THE FRAMEWORK FOR OPERATIONALISING MULTI-HAZARD EARLY WARNING SYSTEM (MHEWS) AT THE LOCAL LEVEL IN NEPAL

Part I: Multi-Hazard Early Warning System and The Proposed Framework

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EXECUTIVE SUMMARY

Nepal is highly vulnerable to multiple hazards, including earthquakes, floods, landslides, and climate-induced extremes. Annually, around 500 disasters lead to significant losses in life, livelihoods, and infrastructure. The country's topography and tectonic activity exacerbate these risks, creating complex and interrelated disaster scenarios that demand a more integrated and systematic approach to disaster management. A Multi-Hazard Early Warning System (MHEWS) offers a solution by addressing multiple hazards within a specific context, considering their interactions and cumulative effects over time. It encompasses four components: Disaster Risk Knowledge, Monitoring and Forecasting, Warning Dissemination, and Preparedness and Response. These components are interconnected and rely on governance, inclusivity, and the integration of scientific and local knowledge. These principles ensure timely and efficient early actions to mitigate risks and reduce disaster impacts.

This report proposes a framework for operationalizing MHEWS at local level, based on the latest insights in multi-hazard early warning system (MHEWS) literature and field-based observations and consultations in Phalelung, Panchthar, Nepal. This framework offers an inclusive and structured basis for operations, employing a practical, stepwise, and iterative process for MHEWS operationalization at local level. The framework aims to address the challenges of fragmented systems, limited funding, and capacity gaps by transitioning from siloed hazard-specific systems to an integrated multi-hazard approach. A people-centered design is essential, ensuring the inclusion of vulnerable groups such as women, children, persons with disabilities, and Indigenous Peoples. The framework completely aligns with the national framework on MHEWS developed by the National Disaster Risk Reduction and Management Authority (NDRRMA). Like the national framework, the local framework emphasizes strengthening the NDRRMA as a central pillar in coordinating the four pillars of MHEWS, while local government playing pivotal role in its operationalization at local level ensuring effective coordination and collaboration across all levels.

The framework outlines an eight-step process for operationalizing MHEWS at the local level. First, the scope of MHEWS must be defined by identifying hazards, vulnerabilities, and capacities specific to local contexts, ensuring that the system addresses the unique risk profiles of different areas. This includes analyzing historical data and emerging trends while considering cascading and cumulative hazard effects. Governance mechanisms must then be established to provide clear roles and responsibilities for all stakeholders, supported by standard operating procedures (SOPs) that detail actions at every stage. Developing a common vocabulary is critical to ensure consistency in understanding and communication, particularly by translating technical terms into locally comprehensible language and culturally relevant contexts.

Selecting and integrating data sources that combine scientific research with traditional and indigenous knowledge on multi-risks ensures that monitoring systems reflect local realities and address specific vulnerabilities. Strengthening and localizing impact-based forecasting (IBF) mechanisms is essential to make warnings actionable by predicting how hazards will impact specific communities and sectors, allowing for tailored responses. The framework also emphasizes the importance of identifying reliable communication channels to reach all at-risk populations, using diverse platforms such as community radio, mobile alerts, and trusted local leaders to disseminate timely and effective warnings. Feedback and evaluation mechanisms are crucial to continuously refine the system based on community input and lessons learned from past events. This includes post-event reviews to measure warning effectiveness, community reach, and response outcomes. Capacity building is an ongoing process, involving regular training, mock drills, and public awareness campaigns to ensure that institutions and communities are prepared to act effectively when disasters occur. These drills and trainings must engage all stakeholders, including marginalized groups, to foster a sense of ownership and readiness within the community. Adhering to this eight steps systematic and iterative approach can help in laying out all the foundational elements necessary for the localization of MHEWS in Nepal.

1 INTRODUCTION

Nepal's geographical location and topography make it highly susceptible to multiple hazards, including earthquakes, landslides, floods, forest fires, extreme heat stress, air pollution and climate-induced extremes. With its fragile geological formations, steep topography, and monsoon-dominated rainfall patterns, Nepal experiences diverse hazards across different elevation zones. Hydrometeorological events dominate, with Glacier Lake outburst floods (GLOFs) and avalanches in the Himalayas, landslides and flash floods in the mid-mountains, and floods, heatwaves, and waterborne diseases in the Terai plains[1]. Annually, around 500 disasters result in significant loss of life, livelihoods, and infrastructure[2].

Additionally, Nepal lies in a tectonically active region where the Indian plate subducts under the Eurasian plate[3]., causing frequent seismic events, such as the 2015 Gorkha earthquake (7.8 Mw), which led to over 9,000 deaths and triggered cascading hazards like landslides, dam outburst floods and other slope failures that continued for years after the main tremor subsided. Landslides, exacerbated by deforestation, poor construction practices, and heavy rainfall, are common in the mid-mountain region. In the active tectonic regions of the mid-mountains and Siwalik, numerous rivers flow through high-gradient channels in narrow gorges, composed of weak geological formations and subject to high-intensity rainfall. This makes the region highly susceptible to frequent landslides, particularly during the monsoon season[4]. Events like the 2014 Jure landslide[5], which caused significant loss of life and displacement, highlight the risks of landslide dam outburst floods (LDOFs) also in these regions.

Glacial retreat due to rising temperatures has increased GLOF occurrences[6], with at least 24 events recorded since the 1950s[7]. Floods occur regionally, with incidents like the 2008 Kosi flood displacing millions in Nepal and India. Between 2011 and 2021, 245 flood events were reported, displacing 3.4 million people[8]. The recent example includes the monsoon floods in August 2017, which affected 35 districts and caused 381,000 new displacements[9]. Melamchi disaster of 2022[10] and Kagbeni disaster of 2023 are some classic examples of multi-hazard disasters. The heavy rainfall in October 2021 in high-altitude regions of Manang, Mustang, and the upper Melamchi River watershed caused extensive damage to settlements, infrastructure, agriculture, transportation, and livelihoods. Forest fires in Nepal, predominantly occurring between February and May, destroy over 40,000 hectares annually[11], with human activities being the primary cause of their ignition and spread[12].

The impact of heatwaves and droughts is also expected to increase during the dry season due to climate change[13]. Upstream factors in Nepal, including various hazards, their interactions, climatic influences, and human-induced factors like land use changes and infrastructure development, directly impact downstream conditions. The interconnectedness between upstream and downstream basin conditions underscores the importance of integrated approaches and basin-wide cooperation in multi-hazard risk and multi-hazard early warning systems [14].

Globally, the Sendai Framework for Disaster Risk Reduction, introduced in 2015, explicitly aims to substantially increase the availability and access to multi-hazard early warning systems and disaster risk information by 2030[15]. Furthermore, the Sustainable Development Goals (SDGs) highlight the importance of MHEWS in Goal 13[16], which aims to strengthen resilience and adaptive capacities to climate-related hazards and disasters by integrating climate change measures into national policies, strategies, and planning. The Paris Agreement also stipulates the implementation of early warning systems as a strategy to enhance adaptive capacity, resilience, and reduce vulnerabilities and losses due to climate change.

Aligning with the global frameworks on disaster risk reduction and climate change, the government of Nepal has been putting its effort in the development of national disaster risk management policies and strategies, the strengthening of preparedness and response capacities, and the creation of methodological documents to support the mainstreaming of climate and disaster resilience in development planning at national and local levels. Recently, the National Disaster Risk Reduction and Management Authority (NDRRMA) has formulated a National Concept Note and Action Plan for Multi-Hazard Early Warning Systems (MHEWS). This approach highlights multi-hazard risk assessment as a core element to generate risk information, focusing on dynamic vulnerability and exposure assessments considering hazard interactions. It further emphasizes creating gender-sensitive risk information, engaging at-risk communities in co-producing knowledge on the evolving impacts of multiple hazards, and assessing spatial and temporal evolution across various factors such as population, infrastructure, environment, and cultural assets.

2 OBJECTIVES AND SCOPE

The primary objective of this research is twofold: first, to propose a framework for implementing a multi-hazard early warning system (MHEWS) at the local level, and second, to recommend an action plan for operationalizing the proposed framework in Phalelung Rural Municipality, Panchthar District, Nepal. The Part I of the report is primarily focussed on the framework for the operationalisation of MHEWS at local level. While the Part II of the report will evaluate the status of the multi-hazard early warning system in Phalelung and recommend options and priority actions for operationalizing of the proposed framework in Phalelung, Panchthar, Nepal.

The proposed framework will encompass priority areas for interventions across all four components of early warning systems: (i) Risk Knowledge, (ii) Detection, Monitoring, and Forecasting, (iii) Warning Dissemination and Communication, and (iv) Preparedness to Respond. These components will be coordinated across various hazards, sectors, actors, and levels. The proposed framework is fully aligned with the disaster and climate change acts and policies of the Government of Nepal, guiding the establishment of the MHEWS. It emphasizes governance priorities to support the sustainable and systematic implementation of MHEWS, focusing on inclusivity, interagency coordination, and knowledge co-production.

3 MULTI-HAZARD EARLY WARNING SYSTEM (MHEWS)

The conventional approach of treating hazards as independent entities, known as the multi-layer single-hazard or multiple-hazard approach, is considered ineffective. This fragmented approach distorts management priorities, increases vulnerability to other hazards, and underestimates associated risks. MHEWS entails examining various hazards within a specific context, considering their interactions and the potential impacts of cascading, cumulative, or concurrent occurrences. This holistic approach comprehensively evaluates hazard potential and risk within a specific context[17].

MHEWS address a wide range of hazards and their impacts, whether independently, simultaneously, sequentially, or cumulatively over time. By considering potential interrelated effects, MHEWS enhance the efficiency, effectiveness and consistency of warnings and the subsequent impact-mitigating action through coordinated and compatible mechanisms. They should be perceived as more than a mere aggregation of single hazard warning systems, instead accounting for all potential risk drivers and involving multiple disciplines, partners, and stakeholders.

MHEWS identify the most significant hazardous events and associated risks within an interconnected scenario. MHEWS ensure the optimal utilisation of the collective capacities of all stakeholders involved in different components of early warning systems for various hazards. They feature well-defined, inter-institutionally agreed plans, standard operating procedures, and financing mechanisms to trigger preventive actions that protect lives and assets. MHEWS benefit from various tools and platforms encompassing risk knowledge, hazard observation, and alerting and communication systems. These mechanisms ensure that at-risk populations are promptly and coherently warned about various hazards, their potential cascading impacts, and the necessary actions to avoid them[18].

3.1 Definitions

The Multi-Hazard Early Warning System (MHEWS) is defined as "An integrated system that addresses several hazards of similar or different types in contexts where hazardous events may occur alone, simultaneously, cascading, or cumulatively over time, taking into account the potential interrelated effects" (UNDRR and WMO 2023).

The Multi-Hazard Early Warning System (MHEWS) comprises four interrelated components: Risk Knowledge; Monitoring, Analysis, And Forecasting; Warning Dissemination and Communication; and Preparedness and Response Capabilities (fig.1). The linkage between the four components is vital for the MHEWS system to be effective. Therefore, a critical aspect of MHEWS is the integration and interaction among these components[19].

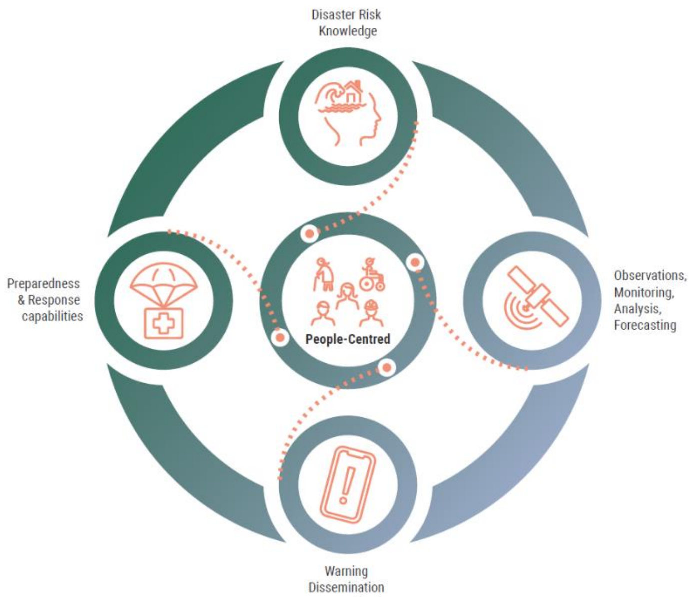


Figure 1: graphical representation of MHEWS (Source: UNDRR,2023)

MHEWS encompasses social and organisational processes that use technology to communicate risks and reduce losses[20]. An effective MHEWS must be people-centred, accounting for the complexities different groups face during disasters. From the outset, people centred MHEWS should be designed and implemented considering the capacities and requirements of at-risk people[21]. Thus, people at risk should be central to all MHEWS processes, with the goal of prompting response actions from the intended recipients. For early warnings to prompt protective or mitigating actions, they must be inclusive, accessible, and actionable.

- **Inclusivity**: MHEWS must include the needs, perspectives, and priorities of diverse societal groups, ensuring meaningful participation. This inclusivity varies according to age, sex, disability, gender roles, indigeneity, sexual orientation, literacy, language, cultural practices, race, geographic location, and socioeconomic status, among other factors. An intersectional approach should be adopted.
- **Accessibility**: MHEWS must ensure that information reaches all potentially affected individuals in an easily understandable manner, regardless of individual circumstances such as disability, literacy, or language.

- **Actionability**: MHEWS should provide information that includes potential impacts and recommended actions that individuals can undertake, enabling them to reduce disaster risk and potential damage and loss.

Several components contribute to the effectiveness of MHEWS. In addition to the four core components, there is growing evidence and understanding to include an overarching and cross-cutting enabler: governance. This component encompasses institutional arrangements that shape and foster early action. It is essential to effectively govern MHEWS, requiring support through appropriate policies, strategies, and an enabling environment with sufficient funding to implement identified outcomes. This relates to clearly define the roles and responsibilities of all stakeholders and establish monitoring and reporting mechanisms to measure progress. Overarching governance ensures institutionalisation through legal and regulatory frameworks and operational procedures that assign clear roles and responsibilities. A comprehensive multi-hazard and multi-actor governance framework enables coherence, facilitates resource access for the system's routine operation, ensures coordination and engagement among key actors and stakeholders, and reinforces integration among the four components. In the context of systemic risk, systemic governance is imperative.

3.2 Common Principles for MHEWS

In 2015, the World Meteorological Organization (WMO) and its partners conducted a global evaluation of Early Warning Systems (EWS) (UNISDR, 2015). Based on an extensive analysis of various national and local cases, ten principles were identified that are crucial for the effective implementation of EWS, which are also applicable to MHEWS[22]. These principles include:

1. *Political Recognition*: a robust political acknowledgment of the benefits of EWS, reflected in harmonized national to local disaster risk management (DRM) policies, planning, legislation, and budgeting.
2. *Core Components*: Effective EWS are built upon four components: (a) risk analysis and incorporation into emergency planning and warnings; (b) hazard detection, monitoring, and forecasting; (c) timely and authoritative warning dissemination; and (d) community planning and preparedness.
3. *Stakeholder Roles and Responsibilities*: EWS stakeholders are clearly identified, with their roles, responsibilities, and coordination mechanisms documented in national to local plans, legislation, directives, and memorandums of understanding.
4. *Resource Support*: EWS are supported by adequate resources (human, financial, and equipment) across all levels, ensuring long-term sustainability.
5. *Risk Assessments*: Hazard, exposure, and vulnerability information is used to conduct risk assessments at various levels, providing critical input into emergency planning and warning message development.
6. *Warning Messages*: Warning messages must be clear, consistent, and include risk information, with considerations for linking threat levels to preparedness and response actions. These messages should be issued from a single, recognized, and authoritative source.
7. *Dissemination Mechanisms*: Mechanisms for warning dissemination must reliably and timely reach authorities, EWS stakeholders, and the at-risk population.
8. *Emergency Response Plans*: These plans should consider hazard/risk levels and the characteristics of exposed communities.
9. *Training and Preparedness*: Training on hazard and risk awareness and emergency preparedness is integrated into various educational programmes, with regular drills to ensure operational readiness.
10. *Feedback and Improvement*: Effective feedback and improvement mechanisms are in place to provide systematic evaluation and ensure continuous system enhancement.

3.3 Key enablers of MHEWS

In the literature review of case studies on Multi-Hazard Early Warning Systems (MHEWS) and their implementations, three key enablers have been identified to operationalise MHEWS in local contexts successfully[23].

As shown in (fig. 3) The enablers for operationalisation of MHEWS are:

- Policy, legislative, and institutional arrangements
- Social and cultural considerations
- Technological and scientific arrangements and their integration in the MHEWS.

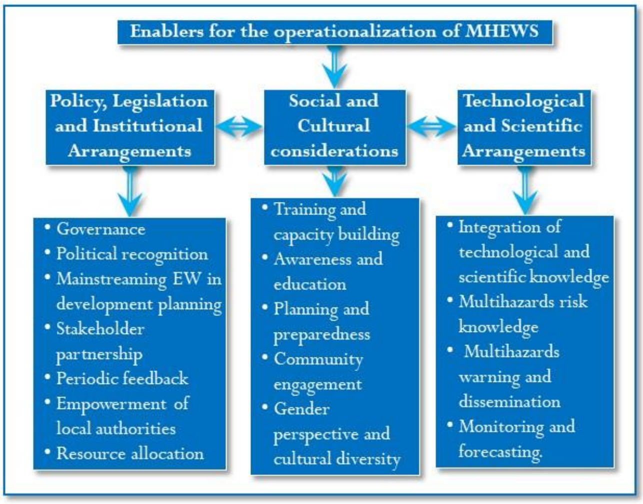


Figure 2: Key enablers for the operationalisation of MHEWS

Each of these enablers for the operationalisation of MHEWS is discussed briefly:

3.3.1 Policy, Legislative, and Institutional Arrangements

Effective governance, accountability, and transparency are fundamental to implementing Multi-Hazard Early Warning Systems (MHEWS). Strong political recognition of disaster risk reduction (DRR) ensures that MHEWS is integrated into national and local policies, while mainstreaming early warnings into development plans helps mitigate risks and enhance resilience. Stakeholder partnerships, particularly in addressing transboundary hazards, foster resource sharing and collective action. Regular feedback and assessments improve MHEWS, while empowering local authorities leverages their contextual understanding to disseminate warnings effectively. Provisioning of adequate resources and infrastructure from public funding sources like sub-national and municipal budgets can ensure sustainable funding channel and long-term viability for the MHEWS.

3.3.2 Social and Cultural Considerations

Engaging and empowering at-risk populations, especially vulnerable and marginalized groups, fosters a culture of preparedness by integrating traditional knowledge and local insights into MHEWS. Gender-sensitive approaches and inclusivity in participation, communication, and response strategies are essential to address the differential impacts of hazards. Training and capacity building enhance the readiness of communities and institutions, while public awareness and education initiatives ensure widespread understanding of disaster risks and resilience strategies. This social integration ensures that early warning systems are accessible, relevant, and effective for all segments of the population

3.3.3 Technological and Scientific Arrangements

The integration of technical and scientific knowledge into decision-making processes enables accurate risk identification and assessment. Comprehensive data on vulnerabilities, exposures, and emergency planning is essential for informed decision-making and effective hazard communication. Timely, clear, and reliable dissemination of warnings through diverse communication channels overcomes potential barriers to reach at-risk populations. Monitoring and forecasting capabilities, supported by real-time data analysis and hazard mapping, are crucial for identifying future risks and providing actionable information for MHEWS. Together, these arrangements strengthen the technological backbone of early warning systems, ensuring precise and effective disaster preparedness.

3.4 Governance Mechanisms for MHEWS

Effective governance for Multi-Hazard Early Warning Systems (MHEWS) requires an integrated framework that combines institutional structures, norms, and stakeholder coordination. This approach enhances efficiency and supports the transition from a technical vision of MHEWS to a systemic perspective that incorporates social and political factors as critical elements of exposure and vulnerability in local or national risk assessments.

The governance mechanisms should clearly define roles, responsibilities, decision-making processes, and communication flows among all stakeholders, including national, regional, and local governments, as well as at-risk communities. The design, implementation, and operation of MHEWS necessitate contributions and coordination from a diverse range of individuals and institutions, particularly those affected[24]. Active participation and collaboration foster knowledge sharing and co-design with affected populations, ensuring transparency, accountability, equity, and legitimacy, which is particularly important in contexts where institutional structures may be weak, dysfunctional, or non-existent[25].

3.4.1 Institutional Arrangements

MHEWS must operate within the framework of national and local Disaster Risk Reduction (DRR) strategies and framework. Establishing and maintaining EWS requires reviewing relevant legislation, institutional roles, and political arrangements. Coordinated mechanisms among institutions, including action plans and resource allocations, provide an overview of institutional capacities and governance related to MHEWS. Identifying regulatory frameworks and institutional mandates, and setting standards or detailed operational procedures for MHEWS, ensures recognition of the responsibilities of key partners. Accountability mechanisms, such as periodic assessments and inspections, should be implemented to ensure MHEWS objectives and effectiveness are met. These mechanisms may include incentives for good performance, penalties for failures, and lessons learned options.

Effective MHEWS governance necessitates vertical and horizontal communication and coordination among early warning stakeholders, involving actors at local, national, and regional levels from various societal sectors. As hazards evolve, institutional and political frameworks must support coordination among stakeholders. Up-to-date and well-structured governance frameworks with long-term commitments are essential for developing and sustaining robust MHEWS[26].

3.4.2 Governance Frameworks

Legal, policy, and regulatory frameworks establish the rules, roles, and responsibilities impacting each crucial component of MHEWS. These frameworks are fundamental instruments of institutional arrangements and governance, influencing the management strategies of the warning systems. However, they must be kept up to date and reviewed regularly to remain effective. By outlining approaches to addressing and resolving issues, they shape the responses of various actors, including local community members. Such frameworks clarify the government's role in EWS implementation, define the responsibilities of different actors and sectors, facilitate planning and monitoring strategies, promote mutual understanding among stakeholders, and create the conditions necessary for the successful implementation of the early warning–early action continuum. Additionally, policy and regulatory frameworks help to ensure adequate financial resources are allocated to institutions responsible for monitoring hazards and forecasting potential disasters.

Robust policies and regulations ensure effective "early warning, early action." Furthermore, the development and implementation of rules and protocols differ for rapid-onset hazards (e.g. floods) compared to slow-onset hazards (e.g. droughts). Implementation timelines are crucial, and establishing appropriate laws, policies, and protocols presents specific challenges. Transboundary hazards also necessitate institutional arrangements and special coordination mechanisms among EWS in neighbouring countries. Such coordination ensures clear communication and dissemination of warnings at all levels and enhances data sharing related to risk knowledge and hazard detection.

Given that risk and hazard information originate from various national agencies, a concerted effort to enhance communication lines among different agencies—both horizontally and vertically—is essential. The success of the warning communication and dissemination component and the overall EWS relies on clearly defining "who does what" in the MHEWS. Implementing standard operating procedures (SOPs) frequently yields benefits such as inter-institutional coordination for issuing warnings or setting warning levels, enforcing inter-institutional agreements regarding evacuation timings, and reinforcing accountability processes based on established and agreed-upon procedures. Communication and warning dissemination protocols must reach the entire at-risk population, ensuring inclusivity of persons with disabilities, children, Indigenous Peoples, remote communities, and sectors such as agriculture, fisheries, energy, education, and health, which are vulnerable due to disasters[27].

3.4.3 Financing mechanisms

Effective financing for MHEWS should enhance the entire value chain inclusively, prioritize people-centred, risk-informed early actions, and support multi-hazard programs while engaging the private sector and academia. As public goods, MHEWS are primarily funded by national and local public institutions, underscoring the need for sustainable and innovative funding mechanisms. Value of an early warning is largely unrealised until its implications are understood and acted upon by relevant groups or institutions. The management of observation and monitoring networks for various hazards, as well as the generation of forecasts and warnings, involves significant expenses. However, most of the financial benefits or revenues associated with these systems are realized at the end-user stage of the value chain. This is because the primary users, such as governments, businesses, and communities, leverage hazard forecasts and warnings to make informed decisions, mitigate risks, and avoid potential losses. For instance, farmers may use drought forecasts to adjust planting schedules, or industries might use flood warnings to safeguard infrastructure. These actions, while invaluable in reducing disaster impact, represent the final point of value realization, often overshadowing the substantial upstream costs.

For hazards like extreme hydrometeorological events (e.g., heavy rainfall, floods), the relatively low costs to end-users are only feasible due to the accessibility of global datasets and shared outputs. Organizations such as the World Meteorological Organization (WMO) and global climate monitoring systems provide free or subsidized access to large-scale, high-quality data. This shared resource model ensures that national and local early warning systems can operate cost-effectively, enabling even resource-constrained nations to generate forecasts and disseminate warnings without bearing the full financial burden of developing global datasets independently. However, ssustainably financing national Early Warning Systems (EWS) presents significant challenges, especially in low- and middle-income countries where resources are often limited and competing priorities strain public budgets. The costs associated with maintaining observation networks, developing advanced forecasting technologies, training personnel, and disseminating warnings are substantial. Many governments in these regions lack the financial capacity to independently fund these critical systems, risking gaps in their ability to provide timely and effective warnings to vulnerable populations. This limitation underscores the need for innovative and collaborative approaches such as public private partnerships, resource sharing across sub-national governments and tapping climate and adaptation funding, which can help to ensure the sustainability of Multi-Hazard Early Warning Systems (MHEWS).

3.5 Vulnerability and Inclusion in MHEWS

Effective Multi-Hazard Early Warning Systems (MHEWS) must consider the diverse vulnerabilities of at-risk groups. Vulnerable populations, as identified by the UN framework on COVID-19 in 2020, include women, children, older persons, persons with disabilities, Indigenous Peoples, migrants, minorities, and those living in poverty or informal settlements[28]. Each group faces unique risks, shaped by socioeconomic, cultural, and environmental factors, requiring tailored interventions.

Understanding the social factors that may inhibit appropriate action upon receiving a warning is crucial for the effectiveness of MHEWS. Douglas and Wildavsky (1982) suggested that risk perception and acceptance is a collective construct in society[29], several scholars[30,31,32] assert that people do not respond to risks individually; people often evaluate their situation by comparing their interpretation with others in their community, referred to as "social milling", which help them decide for actions; therefore, risk perception and acceptance is contextually situated social activity. Similarly, Morgan et al. (2002) suggested that communities perceive and internalise risks through sociocultural processes, and their perception goes through constant moderation by society, and institutions; therefore, the perception of risk is dynamic and variable over time[33]. Furthermore, Walmsley (2006) argued that within each community, different vulnerability, capacity, needs, interests, and knowledge exists in non-homogenous forms[34]. These vulnerabilities arise from socioeconomic, cultural, and environmental factors that shape individuals' exposure to risks and their ability to respond to warnings. Therefore, MHEWS must acknowledge that vulnerability is contextually situated and is addressed based on differing needs.

Tailored interventions are essential to ensure that early warning systems are inclusive, effective, and equitable. Building trust, ensuring reliable communication, and addressing barriers such as language differences, physical disabilities, and access to technology are critical components of a people-centered approach. The involvement of local leaders and community representatives in MHEWS design fosters inclusivity[35] and ensures that the unique needs of all groups are met, while leveraging local knowledge to enhance system effectiveness[36].

3.5.1 Gender-Specific Vulnerabilities

Gender discrimination increases women and girls' vulnerability during disasters by limiting their access to resources, information, and decision-making opportunities, often resulting in higher mortality and livelihood disruptions compared to men. Responsibilities like caregiving may delay their evacuation, as seen during the 2015 Nepal earthquake, where more women perished due to their roles indoors while many men were absent as migrant workers. Women's limited access to technology and reliance on informal communication channels further hinders timely action[37]. Addressing these inequities requires involving women in the design of gender-responsive Multi-Hazard Early Warning Systems (MHEWS) to ensure their needs are met. Women's participation strengthens community resilience, improves accountability, and fosters accurate risk communication by integrating local and scientific knowledge.

3.5.2 Inclusion of Persons with Disabilities

Persons with disabilities face disproportionate risks during disasters, with mortality rates two to four times higher than the general population, largely due to exclusion from disaster risk reduction (DRR) policymaking and practice. Barriers such as societal attitudes, communication challenges, and institutional gaps are compounded for marginalized subgroups, including women, children, and individuals with intellectual or psychosocial disabilities. To address these disparities, DRR initiatives must adopt an intersectional approach, ensuring inclusive participation and accessibility through reliable disability data and alternative communication methods like sign language, Braille, interpreters, and visual alerts[38]. Engaging persons with disabilities and their representative organizations in all phases of early warning systems fosters equitable outcomes and empowers them as agents of change[39].

3.5.3 The Role of Indigenous Peoples

Indigenous Peoples face severe threats due to their reliance on environment and vulnerable ecosystems. Climate-related events, exacerbated by climate change, frequently impact farmland, rivers, and livestock. However, Indigenous Peoples are increasingly recognised as allies in climate change adaptation and disaster risk management, offering sustainable local strategies. Traditional practices like shifting cultivation, food preservation, and local weather observation play a crucial role in disaster prevention and adaptation. Integrating indigenous, and local knowledge with scientific information enhances the reliability, sustainability, and community ownership of Multi-Hazard Early

Warning Systems (MHEWS). People-centred MHEWS can benefit from Indigenous knowledge to assess potential events and design early actions based on historical experiences[40].

3.5.4 Ageing and Vulnerability of Children

While ageing does not inherently create vulnerability, older persons may face increased risks during disasters due to health issues like chronic conditions, sensory impairments, cognitive decline, and reliance on assistive devices. Involving older persons and their representatives in MHEWS development ensures their needs and capacities are addressed. Participatory approaches support their integration and leverage their extensive local knowledge from past disaster experiences, fostering synergies among different community groups and enhancing local resilience[41]. Similarly, children are highly vulnerable in disasters due to their dependence on caregivers, inability to evacuate independently, and challenges like disrupted education, mental health impacts, and limited access to temporary schools. According to UNICEF (2021), disasters affected approximately 66 million children worldwide annually in the late 20th century, a number expected to triple in the coming decades[42].

3.5.5 Twin-Track Approach for Inclusion of At-Risk people

The twin-track approach[43] is recommended to promote the inclusion and equal opportunities and rights of the at-risk people in MHEWS. This includes two-pronged composite action of removing barriers to participation for vulnerable people, as well as improving the access for collaboration and knowledge coproduction. Additionally, it involves launching targeted capacity-building activities and providing customized support to ensure access and inclusion in MHEWS. The twin-track approach includes:

- Promoting Gender and Disability Impact Assessments at local level to gain a nuanced understanding of risk, specific to women and persons with disabilities.
- Documenting Disaster Impacts in a Disaggregated Manner, ensuring that disaster loss databases account for sex, ethnicity, age, and disability.
- Providing Tailored Forecast Information to meet people's needs, including hazard impact details and preparedness actions.
- Ensuring Clear Warning Messages and Actions for effective communication.
- Defining Evacuation Thresholds based on the evacuation timelines of vulnerable groups.
- Addressing Barriers to Accessing Evacuation Centres, making them accessible, comfortable, hygienic, safe, and child friendly.

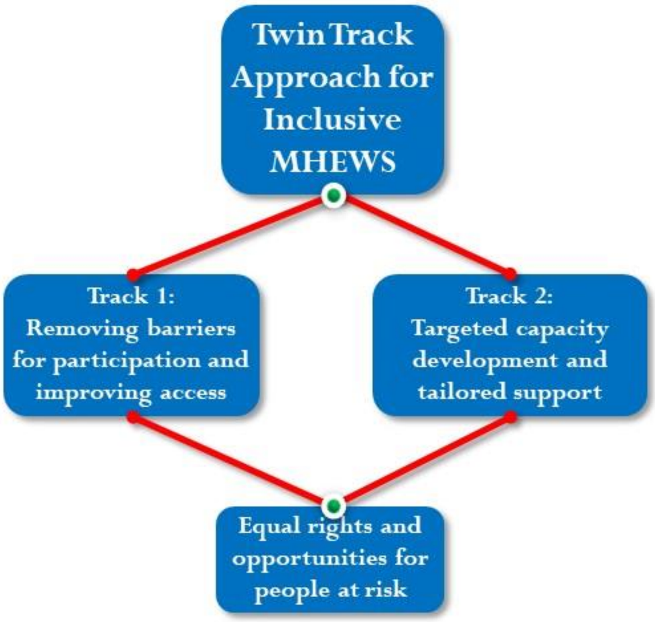


Figure 3: Twin-track approach for inclusive MHEWS (CBM 2012)

- Empowering Indigenous Communities by providing them with communication tools and culturally appropriate training.
- Engaging Educational Communities through formal partnerships to involve them in the MHEWS development process.

3.5.6 Inclusion Of Vulnerable Population in Four Components Of MHEWS

The inclusion of people at risk in four components of MHEWS involves:

- In *Disaster Risk Knowledge*: Engaging communities for understanding contextual knowledge and for the risk assessments, ensuring inclusivity in understanding hazards, vulnerabilities and capacities, livelihoods, social inclusion and exposure. Also, community engagement is essential in combining all forms of knowledge: local, traditional, Indigenous, generational and scientific for the understanding of risks, particularly from the perspective of those who are most vulnerable and those who can help mitigate risks.
- In *Observation, Monitoring, Analysis, and Forecasting*: using accessible technologies and platforms to disseminate hazard information, ensuring it reaches all community members. Enhancing community capacity to develop hazard monitoring and warning dissemination systems for local hazards is vital. This includes training observers, authorities, and communicators who operate the warning system. Traditional and Indigenous knowledge should also be considered.
- In *Warning Dissemination and communication*: training community leaders and trusted figures to reinforce warnings, using multiple channels and languages, and repeating messages multiple times are crucial for effective communication during disasters. Public awareness campaigns tailored to the specific needs of vulnerable groups ensure that warnings are contextualized and accessible, while two-way communication mechanisms help verify information and gather local insights on hazards. Gender aspects also play a significant role, as inequalities in education, economic capital, and access to technology can affect individuals' ability to receive warnings and access information. Additionally, gendered behaviour patterns, information preferences, and the social exclusion of women and marginalized groups must be addressed to ensure inclusive and equitable communication strategies.
- *Preparedness and Response Capabilities*: conducting regular drills and awareness campaigns to familiarise communities with early action plans and evacuation procedures. Implementing training activities for those involved in the operation of all four components of MHEWS is critical. Disaster preparedness and response plans should be developed to address the needs of <u>all</u> community groups, ensuring comprehensive and inclusive strategies. Periodic drills should be conducted to empower at-risk communities, enhancing their understanding of the risks they face and increasing their preparedness to respond to potential disasters[44].

3.6 Challenges in MHEWS

One significant challenge in Multi-hazard Early Warning System (MHEWS) is the lack of a common understanding among disaster practitioners, experts, and at-risk populations regarding the definition and scope of MHEWS. Divergent views and perceptions often lead to confusion, therefore, establishing a uniform understanding of MHEWS is essential[45].

Key findings related to MHEWS and the Sendai Target G underscore the importance of engaging diverse actors, including the private sector. This diversity presents both challenges and opportunities. The primary focus should be reaching communities and individuals through collaboration with multiple stakeholders including private sector for early action, and specific hazard monitoring and anticipatory measures.

Current governance mechanisms for MHEWS are inadequate, necessitating improved arrangements and more coordinated financing. Policies, strategies, legislation, clear mandates, roles, and responsibilities must be enhanced. Budget allocation, capacity assessment, and monitoring mechanisms for MHEWS are currently insufficient. Policy coherence for MHEWS related to sustainable development, climate action, and resilience requires legislative progress, clear roadmaps, and accessible policy information. Enhanced collaboration among various entities is crucial. Optimising and upgrading from existing early warning systems for better response times and coordination can effectively address disasters and positively impact communities. Available tools and technologies, including technical tools and applications, should be utilised efficiently[46].

A siloed approach and narrow administrative scope impede a holistic understanding of transboundary risks. This fragmented approach fails to consider the systemic nature of risks and their interconnections. Consolidating efforts into a unified system involving government, academia, non-government organisations, the private sector, communities, donors, and inter- and intra-governmental bodies is vital. Joint efforts and the co-production of knowledge can translate scientific understanding into robust policy and practice, ensuring the sustainability of MHEWS[47].

Transitioning from hazard-specific warning systems to an integrated multi-hazard approach is another significant challenge for MHEWS. Ensuring these systems communicate and build on one another to provide early warnings for multiple hazards is essential and should be a gradual process. Compatible and interoperable mechanisms and capacities involving different disciplines are required for proper implementation, which is best established at national and local levels[48].

Additionally, the limited capability of risk assessment and analysis mechanisms to capture the complexities and interdependencies of cascading impacts reduces their effectiveness in mitigating risk. Furthermore, limited funding and focus on post-disaster response and recovery rather than preparedness pose significant challenges. A lack of coordination mechanisms among municipalities and provinces within basins exacerbates these issues[49].

MHEWS may also contend with conflicting interests, where different hazards may require completely opposing response measures. For example, during the COVID-19 emergency, isolation strategies conflicted with flood response strategies, highlighting the need for collaborative efforts at the local level. MHEWS must navigate these challenges to provide cohesive, comprehensive, and actionable early warnings[50].

4 CURRENT STATE OF THE EARLY WARNING SYSTEM IN NEPAL

Nepal has made significant progress in early warning systems (EWS) for hazards like floods and Glacial Lake Outburst Floods (GLOFs), with government and non-governmental efforts expanding to include landslide EWS based on rainfall, topography, and geology. While advancements have been made in flood and GLOF warnings, pilot initiatives are underway for monsoon rainfall alerts. Despite these efforts, there is a need for greater capacity in issuing warnings, improved response effectiveness, and better integration of fragmented systems. Effective EWS implementation requires robust disaster preparedness across all levels, which the Government of Nepal supports through annual updates of disaster response plans and mobilization of Humanitarian Clusters at national, sub-national, and local levels.

Hazard Observation, Monitoring and Forecasting

Several hazards are associated with diverse natural phenomena, requiring collaboration among various sector agencies for effective observation and monitoring of hazards. The Department of Hydrology and Meteorology (DHM) oversees monitoring and forecasting of heavy rainfall, drought, cold and heat waves, lightning, snowstorms, and hailstorms, including floods (inundation, flash floods, and glacial lake outburst floods or GLOFs). The DHM uses data from 16 synoptic stations, 106 river gauge station, 50 agro-meteorological stations, and 460 climate observation stations that includes 162 precipitation stations, many with real-time telemetry. The DHM utilizes various forecasting models, including WRF (Weather Research and Forecasting model) for weather forecasting and MIKE11 (a one-dimensional hydrodynamic model), HEC-HMS (Hydrologic Engineering Center-Hydrologic Modeling System), and HEC-RAS (Hydrologic Engineering Center-River Analysis System) for flood predictions in major rivers. Nepal receives seasonal climate outlooks and medium-term forecasts via RIMES (Regional Integrated Multi-Hazard Early Warning System for Africa and Asia) and WMO, and impact-based forecasting (IBF) has been started in four mountain districts to predict heavy rainfall impacts. Additionally, GLOF monitoring is active at Tsho Rolpa and Imja lakes. Air pollution is monitored at 26 stations under the Environment Department, with data shared publicly. Satellite data also aids in precipitation and forest fire detection, with ICIMOD (International Centre for Integrated Mountain Development) providing fire alerts, though suppression measures are still under development. The National Earthquake Monitoring and Research Centre has 21 seismic and 7 accelerometer stations, though early warning systems for earthquakes and landslides are yet to be operational. Post-event data is shared publicly, and landslide monitoring uses remote sensing with plans to expand local monitoring systems in collaboration with ICIMOD. The Epidemiology and Disease Control Division operates the Early Warning and Reporting System (EWARS) across 118 hospitals, detecting outbreaks of vector-, water-, and foodborne diseases, which complements the Health Management Information System (HMIS).

Communication and Dissemination

Forecast and warning information is disseminated through telephones, radio, online platforms like Facebook and twitter, and SMS. The DHM has agreements with Nepal Telecom and Ncell to send free alert messages to the cell phones located in areas at risk. Community-based dissemination mechanisms such as community level early warning channels developed in collaboration with local governments and organisations, ensure wider distribution of warnings.

Preparedness and Response

In Nepal, disaster preparedness and response are coordinated by the National Disaster Risk Reduction and Management Authority (NDRRMA), with federal security force agencies such as the Nepal Army, Nepal Police, and Armed Police Force playing key roles. Emergency Operations Centres (EOCs) collect information on casualties and damages, while the Health Emergency Operations Centre (HEOC) focuses on health-related hazards. Security agencies manage search and rescue operations, while District Disaster Management Committees (DDMCs) oversee district and local responses, supported by local governments and Community Disaster Management Committees (CDMCs) for implementing early warning systems. Additionally, various government bodies, NGOs, the Nepal Red Cross Society, and UN agencies contribute to disaster preparedness and response. However, greater integration and capacity-building efforts are needed to strengthen Nepal's overall disaster management systems.

5 DISASTER GOVERNANCE IN NEPAL

Nepal's disaster governance framework is structured by the Constitution of Nepal (2015) and the Disaster Risk Reduction and Management (DRRM) Act (2017). The Constitution designates disaster risk reduction and management as both the sole responsibility of local governments and a shared responsibility among federal, provincial, and local governments. Local governments are intended to manage disasters independently where feasible, with provincial and federal governments providing support when necessary[51].

The DRRM Act 2017 establishes formal structures and responsibilities at federal, provincial, district, and local levels. At the federal level, it institutes the DRRM National Council, an Executive Committee, and the National Disaster Risk Reduction and Management Authority (NDRRMA). Amendments introduced in 2019 established the Province Disaster Management Council and delineated the structure and functions of Provincial Disaster Management Executive Committees. The Act mandates the formation of Disaster Management Committees at local levels, guided by the Local Government Operation Act 2017[52]. These legislative measures led to the creation of the NDRRMA, responsible for coordinating and implementing DRRM functions nationally. The DRRM Regulations 2019 further specify the functions of various government decision-making bodies in line with the DRRM Act 2017. Additionally, the Government of Nepal has endorsed a National DRRM Policy (2018)[53] and a Disaster Risk Reduction National Strategic Action Plan (2018-2030), providing a comprehensive framework for disaster risk reduction and management[54].

The DRRM Act 2017 mandates the NDRRMA to oversees the development and operation of a national-scale early warning system, investigating relevant modern and traditional technologies for disaster risk mitigation. Furthermore, the NDRRMA shall manage a National Emergency Operations Centre, providing early information on potential disasters, coordinating relief efforts, and activating search and rescue operations. The NDRRMA has also recently drafted a National Framework and Action Plan for Multi-Hazard Early Warning Systems (MHEWS), emphasising multi-hazard risk assessment and a people-centred approach. It integrates within MHEWS to promote inclusive and people-centred approaches, planning and decision-making, interagency coordination, and monitoring and evaluation.

At provincial levels, the Provincial Disaster Management Council and Committee formulate policies, oversee disaster preparedness, and coordinate relief efforts. Similarly, district and municipal levels establish Disaster Management Committees, conduct disaster response activities, and operate Emergency Operation Centres. Local Disaster Management Committees align with national policies, coordinate activities, and develop disaster management information systems and early warning systems.

Local governments, empowered and integrated with national-level early warning mechanisms, are instrumental in EWS design, maintenance, and execution. They must comprehend and effectively disseminate standard advisory and warning information from Multi-Hazard Early Warning Systems (MHEWS) to engage local populations in disaster risk reduction (DRR) strategies, thus enhancing public safety and minimising potential losses.

Development partners' involvement is crucial, supporting government agencies in Nepal in managing disaster risks through various localised initiatives, including early warning system development, infrastructure projects, capacity building, and community resilience programmes. Multilateral and bilateral development agencies, along with international non-governmental organisations (INGOs) and NGOs, contribute significantly to disaster risk management efforts in Nepal, providing technical expertise, and policy guidance, and collaborating closely with local communities to facilitate disaster preparedness, response, and recovery.

6 FRAMEWORK FOR OPERATIONALISATION OF MHEWS AT THE LOCAL LEVEL IN NEPAL

The proposed framework for operationalising MHEWS at the local level is developed based on the latest insights in multi-hazard early warning system (MHEWS) literature and field-based observations and consultations in Phalelung, Panchthar, Nepal. It provides a systematic approach to analysing and addressing specific issues, promoting consistency and coherence in decision-making and implementation of MHEWS. This framework offers an inclusive and structured basis for operations, employing a practical, stepwise, and iterative process. The MHEWS framework outlines a comprehensive vision encompassing all four pillars: Disaster Risk Knowledge, Detection, Monitoring and Forecasting, Warning Dissemination and Communication, and Preparedness to Respond. In addition, the framework requires a people-centred approach and accountable governance to be integrated across all four pillars for effective MHEWS (fig.4).

The framework for operationalising a multi-hazard early warning system (MHEWS) at the local level completely aligns with the national framework developed by the National Disaster Risk Reduction and Management Authority (NDRRMA). Like the national framework, the local framework emphasises strengthening the NDRRMA as a central pillar in coordinating the four pillars of MHEWS, ensuring effective coordination and collaboration. Based on the Disaster Management Act of 2017, the framework envisions support from federal and provincial governments in implementing MHEWS and encourages resource pooling and collaboration among local governments in coordination with the provincial government and NDRRMA. This framework adheres strictly to national policies and institutional settings while incorporating the latest and most advanced understanding of MHEWS in the international context.

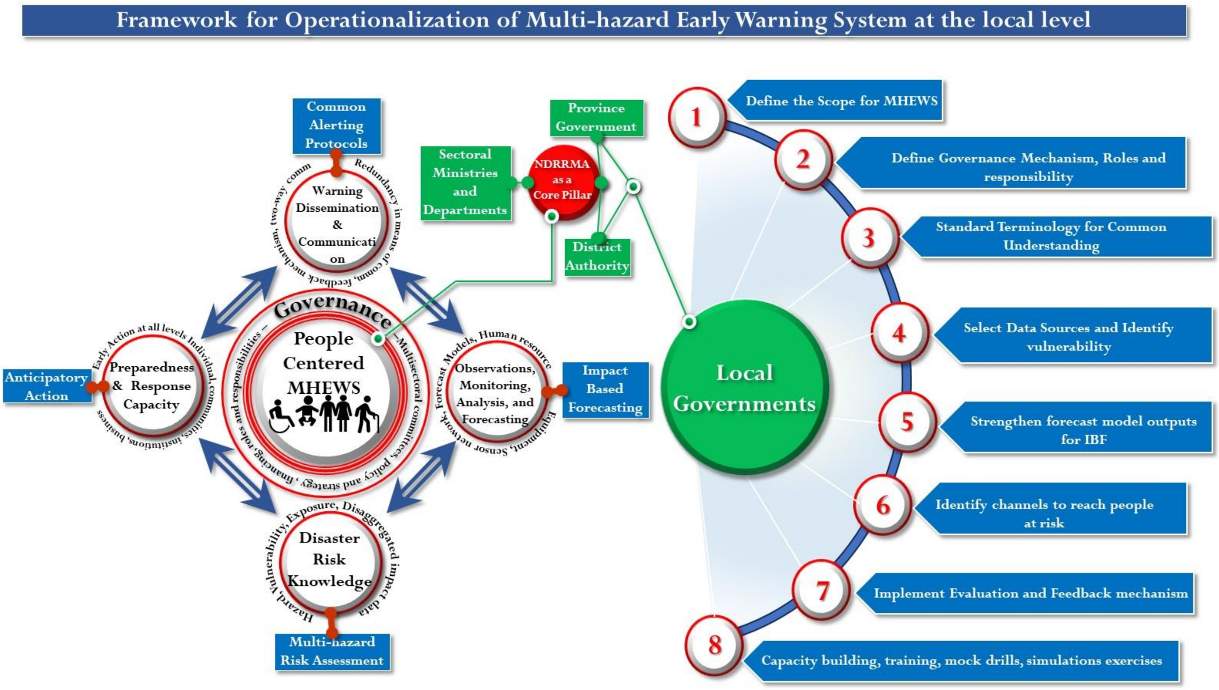


Figure 4: Framework for operationalisation of MHEWS at Local Level, with includes people centred approaches at the core of all four components related to MHEWS and governance as an integral component for facilitating integration. The framework suggests the required activities at all four components, as well as 8-step prerequisites for the operationalisation of MHEWS at the local level.

The framework emphasises a people-centred approach in all MHEWS interventions, placing individuals at the core of the MHEWS process. The people centred MHEWS emphasises inclusive, accessible, and actionable early warnings through the co-production of knowledge with at-risk populations across all the four components. Intersectional vulnerability and the differential needs of individuals, including access abilities, language preferences, and literacy levels, must be considered to ensure effective and equitable early warning systems. This necessitates involving at-risk populations from the outset for knowledge co-production and sustainability, considering various social identities such as gender, age, ethnicity, and disability and structural factors like poverty, governance, and power relations. Tailoring approaches to specific contexts and ensuring cultural appropriateness are essential to meet the diverse needs of different social groups. By adopting a people-centred perspective, interventions and policies can address the multifaceted dimensions of vulnerability and promote inclusivity.

All four components play a crucial role in disaster management. However, integrating these components requires strong governance. In the context of multi-hazard early warning systems (MHEWS), effective governance involves interactions across multiple sectors, appropriate policy and strategy frameworks, adequate financing for implementation, and clearly defined roles and responsibilities for all involved parties. Moreover, monitoring and reporting against established targets are essential to ensure accountability and effectiveness. The governance mechanism also highlights early action to reduce disaster risks and strengthen resilience across all sectors.

Structured governance mechanisms are crucial for developing and enhancing MHEWS, fostering resilience and reducing disaster risks at both local and national levels. Effective collaboration is essential, with partners needing to understand each other's perspectives and develop mechanisms to address diverse needs. The four interrelated components of MHEWS framework and their linkages are discussed as follows:

6.1 The Disaster Risk Knowledge and Multi-Hazard Risk Assessment

Multi-hazard risk assessments are foundational for multi-hazard early warning systems (MHEWS). These assessments provide a comprehensive understanding of hazards, vulnerabilities, and exposures, feeding into the first component of Risk Knowledge in MHEWS. The concept of "multi-hazards" encompasses all possible and relevant hazards and their interactions within a specific spatial and temporal context. When communities face multi-hazard risks, management strategies must consider these hazards and their interactions comprehensively.

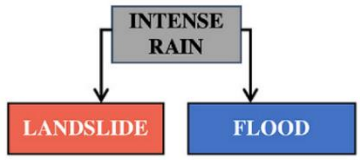
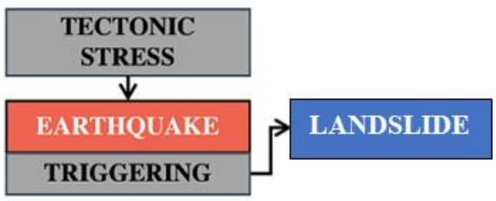
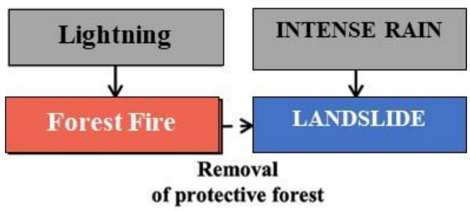
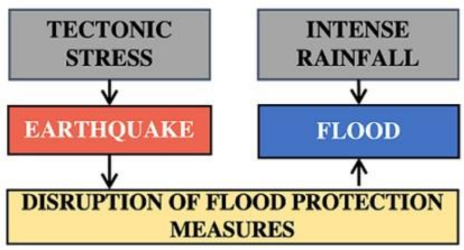
Multi-hazard risk assessments involve multiple hazards that may occur independently, simultaneously, cascading, or cumulatively over time, considering their possible interactions resulting composite effects. Vulnerability and exposure assessments encompass social, environmental, economic, and physical dimensions in multi-hazard context. The dynamic nature of risks must be accounted for, including the evolving nature of hazards, vulnerability, exposure, and inherent uncertainties within natural systems.

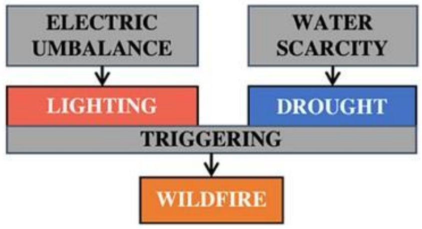
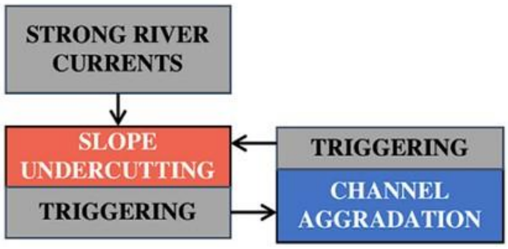
Furthermore, this component should establish knowledge co-production with at-risk individuals, enabling their active participation in generating knowledge. It involves analysing the impacts across time and space from multiple hazards to understand their changing patterns. Exposure assessment should consider population, physical infrastructure, environmental, and cultural heritage assets. The vulnerability assessment should encompass structural, non-structural, and economic factors.

In multi-hazard risk assessment, hazard interactions can be categorized into various types[26], each with distinct characteristics as shown in Table (1). Triggering interactions occur when one hazard induces secondary or tertiary hazards of the same or different nature. For example, earthquakes, rainfall, snowmelt, or slope erosion during flooding can trigger multiple landslides, significantly increasing the overall hazard potential in a region. Simultaneous hazard events can also trigger secondary hazards; for instance, lightning during a drought can cause wildfires. Feedback mechanisms can intensify the primary hazard, leading to recurrent secondary hazards. Mountainous river systems, for example, contribute to cyclic channel aggradation through such feedback processes. Primary hazards can increase the likelihood of secondary hazard occurrences by modifying environmental parameters, pushing the system toward a specific threshold or "tipping" point. In this case, while the primary hazard does not directly trigger the secondary hazard, it elevates the chances of its occurrence. For instance, wildfires that damage vegetation increase susceptibility to landslides triggered by rainfall or earthquakes.

Conversely, hazard occurrences can reduce the probability of secondary hazards. Environmental parameter alterations caused by a hazard can diminish the likelihood of specific secondary hazards. For example, heavy rainfall increases surface moisture content while reducing the water table depth, mitigating the immediate post-rainfall wildfire risk. Spatial and temporal coincidence of hazards constitutes another interaction type. When multiple hazards occur in proximity within a brief timeframe, their cumulative impact can exceed the sum of individual events, creating synergistic effects. This concept applies to both triggered hazards, where primary and secondary hazards occur in close succession, and independent hazards that overlap spatially and temporally. For example, an earthquake can compromise critical infrastructure, making it more susceptible to collapse during subsequent aftershocks if prompt repairs are not undertaken.

Table 1: Hazard interaction types

Hazard Interaction Type	Example
(a) Compound Hazards: It refer to multiple hazards generated by a single trigger, or a "primary event." For instance, an intense rainstorm might trigger both landslides and floods. These resultant hazards are termed "compound hazards."	
(b) Cascading Hazards: Cascading hazards, also referred to as "coupled events," occur when a primary event triggers one or more sequential events. For example, an earthquake might trigger a landslide or a mass movement.	
(c) Disposition Alteration: In disposition alteration, one hazard changes the general setting of another, influencing its susceptibility to a potential trigger event. For instance, lightning can cause a forest fire, which removes the protective forest cover and increases the probability of landslides in the event of intense rainfall. This mechanism can also have a negative effect, such as heavy rainfall reducing a region's wildfire probability.	
(d) Additional Hazard Potential: This mechanism involves the amplification of impact due to the coincidence of different hazards in space and time. Amplification occurs when the primary hazard damages elements designed to mitigate the risk of a secondary hazard, thereby altering the scenario of the second hazard and potentially increasing the risk. An example is the disruption of flood defences by an earthquake, which changes the subsequent flood scenario.	

(e) Coincident Triggering: It refers to the simultaneous occurrence of two unrelated hazards, which then trigger a third hazard. For instance, wildfires may be triggered by lightning during a drought, or a landslide might be triggered by the coincidence of heavy rain and an earthquake.	
(f) Cyclic Triggering: It involves the exacerbation of an initial hazard by the occurrence of a secondary hazard, leading to further episodes of the secondary hazard and creating a positive feedback loop. An example is the undercutting of slopes by river systems, causing channel aggradation, which in turn triggers greater undercutting, thus developing a positive feedback loop.	

Multi-hazard risk assessment involves identifying all potential hazards affecting a specific region. The mechanisms of interaction among these hazards are identified and described using one or more of the six basic interaction mechanisms classified in Table (1). This aims to determine which hazards are involved and to establish the causal dependencies among them, forming the basis for a coherent and realistic multi-hazard risk assessment. Upon identifying the interaction mechanisms and investigating the causal dependencies, comprehensive multi-hazard modelling can be implemented. Due to the variety and heterogeneity of interaction types and hazards, the availability of data, and whether the analysis is quantitative or qualitative, the multi-hazard analysis is highly contextual.

To implement a multi-hazard risk assessment, the first step involves identifying all hazards that might significantly affect a specific region. These include hazards that have already occurred or might occur in the future, either within the region of interest or in other regions that could impact it. Ideally, the hazard list should encompass both unexpected, short-notice events (e.g., earthquakes, flash floods) and longer-term hazards (e.g., drought, subsidence). This initial step focuses on the identification of hazards and their interactions, followed by multi-hazard modelling. This step includes hazard assessment, without considering the potentially exposed elements and their vulnerabilities. The primary objective here is to identify and quantify potential causal dependencies and interaction mechanisms among hazards.

The next step involves assessing the resulting multi-hazard impacts in terms of risks, including vulnerability and exposure to the multiple hazards, considering the hazard interaction in the modelling process. It includes investigates the spatial and temporal overlapping of hazards, determining interactions at the impact level independently of their causal dependencies. The exposed elements and their vulnerabilities are the sole connections among the different hazards considered. It allows for a more practical and effective quantification of the different hazards interacting at these two levels by simplifying the overall modelling approach.

6.2 Observation Monitoring, Analysis, and Forecasting

The Observation, Monitoring, and Forecasting component of Multi-Hazard Early Warning Systems (MHEWS) integrates diverse data sources, sensor networks, and forecast models with human expertise to establish robust hazard detection, monitoring, and forecasting mechanisms. Advanced technological tools, such as remote sensing and satellite systems, are complemented by local and indigenous knowledge to improve effectiveness. A key innovation within this component is the adoption of impact-based forecasting (IBF), which combines weather data with exposure and vulnerability information to predict the potential effects of weather events on communities. This shift from simply forecasting weather to predicting its impacts ensures that warnings are actionable, accessible, and tailored to specific needs.

Effective monitoring requires tracking conditions such as river levels, weather patterns, seismic activity, and land use through specialized departments, like the Department of Hydrology and Meteorology (DHM), Department of Mines and Geology (DMG), Department of Health Services (DHS), and Department of Water Resources and Irrigation (DWRI), hydrology, meteorology, and health services. To strengthen MHEWS, data from these systems must be centralized for analysis and dissemination, ensuring a cohesive multi-hazard approach. While stakeholders may not engage with all components for every hazard, they contribute to a comprehensive system that considers hazards' interconnectedness and impacts.

Impact-based forecasting, a cornerstone of MHEWS, links hazard data with decision-support systems to enable anticipatory actions and mitigate risks. Various sectors—such as agriculture, transportation, health, and disaster management—benefit from IBF, which integrates demographic data, geographic information systems (GIS), and community perspectives. Effective impact-based forecasting requires collaboration with experts possessing additional expertise, resources, and knowledge, such as demographic data, crowd-sourcing techniques, geographical information systems (GIS), interoperability, and third-party data integration and usage. Incorporating the perspectives of vulnerable communities in the information system is crucial[55].This collaborative, cross-sectoral approach ensures that MHEWS comprehensively addresses vulnerabilities and enhances societal resilience.

6.3 Warning Dissemination and Communication

The Warning Dissemination and Communication component of a Multi-Hazard Early Warning System (MHEWS) ensures that hazard alerts reach all at-risk individuals reliably and effectively. To mitigate potential network or system failures, backup communication methods and business continuity plans are essential. Diverse communication channels, such as telephones, radio, television, social media, and sirens, should be used to maximize coverage and accessibility. Messages must account for varying needs like language preferences and literacy levels, ensuring they are clear, actionable, and easy to understand. Trusted, authentic sources are critical to establishing public confidence in the warnings.

Collaboration between forecasting agencies, telecom providers, and media outlets strengthens dissemination efforts, while public engagement is vital to improve the system's responsiveness. Warnings should focus on prompting actionable responses rather than merely informing about hazards. Using multiple communication channels tailored to recipients' capacities and providing transparent messaging—such as communicating scientific uncertainties in local languages—enhances accessibility. Additionally, continuity plans must ensure redundancy in communication methods during disasters, reducing the risk of information delays.

Standardizing warning messages is key to reducing confusion, where Common Alert Protocol (CAP)[56] can play a central role. CAP enables the dissemination of consistent, easy-to-understand alerts across multiple platforms. By addressing essential details—such as the nature, severity, location of the hazard, and recommended actions—CAP ensures the warnings are both comprehensive and actionable. Its inclusive design supports vulnerable populations, making it an indispensable component for effective risk communication in MHEWS.

6.4 Preparedness, Early Action and Response Capacity

Preparedness, early action, and response capacities are critical pillars of Multi-Hazard Early Warning Systems (MHEWS), demanding coordinated and timely responses across individual, community, business, and institutional levels. These elements ensure that all stakeholders are equipped to anticipate, address, and mitigate the impacts of potential hazards effectively. A robust preparedness involves proactive planning, capacity-building, and resource allocation, tailored to the unique vulnerabilities and needs of various groups. It is essential to conduct institutional assessments and implement capacity-building initiatives aligned with local-level policies. These assessments help identify gaps, strengths, and opportunities within institutions, enabling the formulation of targeted strategies to enhance disaster readiness. Clearly defining the roles and responsibilities of all agencies involved in the Multi-Hazard Early Warning Systems (MHEWS) is critical. This can be achieved through the development of well-documented protocols and Standard Operating Procedures (SOPs). Preparedness efforts must prioritize resource allocation and the implementation of regular training programs, mock drills, and simulations. These activities are instrumental in enhancing the practical skills and readiness of responders and communities. By fostering a culture of continuous capacity building, institutions and communities can ensure timely and coordinated responses during disasters, thereby strengthening the overall resilience of the MHEWS framework.

Anticipatory action, based on actionable warnings and pre-planned measures, enables communities and organizations to act swiftly, reducing the impacts of hazards on at-risk populations and safeguarding lives, livelihoods, and development gains. By anticipating hazards before they occur, risks can be better managed through timely actions such as early warning messaging, distribution of essential supplies, cash support, and evacuation measures. For such actions to be effective, warnings must be timely, clear, and actionable, allowing decision-makers and at-risk populations to respond appropriately. Incorporating anticipatory action into the Multi-Hazard Early Warning Systems (MHEWS) enhances disaster response by linking early warnings to flexible funding mechanisms that trigger pre-planned interventions. These measures, implemented within the critical time window between a warning and the disaster's impact, minimize vulnerabilities and strengthen resilience. Trigger systems based on reliable forecasts and risk indicators activate the swift release of pre-allocated funds when agreed thresholds are reached, ensuring rapid, targeted responses to predictable shocks[57].

Finally, enhanced response capacities enable efficient mobilization and deployment of resources, ensuring timely assistance to affected populations and minimizing the adverse effects of disasters. Emergency response plans should be tailored to address the specific needs of various stakeholders, including vulnerable and marginalised communities, authorities, and emergency responders. Enhancing response capabilities necessitates the development and regular updating of Disaster Preparedness and Response Plans (DPRPs) at the local, provincial, and national levels. Establishing emergency evacuation routes and shelters, along with training and equipping standby volunteers and search and rescue teams with appropriate tools and technologies, is also essential. Warehousing and prepositioning relief materials to support affected communities and conducting regular training exercises and mock drills are critical components of disaster preparedness and response. Together, these components create a comprehensive approach to managing multi-hazard risks and strengthening resilience at every level of society.

6.5 Eight step process for the operationalisation of MHEWS at local level

The operationalization of Multi-Hazard Early Warning Systems (MHEWS) at the local level requires a comprehensive process and coordinated approach that can integrate scientific knowledge, traditional practices, and community engagement to address the unique challenges and vulnerabilities of local contexts. MHEWS can be established from the ground up, expanded from an existing hazard-specific warning system, or integrated with two or more existing warning systems (UNDRR 2023). The following prerequisite eight steps can be used to operationalise MHEWS[58] at local level. The eight-step framework serves as a practical guide to building effective MHEWS by systematically addressing the scope, governance, communication, data integration, forecasting, dissemination, feedback, and capacity-building aspects. By tailoring these steps to local needs, capacities, and resources, communities can ensure timely and effective warning systems that empower individuals, institutions, and stakeholders to take proactive measures against multi-hazards risk. This localized approach not only strengthens preparedness but also fosters sustainable development by embedding disaster risk reduction into everyday practices.

Step 1: Define the Scope of MHEWS at Local Level

Operationalizing MHEWS at the local level begins with identifying hazards that pose the greatest risk to the community. Historical data, combined with emerging trends in hazards frequency and intensity and consequences of these hazards occurring alone, simultaneously, cascading, or cumulatively over time, should guide this identification. Local risk assessments must address vulnerabilities specific to the area, including poorly planned urban development, deforestation, and socioeconomic factors like poverty and inequality. The geographical scope of MHEWS and the lead times of multi-hazard warnings can consider village clusters, municipalities, or related watersheds/catchments, ensuring the diverse needs of varying hazards and populations. Existing local capacities, such as community-based organizations (CBOs), municipal disaster management committees, and traditional knowledge systems, should be evaluated to pinpoint strengths and gaps for an effective MHEWS.

Step 2: Define Governance Mechanism, Roles, and Responsibilities at the Local Level

Effective local governance for MHEWS requires developing standard operating procedures (SOPs) and protocols that clearly define the roles and responsibilities of local government, ward councils, community-based organisations, Red Cross partners, communities and other local stakeholders. . SOPs should be tailored to the specific needs of the community, detailing who is responsible for issuing warnings, coordinating evacuation efforts, and providing emergency services. Local government bodies can facilitate legislative or regulatory adjustments to streamline coordination, particularly between municipal councils, sectoral departments, and disaster management agencies. Integrating MHEWS governance into local development plans ensures sustainable funding and institutional support, making the system more resilient to operational challenges.

Step 3: Define Standard Terminology for Common Understanding at the Local Level

A common vocabulary is essential for clarity and efficiency in the operationalisation of MHEWS at local level. This can be achieved by translating technical terms into local languages and culturally relevant contexts. Collaborative processes like workshops with community members, local authorities, and other stakeholders can co-create these terminologies. For instance, terms describing flood levels or landslides should resonate with locally understood indicators, such as riverbank markers or any visible signs and traditional indicators. Collaborative design of warning outputs with community involvement ensures that at-risk populations understand and trust the messaging, fostering quicker and more effective responses. Agreement on inputs and outputs at every stage of the warning system's production chain is critical to achieving a seamless flow of information among partners, enhancing understanding and actionability.

Step 4: Select Data Sources and Identify Vulnerabilities at the Local Level

Data-driven decision-making is fundamental to MHEWS. Localized data collection is key to understanding the specific vulnerabilities of a community. Hazard mapping can leverage data from local public works departments, agricultural offices, or grassroots organizations. For example, drone or satellite imagery may identify flood-prone zones, while socioeconomic surveys reveal household-level vulnerabilities, such as those related to income, access to healthcare, or infrastructure quality. Engaging the community in data collection fosters ownership and enhances the accuracy of assessments, allowing for the identification of marginalized or hard-to-reach groups who may require tailored interventions.

Step 5: Strengthen Forecast Model Inputs and Outputs for Impact-Based Forecasting (IBF) locally

The development of IBF involves validating existing monitoring and forecasting mechanisms, integrating local and traditional knowledge where applicable. Local impact-based forecasting systems must incorporate data from nearby weather stations, river gauges, or community weather observatories. Integrating traditional knowledge, such as patterns in animal behaviour or changes in local ecosystems, can complement modern forecasting tools. Hazard data should be cross-referenced with community-level impact assessments, such as the number of people residing in floodplains or areas susceptible to landslides. Warning messages should be specific and actionable—for example, advising families to relocate livestock or pre-position emergency supplies. Recommendations should address potential scenarios like prolonged power outages or road blockages, helping local residents better prepare.

Step 6: Identify Channels to Reach People at Risk

To ensure warnings reach everyone, particularly vulnerable groups, local communication channels such as community radio, WhatsApp groups, or loudspeakers in public areas can be used. Trusted local figures, such as village elders, schoolteachers or Red Cross volunteers, can act as intermediaries for disseminating warnings. Community forums and workshops should co-design preparedness and early action plans, emphasizing the cascading and compound effects of hazards, such as flooding leading to waterborne diseases. Regular multi-hazard simulation exercises and evacuation drills should be conducted, engaging communities and at-risk groups to ensure readiness and familiarity with warning protocols.

Step 7: Implement Feedback and Evaluation Mechanisms

At the local level, evaluation mechanisms should measure the effectiveness of warnings in terms of accuracy, community reach, and timeliness. Post-event surveys and focus group discussions can collect feedback from communities on what worked and what didn't. For example, farmers may share insights about the timeliness of drought warnings and their ability to protect crops. Local authorities can use this feedback to refine SOPs and communication channels. Regularly revisiting these mechanisms ensures continuous improvement and builds trust in the warning system among the community.

Step 8: Capacity Building, Training, Mock Drills, and Simulation Exercises

Local capacity building efforts should prioritize training for municipal officials, community leaders, and volunteers in interpreting and disseminating warnings. Workshops on multi-hazard risks, tailored to local scenarios, can help stakeholders understand the interconnectedness of hazards. Simulation exercises should reflect real-world challenges, such as practicing evacuation routes during the rainy season when roads may be blocked. Awareness campaigns using folk theatre, local festivals, or school programs on seasonal hazards can engage diverse community members, including those with limited literacy. Institutionalizing these training and awareness programs ensures that local knowledge and preparedness remain strong over time.

7 LOCALISATION OF MHEWS AND THE ROLE OF NEPAL RED CROSS SOCIETY

The Nepal Red Cross Society (NRCS), with its extensive network, grassroots presence, and mandate for humanitarian assistance, is uniquely positioned to play a pivotal role in the operationalisation of multi-hazard early warning system (MHEWS) at the local level. The NRCS has an extensive network of over 1,500 sub-chapters spread across all districts and municipalities, ensuring a robust presence in remote and disaster-prone areas. This widespread reach allows for effective community engagement and localisation of MHEWS components and systems across at-risk communities and population. As a neutral and impartial humanitarian organization, the NRCS has cultivated trust within communities, enabling it to serve as a reliable conduit for early warning information and disaster preparedness initiatives. Further, NRCS has decades of experience in DRR activities, including preparedness, response, and recovery efforts. This expertise can be leveraged to integrate MHEWS components into existing DRR frameworks at the local level. With a cadre of trained volunteers familiar with local languages, cultures, and geographic conditions, the NRCS is well-equipped to roll our people-centric MHEWS that caters the needs of most vulnerable communities and disadvantaged groups.

NRCS can facilitate community-level multi-hazard assessments in coordination with local government bodies. Utilizing tools like enhanced vulnerability and capacity assessments (EVCA), NRCS can mobilise trained volunteers and staff to lead data collection at the community level to map hazards, vulnerabilities, and other risk factors with multi-hazard approach lens, and gather community inputs from vulnerable and marginalized groups, on the likelihood and impact of hazards and their interaction in the given specific context, location and future scenario. Such community scale multi-hazard risk map can be validated further with local governments and technical agencies, and NRCS can advocate local governments to use these maps in land use planning, building regulations, development activities and emergency planning. NRCS can facilitate multi-stakeholder consultations to draft and test SOPs, ensuring clear delineation of roles among LDMCs, WDMCs, and other relevant stakeholders in the operationalisation of MHEWS at local level. Being the auxiliary to the government, NRCS can support government to identify gaps in existing legislation related to disaster management and MHEWS operationalization by providing evidence-base from community experiences to support any legislative amendments. NRCS can advocate for legal provisions that strengthen coordination within local disaster management committee and inclusion of MHEWS funding and institutional support in local development budgets and plans. NRCS can mobilize resources to support pilot projects that integrate MHEWS components into local disaster and climate resilience plans.

NRCS can organize awareness sessions to sensitize stakeholders on MHEWS frameworks and their roles within it. Training sessions for stakeholders on consistent and effective warning communication can be organised. NRCS can create user-friendly, context-specific materials (e.g., brochures, posters, videos) highlighting local hazards, their interactions leading to multi-risk and vulnerabilities, and associated risk reduction and management practices. NRCS can monitor and evaluate the dissemination of warnings to assess comprehension and effectiveness, helping authorities to make iterative improvements based on community feedback. Engaging with private sector stakeholders, such as telecom companies and satellite service providers, NRCS can leverage their platforms like SMS alerts or app-based notifications for risk communication. Outreach strategies that account for cultural norms, literacy levels, and language preferences can be designed to ensure warnings reach all populations. NRCS expertise and resources can be used to assess the condition of critical infrastructure, including schools, hospitals, and water supply systems, identifying those most at risk, thereby supporting municipal authorities in prioritizing infrastructure for retrofitting or strengthening measures.

NRCS can collaborate with government agencies and technical experts like DHM to install and operate monitoring sensors at strategic locations in vulnerable areas, also incorporating indigenous knowledge and practices into hazard monitoring efforts. NRCS can further support in the institutional ownership by ensuring that local authorities and community-based organizations are involved in the maintenance and usage of such equipments. Overall, NRCS can serve as a key intermediary in processing, managing, and disseminating monitoring hazard data to ensure its availability and usability for multi-hazard early warning system. Collaborating with local governments NRCs can establish community-based alert mechanisms, including sirens and visual signals. NRCS can act as a community liaison to build trust in early warning systems by improving public understanding and minimizing false alarms, ensuring that warnings are tailored to local contexts and effectively communicated to diverse populations. NRCS local volunteers can be trained to interpret and explain warnings to communities in a relatable manner. Partnering with local governments, international organizations, and technical agencies NRCS can enhance the accuracy and accessibility of hazard forecasts for early and anticipatory action.

NRCS can facilitate frequent drills to test the effectiveness of evacuation plans, communication systems, early action and response protocols. NRCS can support local authorities and communities to design contingency plans for various potential multi-hazard scenarios, considering local hazards and their interactions and vulnerabilities. NRCS is already building local capacities through training in first aid, search and rescue, and evacuation assistance, which can be further scaled – up and intensified catering the requirements for complex emergencies. NRCS specialised programmes such as CADRE, DDRT, and NDRT can be further tailored and improved considering the multi-hazard disaster context and emergencies.

Achieving a fully operational people-centred Multi-Hazard Early Warning System (MHEWS) will undoubtedly require significant time, resources, and extensive collaboration across all levels of governance and stakeholders. However, the Nepal Red Cross Society (NRCS) can begin by focusing on establishing the foundational elements necessary for the localization of MHEWS. By taking proactive steps aligned with the aforementioned eight recommended steps/areas, NRCS can lay the groundwork for a robust, people-centred system at local level that evolves over time.

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