave."*
Emotional and Relational Decision-Making	*Family ties and shared histories influenced decisions to stay, despite danger.*	*"I lost seven people from my family. I begged them to come. They wouldn't listen."*

Trust Gap in Informal Warnings	*Warnings issued by local leaders were often dismissed without institutional backing.*	*"Without any official alert, they didn't take it seriously. For them, we're just neighbours, not experts."*

5.5 Institutions, Trust, and the Role of Local Governance

Trust plays a pivotal role in how communities respond to early warnings. In Wayanad, although formal alerts were limited, many local figures, such as ward members and school staff, made informal efforts to warn residents. However, these efforts were often not taken seriously. This was not because of disinterest, but due to a deeper issue: the lack of institutional power and formal recognition of local actors in the early warning process.

Several ward members reported that they issued informal warnings and visited households to urge caution. As previously noted, one elected representative shared:

"*We went around telling people to be careful, but we had no official power to make them leave. And they didn't believe it was that serious.*"

"There was no red alert declared at that time. It was the panchayat that took the initiative—we took our own vehicle and went around, talking to people, asking them to move to safety. But some of them went back home at night without informing anyone. They were lost."

This reflects a recurring theme: local credibility without institutional legitimacy. Community leaders are often the first to notice early signs of danger, but without official alerts backing them, their warnings carry limited weight. Residents distinguish between warnings rooted in government channels and those that come from familiar, but unofficial voices.

Teachers, too, were closely involved in the post-disaster response and are deeply embedded in the social fabric of the area. A long-serving teacher reflected on the evolution of the settlement:

"The school played a big role in developing this whole area… We were so proud when our school was upgraded to a higher secondary. Now, our children could complete all 12 years of schooling right here, close to home."

"It was more than just a place of learning — especially for girl children. Most parents worked in the plantations. They would send their kids to school, knowing they were safe here. That trust — that's something very deep."

The relationship between schools, local governance, and early warning is worth noting. While not designed as risk institutions, schools often serve as physical and symbolic hubs of trust and coordination. Similarly, religious institutions—such as the local mosque and church—also played a role in the response. As one community member recalled:

"*This masjid (masque) was where we coordinated the rescue operations. Because it was not affected by the landslide, food and other required things were arranged here immediately.*"

These examples suggest that places of everyday gathering and moral authority, such as schools, religious institutions and local youth clubs[10] can act as informal anchors of resilience. However, their potential is often untapped in formal warning systems. The experience in Wayanad shows that embedding early warning in local institutions and leadership—and recognising their authority—can make warnings more believable and actionable.

5.6 Community Infrastructure and Embedded Resilience

In the aftermath of the landslide, the initial response did not come from formal emergency agencies—it came from the community itself. Schools, places of worship, and local clubs emerged as first-line spaces of rescue, relief, and coordination. These institutions were not designed for disaster response, but they were already embedded in everyday life. When people needed help, they turned to places they knew and trusted.

A ward member described how the relocation effort began even before official rescue arrived:

"*We shifted people to the nearby schools, masjid (mosque), and church. It was faster. Everyone knows these places.*"

These actions were not based on a protocol. Instead, they were based on social familiarity. In the absence of a command structure, local moral infrastructure filled the void. One resident recalled how the masjid became the centre of collective mobilisation:

"*There was no vehicle or ambulance at that time. We carried people on our shoulders. Food and drinking water were arranged from the masjid and church.*"

[10] *Local youth clubs refer to community-based associations formed around shared interests such as sports, arts, culture, or social service led by young individuals. In rural India, these clubs often serve as informal institutions that facilitate community engagement, organize events, and disseminate information, playing a pivotal role in grassroots mobilization and local governance support.*

These institutions, while informal in the eyes of the state, were functionally central in the early hours. Local clubs helped coordinate transport and supply distribution, even guiding rescue teams to places where bodies were likely to be buried. A young volunteer shared:

"*Our club members went into the paadis and houses. We knew who lived where. We showed the army where to dig. Otherwise, they would not know.*"

These moments reveal that community infrastructure is not just spatial, but it is relational. Schools, mosques, and local clubs hold historical meaning and emotional weight. They are places of collective memory and coordination, especially in contexts shaped by marginality and labour migration.

Despite their role, such institutions are rarely recognised in official EWS frameworks. They are not consulted in warning design or included in training. Yet, as Wayanad shows, they are among the first to activate when alerts fail or when response systems are delayed.

Planning for resilience in such settings requires a different lens. Rather than building new institutions, systems should strengthen those that already function in moments of distress. This includes not only technical capacity, but affirming the legitimacy of these spaces and the people who mobilise through them. The Wayanad case shows that resilience does not always come from new infrastructure, it often comes from recognising the social systems already in place. See Table 5-2 for a summary of how embedded institutions shaped the early response.

Table 5-2 Roles of Embedded Community Institutions in Early Response. Source: Authors

Local Institution	***Role in Disaster Response***	***Supporting Quote***
School	*Served as immediate shelter and coordination point, relocated residents quickly.*	*"We shifted people to the school nearby and to the masjid. It was faster. Everyone knows these places."*
Religious Places	*Provided food, water, and staging ground for volunteers and transport.*	*"Food and drinking water were arranged from the masjid and school."*
Local Clubs	*Guided search teams, mapped households, and coordinated supply lines.*	*"We showed the army where to dig. Otherwise, they would not know."*
Embedded Social Networks	*Familiarity, memory, and moral authority made them effective faster than formal systems.*	*Institutions activated not because they were assigned, but because they were trusted and reachable.*

5.7 Rethinking Participation – From Last Mile to Embedded System

Early warning systems have long adopted the language of the "last mile", emphasising the challenge of reaching people in remote, rural, or marginalised areas. But the Wayanad experience reveals that proximity alone does not guarantee effectiveness. Messages may reach a location, but fail to resonate. Warnings may be heard, but not believed. The last mile is not only a physical distance, it is a social and epistemic one[11].

In the days before the landslide, residents received weather-related updates. Some recalled seeing alerts on mobile phones or hearing informal cautions. Yet, these warnings failed to generate widespread mobilisation. One interviewee reflected:

"*People didn't ignore the warning because they didn't care. They just didn't think it applied to them. We get so many alerts now—it's hard to know what's real.*"

"Yes, we were warned before the landslide—but it wasn't really a strict warning. They just asked us to be cautious. The fire force people came to Mundakkai and told us to consider relocating for safety. But it didn't feel serious," reported a resident survivor.

This gap points to a deeper design flaw. Participation is often treated as outreach, consultation meetings, awareness campaigns, or translation of messages into local languages. While important, these measures do not necessarily embed the system within community life. In contrast, what Wayanad showed was that participation happens organically when trusted institutions and individuals are recognised as part of the warning process.

Teachers, ward members, religious leaders, and even auto drivers became key actors—not because they were trained by the state, but because they were trusted and visible. One resident told us:

"*The auto driver knew everyone. He was the one who told us who was safe, who was missing. No official came in those first hours.*"

To move beyond the "last mile" paradigm, early warning systems must be reframed as embedded systems[12]—designed from within communities rather than simply reaching down to them. This means rethinking participation not as dissemination, but as co-production[13]:

[11] *Epistemic distance refers to the gap between how formal systems define and communicate risk, and how communities interpret that risk based on lived experience, trust, and cultural knowledge.*
[12] *Embedded systems are EWS designed not as external layers but as systems co-located within everyday institutions—schools, panchayats, mosques—already embedded in local life and trust networks.*
[13] *Co-production involves collaborative design, where knowledge and authority are shared between formal systems and community actors during all stages of risk communication and response planning.*

- Involving local actors in the design and interpretation of warnings;
- Recognising schools, religious institutions, and clubs as infrastructural assets;
- Enabling trusted figures[14] to trigger warnings, not just pass them along.

Such an approach also requires institutional shifts. Formal systems must become more porous—allowing community knowledge, local sensing, and relational trust to shape when and how warnings are issued and acted upon. This is not a rejection of science or technology; rather, it is a call to make them understandable, responsive, and relevant within the communities they are intended to serve.

The contrast between formal outreach and lived community response in Wayanad highlights the need to move from linear delivery models to embedded, participatory systems. Table 5-3 summarises this shift by comparing conventional "last mile" approaches with more grounded, co-produced early warning models.

Table 5-3 Comparison of Early Warning Models: From Last Mile to Embedded Systems. Source: Authors

Model	***Key Characteristics***	***Limitations***	***What Wayanad Suggests***
Last Mile Approach	*Top-down alerts, centralised communication, and focus on outreach*	*Assumes message reception equals belief or action*	*Messages reached people but failed to trigger mobilisation*
Embedded System	*Community-led design, local institutions involved, trust-based logic*	*Requires institutional openness to informal knowledge*	*Trusted actors acted early but lacked formal authority*
Co-production Model	*Joint framing, warning design include local interpretation*	*Demands structural shifts in governance and protocol*	*Effective warnings must be both heard and socially anchored*

5.8 Schools as Anchors of Early Warning

Among the many institutions that played a role during the Wayanad landslide response, schools stood out not only as physical shelters but as trusted spaces of coordination, emotional safety, and community memory. Their centrality in this context was not incidental. In rural Kerala, particularly in areas shaped by histories of plantation labour and marginalisation, schools are among the few institutions that consistently serve all sections of the population, regardless of age, gender, or economic status.

[14] *Trusted figures, also referred to as embedded figures (see Footnote 2), are individuals within a community who, due to their consistent presence, social relationships, and cultural alignment, are regarded as credible sources of information and guidance.*

Schools offer more than education. They are sites of civic life. They are familiar, morally significant, and physically accessible. This familiarity was particularly important for women and children. As one resident put it,

"*This school is where our children learned, where we had our meetings, and where we slept during floods. It's where we go when we don't know where else to go.*"

A long-serving teacher at the school reflected on the trust parents placed in them:

"Most of the parents worked in the plantations, and while they were away all day, they didn't want their children to be alone in the paadi. So, they would send them to school, knowing they were safe here. After finishing work, they would come and pick them up. That trust of leaving your child in someone's care while you work all day, that's something very deep."

Despite this trust and embeddedness, schools remain largely peripheral in formal early warning planning. Teachers are seldom trained in risk communication, and schools are not routinely included in preparedness drills, hazard mapping, or early alert dissemination. This gap is not unique to Wayanad. Globally, despite increasing recognition of education's role in disaster resilience, integration into EWS frameworks remains weak (Shaw et al., 2011).

Recent scholarship from Japan and Nepal also supports the value of embedding disaster education in local institutions. For instance, after the 2021 Atami landslide in Japan, schools and teachers played key roles in disseminating alerts and supporting elderly residents, even in the absence of fully functional digital systems (Thapa et al., 2023; Poudel et al., 2024). Similarly, Kanbara & Shaw (2022) argue that schools offer a natural platform for participatory governance in early warning, particularly when they are integrated with local risk information and communication channels.

Based on the Wayanad case and supported by broader evidence, this report proposes a school-anchored early warning model. In this framework, schools function as trusted, decentralised hubs for early warning communication. Teachers are positioned as early warning ambassadors, responsible for interpreting alerts, contextualising risk, and initiating local mobilisation. Students act as messengers of risk, carrying information, preparedness practices, and protective advice back into their homes and neighbourhoods, strengthening the community's overall responsiveness to hazards.

Rather than building new communication systems from scratch, this approach builds on the existing infrastructure of trust. The school is not an accessory to early warning. It is an under-recognised core node that connects technical systems to community response. In many rural contexts, it is the only institution with a direct line to nearly every household.

The following section presents a visual model of this framework, mapping the roles of schools, teachers, and students within a community-embedded early warning system.

5.9 Proposed Framework

The Wayanad case, along with other disaster contexts, underscores the need for early warning systems that are not merely built around command centres and centralised communication, but deeply embedded within the places where people live, interact, and make critical decisions. This chapter proposes a reframing of early warning systems: moving from a broadcast-centric model to a school-anchored, community-responsive structure that operates through two-way communication.

At the heart of this framework is a simple but powerful insight: schools are consistent, trusted, and spatially accessible institutions, already connected to most households through everyday routines involving teachers, students, and parents. Schools are uniquely positioned to serve as both receivers of formal early warnings and transmitters of locally sensed threats, making them dynamic hubs rather than passive endpoints.

In this proposed model:

- Schools act as local early warning hubs—hosting preparedness drills, maintaining community risk maps, and serving as the first point of coordination for warning dissemination and local observations.
- Teachers are trained as EWS ambassadors, responsible for interpreting official alerts, contextualising their meaning, and initiating action at the school and ward levels.
- Students function as messengers of risk, carrying early warning information to households through familiar channels such as conversations, notes, and peer discussions.
- Households are not simply passive recipients; they are also active participants, reporting unusual environmental signs or emerging threats through students and local networks.
- Panchayats act as critical intermediaries, receiving both formal alerts from district EWS cells and community-generated warnings from schools.
- Religious Institutions and Youth Clubs are mobilised to amplify warning messages, using trusted community spaces and existing communication infrastructures like mosque microphones and club gatherings.

This design recognises that early warning must function in both directions:

- Top-down dissemination: Formal alerts flow from the State Disaster Management Authority through district EWS cells and panchayats to schools, and then outward to the broader community.

- Bottom-up escalation: Locally sensed risks flow from households to schools, onward to panchayats, and then upward to district and state institutions for validation and action.

Rather than treating early warning as a one-way transmission of technical information, this model builds outward from the embedded social structures that people trust most. Schools become the relational bridge between institutional alerts and community response, ensuring that warnings are not only received but believed, understood, and acted upon.

Crucially, this framework does not replace technical agencies or scientific monitoring. Instead, it complements them by embedding the critical functions of interpretation, relational trust, and early sensing within everyday social systems. It enables formal agencies to remain authoritative while making the warning process more accessible, legible, and meaningful to the communities it seeks to protect.

Figure 5-1 illustrates this community-embedded early warning model, highlighting the two-directional flows between state institutions and local communities, with schools positioned as the operational and relational centre of the system.

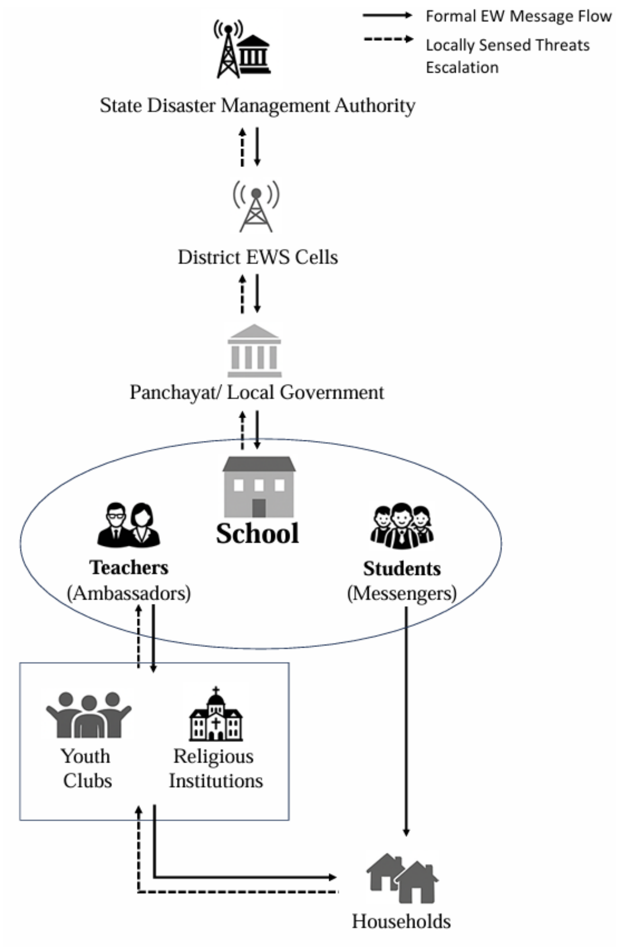

Figure 5-1 Community-Embedded EWS Communication Framework

5.10 Conclusion and Policy Recommendations

The 2024 Wayanad landslide was not just a natural disaster. It marked a profound rupture in the social fabric of the community. Warnings were issued. Alerts were available. But they did not convert into meaningful action. The gap lay not in the absence of information, but in the absence of connection. The system spoke, but it did not speak in ways that people trusted, understood, or felt compelled to act upon.

This chapter has argued that early warning is not simply about detecting hazards or broadcasting alerts. It is about understanding how risk is lived, felt, and interpreted in specific places, cultures, and histories. In Wayanad, risk was interpreted not through rainfall metrics, but through memory, familiarity, and community routines. The warnings failed not because they were technically flawed, but because they were not embedded in the everyday interpretive world of those they aimed to protect.

At the heart of this analysis is a call to rethink early warning not as a “last mile” delivery challenge, but as a relational, embedded system. This means designing early warning systems not around abstract recipients, but around the trusted figures, institutions, and spaces that people already rely on—ward members, teachers, auto drivers, mosques, schools, and local clubs. These are the social infrastructures that actually function in crisis, yet they remain overlooked in formal frameworks.

The proposed school-centred early warning model presented here offers one possible pathway toward such a shift. By repositioning schools as EWS hubs, training teachers as ambassadors, and recognising students as messengers, we move toward a system that is locally grounded, socially resonant, and more likely to trigger protective action.

These ideas are not context-bound. Comparative insights from Japan reinforce the same argument. In the 2021 Atami landslide, despite the presence of digital warning systems, delays in action stemmed from gaps in local engagement, ageing populations, and trust dynamics (Poudel et al., 2024). Japan’s evolving disaster risk reduction model now prioritises open governance, community co-production, and decentralised data ownership (Kanbara & Shaw, 2022), principles that echo the embedded approaches discussed here.

Similarly, in Nepal’s Methum landslide context, low-cost community-led early warning systems have proven effective not because of cutting-edge sensors, but because of local involvement, terrain-specific knowledge, and embedded volunteer networks (Thapa et al., 2023). These cases remind us that the cultural architecture of risk response is as important as the technical architecture of alerts.

Cross-national learning between contexts like Wayanad, Atami, and Methum is not just desirable, it is essential. While the social and institutional structures may differ, the core insight holds: people act on warnings when they are interpreted through trusted systems of meaning.

Key Policy Recommendations:

- Design context-specific early warning systems that are sensitive to local geography, topography, settlement patterns, cultural dynamics, and community histories, rather than relying solely on standardised templates.
- Reframe early warning systems as embedded community structures, moving beyond the "last mile delivery" approach toward models rooted in trusted local institutions and relational trust.
- Integrate schools into state and district early warning protocols as decentralised risk communication hubs, capable of receiving, contextualising, and disseminating alerts in a culturally resonant manner.
- Train teachers as early warning ambassadors, equipping them not only to interpret formal alerts but to initiate local mobilisation through trusted interpersonal networks.
- Include students in preparedness education, enabling them to serve as intergenerational risk messengers who bridge institutions and households.
- Build the capacity of ward members as frontline communicators and risk interpreters, providing them training in both formal early warning procedures and community-based threat recognition, to strengthen their role as local connectors between institutions and residents.
- Recognise and support informal institutions—such as mosques, religious centres, youth clubs, and neighbourhood groups—as integral extensions of the early warning system, particularly in the last-mile and hard-to-reach areas.
- Facilitate cross-national knowledge exchange between Indian, Japanese, Nepalese, and other community-based EWS practitioners through joint learning platforms, field exchanges, and contextually adaptive training modules.

The future of early warning lies not in louder alerts, but in deeper attunement—to how people live, to where they turn in moments of doubt, and to who they trust when danger draws near. If the early warning system is to protect lives, it must first learn to speak the language of those it seeks to save.

06

The Technological Dimension of Early Warning Systems: Capabilities, Challenges, and Lessons from 2024 Wayanad Landslide in India

Chapter 6: The Technological Dimension of Early Warning Systems: Capabilities, Challenges, and Lessons from 2024 Wayanad Landslide in India

Summary: The world is witnessing a frequent increase in the frequency and intensity of disasters, which amplify the need for an efficient and reliable Early Warning System (EWS). The rapidly evolving technology applications (such as RS&GIS, IoT, Big Data and AI/ML) in disaster management is expected to strengthen the EWS and response strategies. This chapter explores the present status of EWS with a special focus on technical dimensions and highlights the components, capabilities, and challenges, with reference to the 2024 Wayanad landslide in India.

6.1 Introduction

An Early Warning System (EWS), a critical component of disaster risk reduction and climate adaptation strategies, is designed to detect impending hazards and provide timely warnings to the people. EWS is an integrated system comprising hazard monitoring, forecasting and prediction, disaster risk reduction, communication and preparedness activities, systems and processes. These processes enable individuals, communities, governments and others to take timely action to reduce the risks of hazardous events. (UNDRR, 2022).

EWS drives its ability to give timely and accurate warnings through the technology dimension, encompassing tools, infrastructure and innovations. Technology plays a central role in the functioning and evolution of EWS. From monitoring hazards to disseminating warnings, the technological components of EWS are central for timely and effective disaster response. The technology has its share of challenges also ranging from data accuracy to system integration and operational reliability. The landslides of Wayanad on July 30th 2024, which caused the death of around 400 people (Standard, 2024), is a specific case study to explore the capabilities and limitations of EWS technology.

This chapter explores the present status of EWS with a special focus on technical dimensions and highlights the components, capabilities, and challenges, with reference to the 2024 Wayanad landslide in India.

6.2 Landslides EWS

Landslide Early Warning System is defined as a system designed for monitoring, predicting and disseminating timely information about the potential landslides to enable the communities to take appropriate action and minimize the risk associated with them. It combines real-time or near real-time data collection (such as rainfall, soil moisture, slope movement) with forecasting models to anticipate when and where a landslide might occur. It involves monitoring or collecting data, processing data and predictive analysis and disseminating the alerts based on the analysis.

6.2.1 Literature Review

6.2.1.1 Early conceptualization of LEWS and Threshold Development

The Campbell's work (1975) is considered as the foundational step in the development of Landslide Early warning system. He formularized the concept of using environmental parameters to predict landslides, he proposed that rainfall thresholds could be used to forecast landslides occurrences. His study of South California demonstrated that antecedent rainfall and storm intensity could be correlated with landslide prediction, which lays the foundation of early warning systems based on the empirical thresholds. (Campbell, 1975)

Building on this foundational work, Caine (1980) developed widely referenced global intensity-duration threshold, that proposed landslides generally occur when rainfall intensity and duration exceed certain limits. This research showed that short intense rainfall and prolonged moderate rainfall events could trigger landslides. (Caine, 1980)

Keefer and Wilson (1987) operationalized these concepts by developing one of operational real time landslide warning system at San Francisco Bay area. It used rainfall intensity and cumulative rainfall thresholds to trigger warnings, demonstrating that real-time monitoring and communication can significantly reduce landslide risk. (Keefer, 1987)

Subsequent studies by Aleotti (2004) and Guzzetti (2007) systematically reviewed the application of rainfall thresholds across different geographical contexts. It emphasizes the need of region-specific thresholds for local environmental, hydrological, geological variations, leading to the adoption of threshold based LEWS, particularly at regional scale (Aleotti, 2004) (F. Guzzetti, 2007).

6.2.1.2 Technological Innovations and Local monitoring

Gili et al. (2000) and Intrieri et al. (2012) reviewed the different emerging monitoring technology like Ground-based Interferometric Synthetic Aperture Radar (GB-InSAR), GPS and remote sensing techniques. These technologies help in monitoring of slope deformations. Significantly improve the accuracy and lead time of local LEWS. (Emanuele Intrieri, 2012) (Josep A. Gili, 2000)

Piciullo et al. (2018) further proposed a typology for LEWS, distinguishing systems based on their scale, warning targets and operational characteristics. His research stressed that the technological advancements must be complemented by the effective community engagement, warning dissemination strategies and institutional integration to achieve the desired results. (Luca Piciullo, 2018)

6.2.1.3 Indian Context

In India, several significant efforts have demonstrated to develop the LEWS using the rainfall-based threshold and real-time monitoring of different parameters of landslides. The research team from IIT Mandi, Amrita Vishwa Vidyapeetham, IIT Roorkee are leading in these efforts. More recently, The LANDSLIP Project (2017-2022), an India-UK collaborative effort, aimed to develop a regional LEWS. It tries to integrate meteorological forecasting, susceptibility mapping and community-based dissemination strategies to tailor early warning approaches to India’s complex socio -economic settings.

6.3 Overview of the Technological Applications of Landslide EWS

The technological dimension of EWS is a multilayered ecosystem that refers to the tools, infrastructure, innovation and processes used to detect, monitor, analyze, disseminate and respond to hazards in a timely manner. At their core, EWS depends on effectively integrating technologies to predict, communicate, and mitigate risks. **Figure 6-1** illustrates the EWS workflow, from data collection to dissemination of alerts.

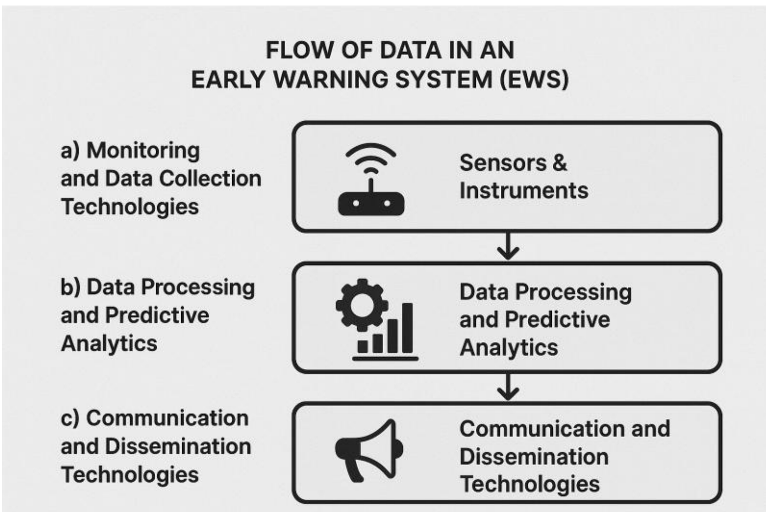

Figure 6-1 A Flow of data through EWS components, from sensors to public alerts.

6.3.1 Monitoring and data collection technologies

The two central pillars of EWS are monitoring and data collection. It highlights that it is essential to collect the data in an accurate and timely manner to assess risks and forecast hazards. For landslides-specific systems, the key technologies are:

6.3.1.1 Seismic sensors

They detect and measure the ground motions caused by earthquakes by converting the vibrations into electronic signals. They are helpful in earthquake-prone areas, where earthquakes trigger landslides, especially in the Himalayan region.

6.3.1.2 Rain gauges and Weather Station

This technological instrument helps measure the intensity and duration of rainfall, which are crucial for rainfall-induced landslides.

6.3.1.3 Remote Sensing data

Remote sensing data using satellite-based and drone platforms provides high-resolution and real-time data on vegetation, geological shifts, and weather patterns. It offers the wide-area monitoring of terrain changes and localized mapping of inaccessible areas at the same time.

6.3.1.4 Soil moisture and Pore pressure sensor

These sensors monitor the subsurface conditions and detect the saturation levels that destabilize the slopes. It quantifies subsurface saturation (e.g., volumetric water content in %) to detect slope destabilization.

6.3.1.5 Inclinometer and Tiltmeter

These sensors track the movement of the slope, which is the precursor of landslides. These measure slope deformation, providing early signs of instability with ±0.1° accuracy.

6.3.2 Data Processing and Predictive Analytics

This dimension converts the raw data into actionable information. It uses advanced computational methods, which transform the data into information. Some of the data processing and predictive tools are the following:

6.3.2.1 Numerical Modelling

Numerical modelling is a physics-based model that simulates the physical behavior of disasters. In the case of landslides, it simulates the slope stability based on rainfall threshold and soil properties requiring high-performance computing.

6.3.2.2 Artificial Intelligence and Machine Learning

Artificial intelligence and Machine learning techniques enhance forecasting accuracy by learning from past events and identifying complex patterns. The large-scale AI and ML models are trained on historical data and analyze real-time data to predict the likelihood of hazards. Machine learning models can simulate disaster scenarios and identify vulnerable areas. These technologies are particularly useful in modelling non-linear systems and high-uncertainty environments. For example, ensemble models of XGBoost and Random Forest models, trained on historical landslide data, achieve ~85% accuracy in predicting rainfall-induced landslides in our study of Western Ghats.

6.3.2.3 Geospatial Tools

It helps in collecting, analyzing, and visualizing spatial data and also facilitates the integration of diverse datasets, which provide a comprehensive image of the risk landscape. For example, the GIS platform visualizes spatial data. It integrates datasets (such as rainfall, terrain, and population) to create risk maps, visualizing hazards like a digital map that layered multiple risk factors.

6.3.2.4 Data Integration Platforms

The EWS systems use multiple data at the same time, and it need a data integration platform for aggregating the data from heterogenous sources, including satellite data, sensor data, historical records and meteorological data. These platforms aggregate heterogeneous sources to provide a comprehensive risk landscape.

6.3.3 Communication and Dissemination Technologies

After analyzing the different data sets through different predictive models and finalizing the testing process, it is necessary to ensure the timely delivery of warnings to the population at risk. An effective EWS requires a robust communication infrastructure to relay the warnings. Some of the communication channels used in EWS are the following:

6.3.3.1 Satellite Systems

Satellite-based communication systems ensure connectivity in remote or disaster-hit areas. For example, INMARSAT and Iridium provide global satellite communication services for disaster alerts.

6.3.3.2 Cellular Networks

Cellular Broadcast services help send geo-targeted alerts to all devices in disaster-prone areas, bypassing network congestion. It ensures that the audience gets disaster alerts with audible and unique on-screen alerts.

6.3.3.3 Internet and Mobile Apps

In the age of the internet, there are lots of news portals, applications and customized apps for disaster warnings. For example, Bhooskhalan was used by the GSI for landslides, and Sachet was used by the NDMA for disasters ((GSI), 2024).

6.3.3.4 Traditional Media

Traditional media is indispensable in disaster communication, especially in remote, resource-limited areas. There are multiple traditional methods for disseminating alerts to the people at risk. For example, sirens. Community networks and public announcement.

In Wayanad, early warnings were intended for the district authorities, not the general people, as the EWS was in the experimental or trial phase. This shows the gaps in communication reach and emphasizes the need for a strong communication and dissemination infrastructure.

6.4 Technological challenges in Landslides EWS

The EWS faces significant technical challenges also. Some of the technical challenges are the following:

6.4.1 Data gaps and accuracy

Data is the foundation of any technical system; in the case of EWS, the quality and completeness of input data are essential. Any inaccuracies or errors in data lead to unreliable predictions with severe consequences.

6.4.1.1 Incomplete or insufficient data

The EWS requires a detailed and complete dataset, such as historical landslide data, rainfall data, and slope movement, to make accurate predictions. However, these datasets are often missing in a complex terrain region or a developing region. For example- In the case of landslide EWS, like the one in the Wayanad area, critical parameters like soil parameters, slope movement, and rainfall threshold data are often unavailable.

The EWS with incomplete data will generate vague or incorrect outputs, which reduces the confidence in EWS.

6.4.1.2 False Positives and Negatives

A careful balance between specificity and sensitivity is required to function the EWS effectively. The EWS's high sensitivity ensures that the system detects as many potential hazards as possible to minimize the risk of failing to issue an alert before hazards occur. However, overly sensitive systems may generate false positives, leading to unnecessary alarms, resource strain and warning fatigue among the communities.

6.4.1.3 Data Latency and Resolution

Data latency, in the case of EWS, refers to the time delay between data acquisition and the availability of analysis or decision-making. High data latency can critically impair the timeliness of alerts, especially for rapid-onset hazards such as landslides and flash floods. The low or coarse resolution misses the level of details or granularity of datasets, which significantly compromises the timeliness and precision of early warning.

6.4.2 Limited coverage and scalability

The existing infrastructure of EWS is in the urban areas and high-priority zones, which leaves the large area undetected. The scalability of EWS is also a significant challenge, as expanding networks requires a considerable investment.

6.4.2.1 Geographical Gaps

In India, the distribution of sensor networks and monitoring systems is uneven and gives priority to the urban and accessible areas over the remote and rugged terrain areas. For example, In Kerala, only 100 weather systems (or observatory network) were operational in 2024, much less than the required number, i.e. 256 for statewide coverage. Wayanad's hilly terrain had sparse rain gauge density, limiting the NLFC's ability to detect localized rainfall spikes. ((KSDMA), 2025)

6.4.2.2 Scalability Constraints

The expansion of EWS at the national or global level requires significant investment in hardware, software, and personnel. For example, funding shortages and technical complexities delayed India's goals for establishing Landslide EWS for all vulnerable states by 2030. The Wayanad system launched a few days before the landslide, which is still in the experimental phase, shows scalability issues.

6.4.3 Integration and Interoperability

EWS use different datasets from different sources, and it needs an integration between these, whether it is meteorological, geological or environmental data. The interoperability of the technologies that process and disseminate them is also required. However, these integration and interoperability are missing some of the EWS.

6.4.3.1 Siloed Systems

In EWS, different types of data and components, such as sensors, rainfall data, and communication channels, are managed by different agencies. It leads to disjointed workflows and fails the concept of EWS. For example, the IMD, GSI, and local disaster management authorities operate independently in Wayanad. The Hume Centre's (not a legal entity authorized to issue warnings or alerts) community-based warning (issued 16 hours prior) was not integrated into official channels, missing a chance to escalate alerts.

6.4.3.2 Lack of Standardization

The adoption of a universal standard is required for the smooth functioning and dissemination of alerts. EWS struggles to share data across platforms without universal formats like the Common Alerting Protocol (CAP). India's EWS frameworks have not entirely accepted the CAP, complicating integration with global systems like the WMO's alert hubs.

6.4.4 Maintenance and Reliability

The effectiveness and operational integrity of EWS depend on their maintenance and operational reliability.

6.4.4.1 Sensor Malfunctions and Vandalism

The sensors and weather stations of EWS, exposed to harsh environmental conditions, are prone to failure and vandalism, and theft disrupts the networks. These issues generally happen in remote and inaccessible areas. In Wayanad, after a landslide incident, reports surfaced of AWS malfunctions in Kerala, with some stations providing questionable rainfall data (Jisha Surya, 2024). IIT Mandi notes similar issues in some areas of Himachal Pradesh, where sensors were stolen or damaged.

6.4.4.2 Power Supply Issues

The components of EWS installed in remote or inaccessible areas often use solar panels for power supply, which may fail due to prolonged adverse weather conditions. Landslide sensors in inaccessible terrain often face power disruptions during monsoons. It disables sensors or communications and renders the system inoperative at critical moments.

6.4.4.3 Funding and Maintenance Shortfalls

The maintenance of critical field components of EWS is necessary, and it requires a sustainable funding source. It must balance initial deployment costs with long-term maintenance with innovative financing models, like public-private partnerships.

6.4.5 Human-Technology Interface

The warning disseminated by EWS can fail if warnings are not understood or acted upon. It is a critical technical issue tied to system design and dissemination.

6.4.5.1 Ineffective Communication

The warning issued by EWS must be clear, accessible, and tailored to diverse audiences. It should also be in the local language and free from technical jargon because it creates confusion. In Wayanad, an orange alert from the IMD reached authorities but not residents, who were complacent after a sunny day on July 29 (IMD, Press Release , 2024).

6.4.5.2 Technical Complexity for Users

Technical Complexity for Users- The EWS components should be simple to use and provide proper training to the community and local officers. In Wayanad, experts managed the experimental EWS, but local officers could not interpret the probabilistic forecast, delaying actions (Onmanorama, 2024).

6.4.5.3 Warning Fatigue and Trust

Frequent and inaccurate alarms lead to warning fatigue, desensitizing the users towards the warnings, and false alarms erode their confidence in the system. This is problematic in an area like Western Ghats, where recurrent false alarms or generalized warnings such as district-wide alerts that miss local variability can erode public confidence in the system.

6.5 A Case Study of 2024 Wayanad Landslide

6.5.1 Background and Timeline

In the context of Wayanad, the Geological Survey of India (GSI) deployed the experimental landslide forecasting tools in July 2024 under the National Landslide Forecasting Centre (NLFC) facility ((GSI), 2024). It includes rain gauges and satellite data; the forecasting is for ground validation and testing purposes and is not for public use yet. However, sparse sensor coverage limited its effectiveness, as shown in **Figure 6-2**.

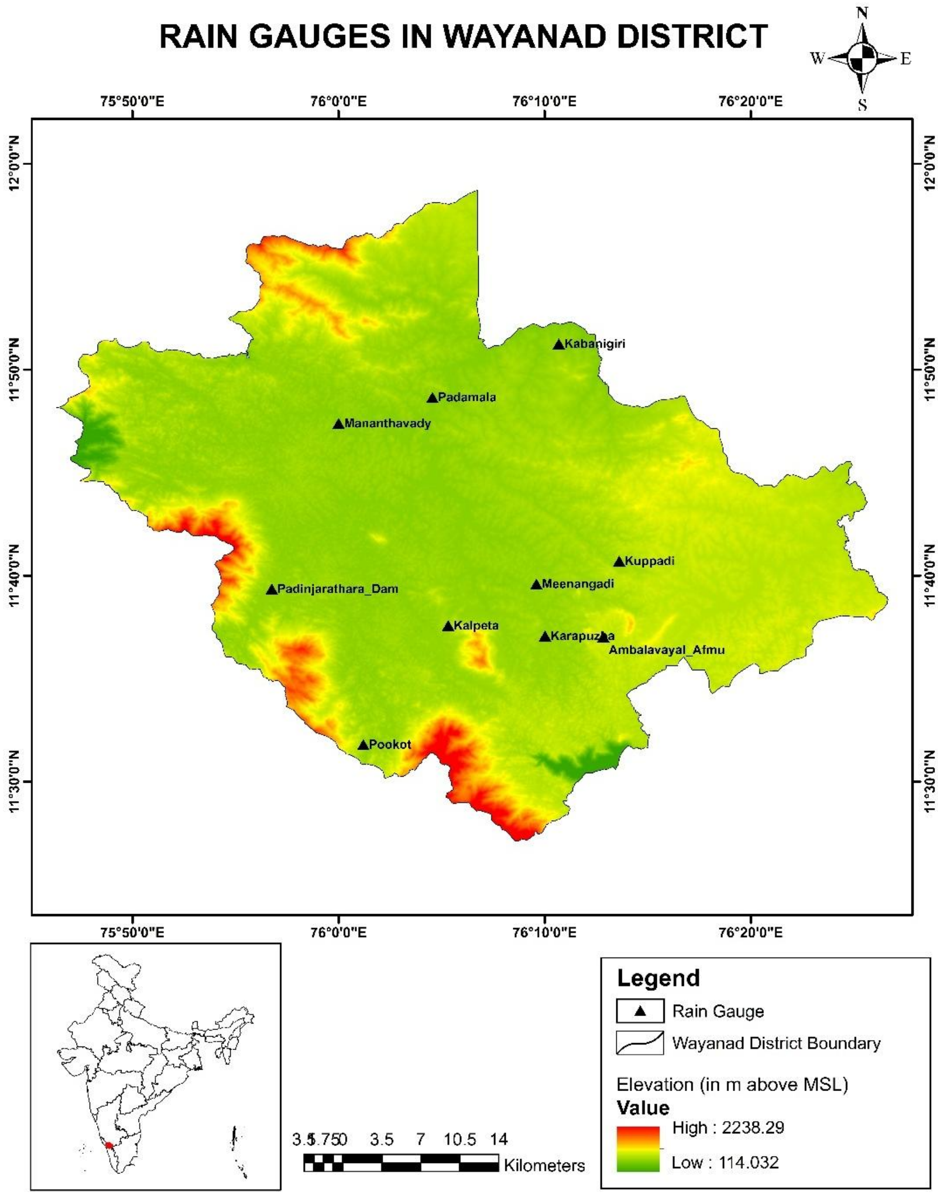

Figure 6-2 Location of Rain gauges in Wayanad. Source: Author

On 30th July 2024, 2:17 AM, Wayanad landslide, triggered by 572 mm of rainfall in 48 hours, killed over 400 people, injured 273, and displaced 10,000 in Mundakkai and surrounding areas (Das, 2025) (Hindu, 2024).

- **July 19, 2024**: NLFC inaugurated with experimental rain gauges and satellite data.
- **July 29, 2024**: NLFC issues bulletin predicting "low possibility" (10%) of landslides, underestimating rainfall (forecast: <200 mm; actual: 572 mm) (Staff, 2024).
- **July 30, 2024**: Landslide strikes at 2:17 AM, devastating Mundakkai.

6.5.2 Existing Warning Mechanism

Kerala had some existing landslide warning mechanism before the Wayanad landslide incident, but these were limited in integration, coverage and accuracy. The independent organization like Hume Centre operated rainfall monitoring networks and issued early warning based on rainfall data, these alerts were not integrated in official alerts, leading to poor coordination. The GSI's EWS was still in trial phase and failed to predict. The IMD provided broad heavy rainfall alerts but lacked sufficient spatial resolution and underestimated actual rainfall. The proven technologies like Amrita University EWS were limited to Idukki district, not yet deployed in Wayanad. In short, the existing warning mechanisms suffered from poor integration, insufficient real time monitoring and weak institutional co-ordination.

6.5.3 Analysis of NLFC's Experimental System

The NLFC used a Random Forest model trained on historical landslides, relying on IMD forecasts (25 km resolution) and limited rain gauge data. Its 200 mm rainfall threshold failed to account for hyper-local extremes. GSI noted, "We are still streamlining the automated system" (New Indian Express, 2024). The underutilization of available doppler radar data (1km resolution) highlights the need of real time integration of different data sets to improve the accuracy (Onmanorama, 2024).

6.5.4 Role of Hume Centre

The Hume Centre issued a warning 16 hours prior based on local observations (e.g., soil saturation, streamflow). Lacking formal integration, its alert was not escalated, underscoring the need for grassroots EWS inclusion (Onmanorama, 2024).

6.5.5 Socio-Economic Context

The dense population of Wayanad (817,420 in 2011) and weak infrastructure (50% non-resilient homes) increased the impact of disaster. The residents were unaware of the orange alert, which reflects the communication failures, and therefore, there were no evacuation plans. (Census 2011).

6.5.6 Implications on Wayanad landslide

The Wayanad Landslide, which occurred on July 30, 224, were triggered by the very heavy rainfall. It reveals the critical gaps in EWS and emphasizes the need for a reliable and efficient EWS that can predict disasters accurately and timely.

The NLFC, inaugurated on July 19, 2024, was still experimental, failing to predict the event, rating the possibility as 'low' with rainfall intensity forecasted at less than 200 mm against the actual 572 mm (IMD, Press Release , 2024). The Geological Survey of India (GSI) officer noted, "We could not predict the landslide in Mundakkai as we are still streamlining the automated system". (S, 2024) The tragedy highlights the urgency of accelerating EWS development from the experimental to operational phases. Our research suggests integrating diverse data sources, such as real-time satellite imagery, historical rainfall data, and hill slope studies, to enhance predictive models.

The implications drawn from this tragedy are summarized in the following table.

Table 6-1 Table of Implications

Implication Category	**Details**
EWS Development	Urgency to move from experimental to operational, integrate diverse data sources.
Coordination and Integration	Need for robust, integrated systems, addressing agency silos, adopting MHEWS.
Public Dissemination	Enhance mechanisms for clear, accessible alerts, community engagement via mobile apps.
Policy and Regulation	Stricter land use, construction norms, increased funding for disaster infrastructure.
Psychological and Social	Address survivor trauma, design community-centric, trauma-informed EWS.
Climate Adaptation	Evolve to dynamic, impact-based forecasting for increased rainfall variability.

6.6 Summary and a way forward

The technological dimension of EWS offers an excellent way to mitigate and manage disasters, but challenges like insufficient data, integration, and operational issues hinder how EWS is managed. This chapter has explored the technical dimension of EWS, ranging from data acquisition and analyses of data to dissemination of alerts. It also underlines the technological challenges of EWS, such as data latency, low spatial resolution, limited coverage, poor system integration, and challenges in maintenance and reliability.

The Wayanad Landslide of 2024 illustrates these issues, where a nascent EWS failed to match the expectations and technical dimension of EWS. The lessons from the Wayanad landslide 2024 highlight the need for targeted investments in technology deployment and policy reforms to make EWS more inclusive and effective.

07

Way Forward

Chapter 7: Way Forward

The Wayanad Landslide of 2024 has underscored the critical importance of a robust, community-centered early warning system (EWS) tailored to the region's unique topographical and socio-environmental characteristics. While existing systems provided valuable alerts, there remains significant scope for enhancement in terms of coverage, accessibility, and community response. Cultural component is a critical issue, which needs to be kept in mind while designing community based early warning system.

To strengthen disaster preparedness and resilience in Wayanad, the following forward-looking actions are recommended:

1. **Integrated All-Hazard Early Warning System (AHEWS):** Develop a cohesive AHEWS that integrates rainfall thresholds, soil moisture data, terrain mapping, and real-time landslide monitoring technologies. These systems should be capable of correlating data from meteorological, geological, and hydrological, as well as other non-natural hazards sources for comprehensive risk assessment.
2. **Localized Risk Mapping and Zonation:** Update and refine landslide susceptibility and hazard zonation maps using high-resolution remote sensing and geospatial data. These should be made available to local authorities and the public for informed planning and response.
3. **Community-Centric Alert Mechanisms:** Strengthen last-mile connectivity of alerts through mobile-based alerts, loudspeakers, community radio, and SMS services in local languages. Training local volunteers as part of disaster response units will ensure swift dissemination and action during emergencies.
4. **Capacity Building and Culturally sensitive Community Engagement:** Continuous awareness campaigns, school-based disaster education, and regular simulation drills must be institutionalized. Active involvement of Panchayati Raj Institutions, Self-Help Groups, and tribal communities can enhance trust and cooperation. Cultural calibration is the core of the community based EWS.
5. **Inter-Agency Coordination:** Foster stronger coordination among the India Meteorological Department (IMD), Geological Survey of India (GSI), Kerala State Disaster Management Authority (KSDMA), and district-level authorities to ensure seamless flow of data and unified action.
6. **Infrastructure Investment:** Install automated rain gauges, geotechnical sensors, and slope movement detectors in high-risk zones. Encourage the use of AI and machine learning for predictive modeling and anomaly detection.
7. **Policy and Funding Support:** Secure sustained government funding for the development and maintenance of EWS infrastructure. Incorporate lessons

learned from the 2024 event into state and national disaster risk reduction (DRR) policies.

In conclusion, the advancement of a comprehensive and community-responsive early warning system will not only save lives but also safeguard livelihoods, ecosystems, and infrastructure in Wayanad and other vulnerable hill districts of India. The 2024 landslide should serve as a turning point in transitioning from reactive to anticipatory disaster risk governance.

References

1. Abraham, M. T., Satyam, N., Pradhan, B., & Alamri, A. M. (2020). IoT-based geotechnical monitoring of unstable slopes for landslide early warning in the Darjeeling Himalayas. Sensors, 20(9), 2611.https://doi.org/10.3390/s20092611
2. Aleotti, P. (2004). A warning system for rainfall-induced shallow failures. Engineering Geology, 247-265. doi:https://doi.org/10.1016/j.enggeo.2004.01.007
3. Bankoff, G. (2003). Cultures of disaster: Society and natural hazard in the Philippines. Routledge.
4. Bhusanket. (2024). GSI's view on landslide forecast for Kerala. Retrieved from Bhusanket Website: https://bhusanket.gsi.gov.in/Public_Portal_News_pdf/GSI's%20view%20on%20landslide%20forecast%20for%20Kerala.cleaned.pdf
5. Caine, N. (1980). The Rainfall Intensity: Duration Control of Shallow Landslides and Debris Flows. Geografiska Annaler. Series A, Physical Geography, 23-27. doi:https://doi.org/10.2307/520449
6. Campbell, R. H. (1975). Soil slips, debris flows, and rainstorms in the Santa Monica Mountains and vicinity, southern California. U.S. Govt. Print. Off. doi:https://doi.org/10.3133/pp851
7. Capobianco, V., Choi, C.E., Crosta, G. et al. Effective landslide risk management in era of climate change, demographic change, and evolving societal priorities. Landslides (2025). https://doi.org/10.1007/s10346-024-02418-2
8. Centre for Research on the Epidemiology of Disasters (CRED). (2025). 2024 Disasters in Numbers: A Hot and Stormy Year. Brussels, Belgium: CRED. Available at https://files.emdat.be/reports/2024_EMDAT_report.pdf
9. City of Hiroshima (n.d.). Warning Levels and What They Mean: Emergency Evacuation Information. Article ID 1009824. Available at : https://www.city.hiroshima.lg.jp/english/emergency/1029785/1009824.html [accessed on 16 April 2025]
10. Cvetković, V. M., Renner, R., Aleksova, B., & Lukić, T. (2024). Geospatial and Temporal Patterns of Natural and Man-Made (Technological) Disasters (1900–2024): Insights from Different Socio-Economic and Demographic Perspectives. Applied Sciences, 14(18), 8129. https://doi.org/10.3390/app14188129
11. Das, R. (2024). Catastrophic landslide in Wayanad district of Kerala, India on July 30, 2024: A complex interplay between geology, geomorphology, and climate. Landslides. Advance online publication. https://doi.org/10.1007/s10346-024-02385-8
12. Dave Petley. Fatal landslides to the end of July 2024. 13 Auguat 2024. https://eos.org/thelandslideblog/fatal-landslides-july-2024

13. Emanuele Intrieri, G. G. (2012). Design and implementation of a landslide early warning system. Engineering Geology, 124-136. doi:https://doi.org/10.1016/j.enggeo.2012.07.017.
14. EOC_Guidelines_Oct_2024. (n.d.).
15. EOC_Kerala. (n.d.).
16. F. Guzzetti, S. P. (2007). Rainfall thresholds for the initiation of landslides in central and southern Europe. Meteorology and Atmospheric Physics, 239-267. doi:https://doi.org/10.1007/s00703-007-0262-7
17. Fausto Guzzetti, Stefano Luigi Gariano, Silvia Peruccacci, Maria Teresa Brunetti, Ivan Marchesini, Mauro Rossi, and Massimo Melillo. "Geographical landslide early warning systems." Earth-Science Reviews 200 (2020): 102973. https://doi.org/10.1016/j.earscirev.2019.102973
18. GoI, U. (n.d.). ICT for Disaster Risk Reduction: The Indian Experience.
19. Gopinath, G., A.L., A., Bhadran, A., Girishbai, D., & Pulpadan, Y. A. (2024). Preliminary report of the most disastrous landslide on 30th July 2024 Wayanad Plateau, Kerala, India. Journal of the Geological Society of India, 100(11), 1640–1641. https://doi.org/10.17491/jgsi/2024/174028
20. GSI, G. S. (2024). National Landslide Forecasting Centre. Retrieved 02 16, 2025, from https://www.bhusanket.gsi.gov.in/
21. Hamza, M., & Månsson, P. (2020). The human dimension of early warning – a viewpoint. International Journal of Disaster Resilience in the Built Environment, 11(2), 263–274. https://doi.org/10.1108/IJDRBE-07-2019-0040
22. Hermans, T. D. G., Šakić Trogrlić, R., van den Homberg, M. J. C., Bailon, H., Sarku, R., & Mosurska, A. (2022). Exploring the integration of local and scientific knowledge in early warning systems for disaster risk reduction: A review. Natural Hazards, 114, 1125–1152. https://doi.org/10.1007/s11069-022-05468-8
23. Hindu, T. (2024, July 31). THE HINDU NEWSPAPER. Retrieved from The Hindu: https://www.thehindu.com/news/national/kerala/it-rained-buckets-on-the-fateful-night-in-wayanad-that-led-to-the-catastrophe/article68465406.ece#:~:text=However%2C%20the%20area%20where%20the,rain%20in%20just%2048%20hours.
24. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=10673318
25. https://link.springer.com/chapter/10.1007/978-3-031-18471-0_21
26. https://sdma.kerala.gov.in/about-ksdma/
27. IMD. (2024, 07 29). India Meteorological Department Press Release. Retrieved 02 15, 2025, from India Meteorological Department: https://internal.imd.gov.in/press_release/20240729_pr_3118.pdf
28. Jisha Surya. (2024, July 31). Wayanad's tragic landslides reveal gaps in weather prediction systems. Retrieved from The News Minute: https://www.thenewsminute.com/kerala/wayanads-tragic-landslides-reveal-gaps-in-weather-prediction-

systems#:~:text=However%2C%20sources%20said%20that%20some%20are%20not,Kabanigiri%2C%20Kalpeta%2C%20Karapuzha%2C%20Kuppadi%2C%20Padamala%20and%20Padinjarathar

29. Josep A. Gili, J. C. (2000). Using Global Positioning System techniques in landslide monitoring. Engineering Geology, 167-192. doi:https://doi.org/10.1016/S0013-7952(99)00127-1
30. Kanbara, S., & Shaw, R. (2022). Toward disaster risk reduction 4.0: Reframing participatory governance in Japan. Sustainability, 14(24), 17012. https://doi.org/10.3390/su142417012
31. Keefer, D. &. (1987). Real-Time Landslide Warning During Heavy Rainfall. Science, 921-925. doi:DOI: 10.1126/science.238.4829.921
32. Kelman, I., & Glantz, M. H. (2014). Early warning systems defined. In Z. Zommers & A. Singh (Eds.), Reducing disaster: Early warning systems for climate change (pp. 89–107). Springer. https://doi.org/10.1007/978-94-017-8598-3_5
33. Kerala State Disaster Management Plan 2016. (n.d.).
34. Krishna, G. R., & Nandini, D. U. (2024, August). Comparative Analysis of Early Warning System for Landslide Prediction and Mitigation. In 2024 7th International Conference on Circuit Power and Computing Technologies (ICCPCT) (Vol. 1, pp. 640-647). IEEE.
35. KSDMA, K. S. (2025). Automated Weather Stations. Retrieved 02 20, 2025, from Kerala State Disaster Management Authority: https://sdma.kerala.gov.in/automated-weather-stations/
36. KSDMA-Policy-2010. (n.d.).
37. Lakshmi R, J. T. (2024). Impacts of recent rainfall changes on agricultural productivity and water resources within the Southern Western Ghats of Kerala, India. Environmental Monitoring and Assessment. doi:https://doi.org/10.1007/s10661-023-12270-x
38. Li, Z., Fang, L., Sun, X., & Peng, W. (2021). 5G IoT-based geohazard monitoring and early warning system and its application. EURASIP Journal on Wireless Communications and Networking, 2021(1), 160. https://doi.org/10.1186/s13638-021-02033-y
39. Local Self Government DM Plans—Kerala State Disaster Management Authority. (2020, November 9). https://sdma.kerala.gov.in/local-self-government-dm-plans/
40. LSGI of Kerela Prepared DM Plans_KSDMA. (n.d.).
41. Luca Piciullo, M. C. (2018). Territorial early warning systems for rainfall-induced landslides. Earth-Science Reviews, 228-247. doi:https://doi.org/10.1016/j.earscirev.2018.02.013.
42. Memorandum_Meppadi Landslide. (n.d.).

43. Moretto, S., Bozzano, F., & Mazzanti, P. (2021). The role of satellite InSAR for landslide forecasting: Limitations and openings. Remote sensing, 13(18), 3735. https://doi.org/10.3390/rs13183735
44. Onmanorama. (2024, December 20). When the earth gave way: The Wayanad landslide and grim warnings for Kerala. Retrieved from Onmanorama: https://www.onmanorama.com/news/kerala/2024/12/20/wayanad-landslide-kerala-yearender-2024.html
45. Orange-Book-of-Disaster-Management-1-2020. (n.d.).
46. Osanai, N., Shimizu, T., Kuramoto, K., Kojima, S., & Noro, T. (2010). Japanese early-warning for debris flows and slope failures using rainfall indices with Radial Basis Function Network. Landslides, 7, 325-338.
47. Papathoma-Köhle, M., Thaler, T., & Fuchs, S. (2021). An institutional approach to vulnerability: Evidence from natural hazard management in Europe. Environmental Research Letters, 16(4), 044056. https://doi.org/10.1088/1748-9326/abe88c
48. Paul, B. (2011). Environmental Hazards and Disasters: Contexts, Perspectives and Management. Environmental Hazards and Disasters: Contexts, Perspectives and Management. https://doi.org/10.1002/9781119979616
49. Poudel, N., Chi, G., Yuqiu, C., & Shaw, R. (2024). Atami landslides 2021 Japan: Landfill issues, elderly casualties, key lessons and challenges. Natural Hazards Research. 5, 88-94. https://doi.org/10.1016/j.nhres.2024.06.006
50. Ramesh, M. V., Thirugnanam, H., Singh, B., Nitin Kumar, M., & Pullarkatt, D. (2023). Landslide early warning systems: requirements and solutions for disaster risk reduction—India. In Progress in Landslide Research and Technology, Volume 1 Issue 2, 2022 (pp. 259-286). Cham: Springer International Publishing.
51. Ray-Bennett, N. S., & Shiroshita, H. (2019). Disasters, Deaths and the Sendai Framework's Target One: A Case of Systems Failure in Hiroshima Landslide 2014, Japan. Disaster Prevention and Management, 28(6), 764-785. https://doi.org/10.1108/DPM-09-2019-0302
52. S, U. (2024, July 31). New Indian Express. Retrieved from New Indian Express website: https://www.newindianexpress.com/states/kerala/2024/Jul/31/early-warning-system-for-natural-disaster-fails-wayanad
53. Sattar, A., Cook, K. L., Rai, S. K., Berthier, E., Allen, S., Rinzin, S., ... & Bhat, S. Y. (2025). The Sikkim flood of October 2023: Drivers, causes, and impacts of a multihazard cascade. Science, 387(6740), eads2659.
54. Shaw, R., Takeuchi, Y., Gwee, Q. R., & Shiwaku, K. (2011). Chapter 1 Disaster Education: An Introduction. In Community, environment and disaster risk management (pp. 1–22). https://doi.org/10.1108/s2040-7262(2011)0000007007
55. Sim, K.B., Lee, M.L., and Wong, S.Y. (2022). A review of landslide acceptable risk and tolerable risk. Geoenvironmental Disasters. 9(3), https://doi.org/10.1186/s40677-022-00205-6

56. Staff, O. (2024, July 30). Epicentre of Wayanad landslides recieved 572 mm rainfall in 48 hours. Retrieved from Onmanorama: https://www.onmanorama.com/news/kerala/2024/07/30/wayanad-landslides-572-mm-rainfall-in-48-hours.html
57. Standard, B. (2024, August 07). Wayanad landslides: Death toll crosses 400-mark, over 150 still missing. Retrieved from Business Standard: https://www.business-standard.com/india-news/wayanad-landslides-death-toll-crosses-400-mark-over-150-still-missing-124080700592_1.html
58. State Relief Commissioner—Kerala State Disaster Management Authority. (2018, October 27). https://sdma.kerala.gov.in/state-relief-commissioner/
59. Thapa, P. S., Adhikari, B. R., Shaw, R., Bhattarai, D., & Yanai, S. (2023). Geomorphological analysis and early warning systems for landslide risk mitigation in Nepalese mid-hills. Natural Hazards, 119, 185–207. https://doi.org/10.1007/s11069-023-05929-8
60. Tierney, K. (2019). Disasters: A sociological approach. Polity.
61. UNDRR. (2022). Early Warnings for All. Retrieved Feb 09, 2025, from https://www.undrr.org/implementing-sendai-framework/sendai-framework-action/early-warnings-for-all
62. UNISDR. (2005). Hyogo Framework for Action 2005–2015: Building the resilience of nations and communities to disasters. United Nations Office for Disaster Risk Reduction. https://www.preventionweb.net/files/1037_hyogoframeworkforactionenglish.pdf
63. UNISDR. (2015). Sendai Framework for Disaster Risk Reduction 2015–2030. United Nations Office for Disaster Risk Reduction. https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030
64. United Nations Development Programme. (2025). What are early warning systems and why do they matter for climate action? February 28. 2025. United Nations Development Programme, Climate Promise.
65. United Nations, Global Survey of Early Warning Systems, United Nations report, 2006.
66. Wang, X., Wang, Y., Lin, Q. et al. Assessing Global Landslide Casualty Risk Under Moderate Climate Change Based on Multiple GCM Projections. Int J Disaster Risk Sci 14, 751–767 (2023). https://doi.org/10.1007/s13753-023-00514-w
67. Wayanad Preliminary Assessment Report Aug 2024. (n.d.).
68. Wisner, B., Blaikie, P., Cannon, T., & Davis, I. (2004). At Risk: Natural Hazards.
69. Zia, A., & Wagner, C. H. (2015). Mainstreaming early warning systems in development and planning processes: Multilevel implementation in Sri Lanka. Environmental Science & Policy, 54, 421–431. https://doi.org/10.1016/j.envsci.2015.07.008

A Joint Report by

India-Japan Center on Climate and Culture	Center for Climate Resilience and Disaster Management	Centre for Technology Alternatives for Rural Areas	India Japan Laboratory
IIM KOZHIKODE	**NIT CALICUT**	**IIT BOMBAY**	**KEIO UNIVERSITY, JAPAN**