Chapter 2
Early Warning Systems and Their Role in Disaster Risk Reduction

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Abstract In this chapter, we introduce early warning systems (EWS) in the context of disaster risk reduction, including the main components of an EWS, the roles of the main actors and the need for robust evaluation. Management of disaster risks requires that the nature and distribution of risk are understood, including the hazards, and the exposure, vulnerability and capacity of communities at risk. A variety of policy options can be used to reduce and manage risks, and we emphasise the contribution of early warnings, presenting an eight-component framework of people-centred early warning systems which highlights the importance of an integrated and all-society approach. We identify the need for decisions to be evidence-based, for performance monitoring and for dealing with errors and false information. We conclude by identifying gaps in current early warning systems, including in the social components of warning systems and in dealing with multi-hazards, and obstacles to progress, including issues in funding, data availability, and stakeholder engagement.

Keywords Governance · Risk management · People-centred · Hazard · Exposure · Vulnerability · Impact · Early Warning Systems · Risk

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2.1 Introduction

Despite decades of progress in our understanding of disaster risks, how they should be dealt with and international agreements to build resilience of people and nations, hardly a week passes without devastating news of natural hazards causing havoc in both developed and developing countries. While the world was busy taming the beast of COVID-19, Tropical Cyclone Amphan unleashed its power over India and Bangladesh in May 2020, killing 72 people and causing over 13 billion dollars of damage in West Bengal (Sarkar 2021), with total loss and damage still unknown. In July 2020, heavy rainfall in Nepal triggered flooding and landslides, leaving a death toll and shattering the livelihoods of many.

Examples like these are countless. Although all impacts of natural hazards on people, economies and environment cannot be completely avoided, they can be substantially reduced. One of our 'best bets' is to implement early warning systems (EWS), as they nurture learning and understanding of natural hazards, provide us with warning information and give time to take early action, so as to avoid unnecessary consequences. Despite some progress in enhancing EWS globally, the recent report on the state of climate services (WMO 2020a) shows that, in the 73 countries considered, one-third of people are not covered by early warnings, and just 40% have multi-hazard EWS.

The world's climate is changing, and those changes also manifest themselves in a changing risk from weather-related hazards in every country. The intensity and frequency of hazards will change with climate change. This implies that, in some countries, there will be additional hazards for which EWS are required (e.g., EWS for heat waves in locations where this was previously not necessary) while others may become less significant. At the same time, socio-economic development in each country is changing the exposure to hazards and the vulnerability of their populations. Mitigating the increases in risk arising from these changes and further adaptation are crucial for sustainable development of societies. In this chapter we shall:

- Introduce the key concepts of hazard, exposure, vulnerability and risk.
- Outline measures that can be taken to reduce disaster risk.
- Situate EWS in the landscape of available options to reduce disaster risks.
- Elaborate on the main components of an EWS, presenting an eight-component framework of people-centred EWS which highlights the importance of an integrated and all-society approach.
- Identify gaps in current capability, especially in the social components of EWS and in dealing with multi-hazards, and obstacles to progress, including issues in funding and stakeholder engagement.

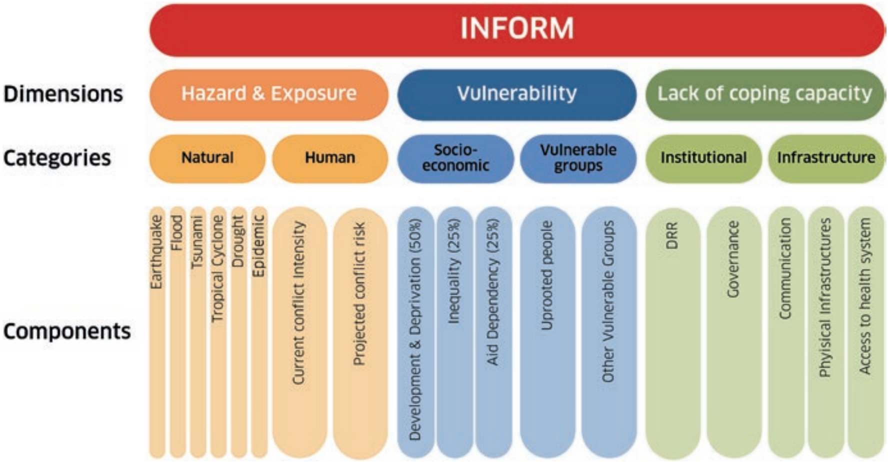

Fig. 2.1 The different risk dimensions, categories and components of INFORM. The final selection of the components and underlying indicators is country-specific. (Based on Marin-Ferrer et al. 2017)

2.2 Disaster Risks and Impacts

Risk from natural hazards arises from a combination of dimensions: natural hazard, exposure of people or assets to that hazard and the vulnerabilities and coping capacities of each person or asset to that hazard. Several multilateral organisations such as UNFCCC/IPCC, UNDRR and the Inter-Agency Standing Committee (IASC) Reference Group on Risk, Early Warning, and Preparedness, together with the European Commission, have put forward definitions of risk and its dimensions. For instance, IASC and the EU Joint Research Centre have developed the global open-source INFORM Risk Index that can be used to calculate risk at the national or sub-national level (Marin-Ferrer et al. 2017), specifically for humanitarian crises and disasters. Box 2.1 outlines the definitions by the United Nations Office for Disaster Risk Reduction. These definitions are widely accepted in the DRR community of practitioners. We note that the INFORM Risk Index relates closely to definitions proposed by UNDRR but also defines a methodology to calculate a composite risk index based on different risk dimensions, categories, components and indicators (Fig. 2.1).

2.2.1 *Hazard*

The hazard dimension is – in comparison with vulnerability and exposure – relatively well characterised, at least for single hazards. UNDRR (2020b) categorises hazards into biological, environmental, geological, hydrometeorological, technological and societal. Here we are primarily concerned with hydrometeorological

Box 2.1 Risk Dimension Definitions Based on the UNDRR Definitions (UNDRR 2016)

Vulnerability

The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards.

Coping capacity

The ability of people, organisations and systems, using available skills and resources, to manage adverse conditions, risk or disasters.

Exposure

The situation of people, infrastructure, housing, production capacities and other tangible human assets located in a hazard-prone area or lying in the path of a specific hazard. Measures of exposure can include the number of people or types of assets in an area.

Hazard

A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation. Hazards may be natural, anthropogenic or socio-natural in origin. Natural hazards are predominantly associated with natural processes and phenomena. Anthropogenic, or human-induced, hazards are induced entirely or predominantly by human activities and choices. Several hazards are socio-natural, in that they are associated with a combination of natural and anthropogenic factors, including environmental degradation and climate change. Hazards may be single, sequential or combined in their origin and effects. Each hazard is characterised by its location, intensity or magnitude, frequency and probability. Biological hazards are also defined by their infectiousness, toxicity, etc.

hazards. Hazards are dynamic in nature due to both climate variability and climate change. Forecasts of hazards occurring can range from climate change projections to decadal, seasonal, sub-seasonal and short-term forecasts. Early warning systems use seasonal up to short-term forecasts, a progression in which precision and confidence should grow as the length of the forecast decreases. The lead time for which useful information can be provided varies widely, from seasonal timescales for droughts to just a few seconds for an earthquake.

Apart from these different temporal dimensions of hazard forecasts, the spatial dimension is also very important. Spatial maps of the frequency of hazardous conditions are required for the planning and implementation of preparedness and response interventions as well as for longer-term interventions such as land-use zoning. These are typically based on observation or modelling of past conditions but should be adjusted using projections of future change (both human change and climate change). For example, observed flood depths can be combined to create a flood extent map representative of a historical flood, and hydrological and hydrodynamic models can be used to create hypothetical flood extent maps for different levels of probability.

There are slow- and sudden-onset hazards. Sudden-onset hazards refer to hazardous events that emerge quickly or unexpectedly, such as river and flash floods, wildfires or extreme winds. Slow-onset hazards occur gradually over time, such as droughts or sea-level rise. Some hazards can show intermediate-onset behaviour, such as disruptive winter weather. To add to the complexity, disasters are often consecutive. This means that the impacts of two or more disaster events overlap both spatially and temporally before recovery from the first event is considered to be complete. Multiple hazard events can be classified as compound events or cascading events (Ruiter et al. 2020), covering both the interaction of discrete natural hazards (Gill & Malamud 2014) and the interaction of natural hazards with shocks and stresses in social, cultural, political, economic, health and technological systems.

While the risks associated with multi-hazard events are recognised, and approaches for managing them are increasingly advocated as part of DRR policies and practice (UNDRR 2015), these risks are not well defined. Key challenges and gaps must be addressed to enable informed assessments of the likelihood of multi-hazard events and their impacts.

Hazards have different levels of intensity. Whereas scientists may describe a phenomenon using a physically continuous scale of intensity, for hazard warnings it is often more helpful to use discrete classes of intensity that are associated with degrees of impact, e.g. the Richter scale for earthquakes or the Fujita scale for tornadoes.

Several methodologies, including the INFORM Risk Index, merge aspects of the hazard and exposure dimensions into one risk dimension to reflect the probability of physical exposure associated with a specific hazard. For floods and drought, this identifies exposed cropland (e.g. in a floodplain or in a drought-prone area) and affected communities. An example is how UNEP, on their Global Risk Data Platform, calculates physical exposure to floods (UNEP 2021). To determine hazard exposure, hazard frequency data are combined with exposed population datasets. Long-term frequency data can be used to generate return periods, commonly used to communicate the probability of an event exceeding a certain magnitude happening in a given year. The ThinkHazard! tool of Global Facility for Disaster Reduction and Recovery (GFDRR) provides the likelihood of multiple natural hazards affecting a certain area, drawing from published hazard data, provided by a range of private, academic and public organisations (GFDRR 2021). Table 2.1 presents a non-exhaustive overview of hazard data providers.

Table 2.1 Non-exhaustive overview of hazard data providers

Primary hazard data providers	Data repositories
Communities Local knowledge Citizen science Government National Meteorological and Hydrological Services UN World Meteorological Organization (WMO) World Health Organization (WHO) United Nations Environment Programme (UNEP) Global Facility for Disaster Reduction and Recovery (GFDRR)	By hazard: FloodScan FloodList Global Precipitation data sets (Sun et al. 2018) Dartmouth Flood Observatory Smithsonian Institution Volcanism Programme Global Historical Tsunami Database (NOAA) Cyclones: International Best Track Archive for Climate Stewardship (IBTrACS) Earthquake database (USGS) WHO Epidemic For multiple hazards: UNEP Grid GFDRR ThinkHazard! Global geospatial earth observation-related data on drought and floods (Lindersson et al. 2020)

2.2.2 Vulnerability and Coping Capacity

Vulnerability and exposure are distinct but closely linked. Exposure is a necessary but not sufficient determinant of risk. It is possible to be exposed but not vulnerable (e.g. by living in a floodplain but having adequate means to modify building structure and behaviour to mitigate potential loss). Similarly, vulnerability to a hazard does not lead to impact until the vulnerable asset is exposed to the hazard. While vulnerability is defined with respect to a specific hazard, socio-economic factors, such as poverty and the lack of social networks and social support mechanisms, will aggravate or affect vulnerability levels irrespective of the type of hazard. Unfortunately, in many developing countries, this kind of socio-economic data is not available at a sufficiently granular level or gets lost in the way data are aggregated. Furthermore, this is a very dynamic landscape, for example, areas facing rapid urbanisation can be growing at a rate of 6 to 8% each year, and data can quickly become obsolete.

Although vulnerability data are often treated as static, there is growing evidence of the need to allow for its dynamic nature. For example, vulnerability of a household can change over short-term timescales, such as during the response and recovery phases of a disaster, perhaps due to loss of its income for a period. Vulnerability is also dynamic across different scales. For instance, a region's vulnerability can change due to deforestation or urbanisation.

The hazard-specific part of vulnerability may be described by vulnerability functions (also known as hazard damage curves), often used to describe physical vulnerability. These functions describe an exposed asset's response to the forces associated with a hazard, for instance, the reaction of a building to shaking of the earth during an earthquake, to wind during a tropical cyclone or to water depth in a flood. Vulnerability functions are often either proprietary or very generic, but they are critical for realistic assessment of potential loss. Once developed, they may be usable and adaptable to other areas with similar exposure profiles. Unfortunately, there are few openly available, high-quality vulnerability functions, such as the ones available from the open-source software CAPRA (Comprehensive Approach to Probabilistic Risk Assessment) platform (Cardona et al. 2010).

Coping capacity is an important component of disaster risk. It is usually conceptualised as short-term measures employed by individuals and communities in light of extreme events (Wamsler and Brink 2014), but it can also be considered at a country level (such as in the INFORM national risk index). Wisner et al. (2004) presented a range of coping strategies employed before, during and after an event. They identified preventative strategies, impact-minimising strategies, storing food and saleable assets, diversifying production and income sources, developing social support networks and post-event coping strategies. In some definitions, coping capacity is part of vulnerability, while in others, such as the aforementioned INFORM index, it is considered a separate risk dimension. Capacities should not be seen as opposite to vulnerability on a single spectrum, since vulnerable people might also possess a vast array of capacities (Gaillard et al. 2019).

2.2.3 Exposure of People and Assets

A hazard causes losses only when vulnerable people and assets are exposed to it. Exposure is thus the key that determines whether a hazard causes loss and whether vulnerabilities are tested. Exposure is a dynamic quantity changing on all timescales. On an annual timescale, a growing city has an increasing spatial extent, an increasing population and new buildings; a developing country has new infrastructure. At shorter timescales, people move around for summer holidays or festivals, and there are the daily movements of children to school, workers into and out of cities and travellers on roads, railways and aircraft. To adequately account for exposure in risk assessment, extensive data are needed in a form that enables it to be easily combined with hazard and vulnerability data.

In many countries, developing an exposure dataset is one of the biggest hurdles for completing a risk assessment. Low-resolution exposure data can be derived from existing and open global datasets, but they are not sufficient for detailed risk assessments that would be needed at a project or EWS level. Basic census data, asset inventories, city plans and topographic maps exist in most countries but are often out of date and are not always accessible to those who need them for reducing and managing disaster risks. Very few countries have dynamic exposure data suitable for use in early warnings. However, individual disaster risk managers and weather service personnel will use personal knowledge of major gatherings of people, for instance, in preparing their warnings and in promulgating them beyond the standard address lists. Exposure is strongly correlated with socio-economic indicators, as also used for vulnerability. Where full inventories do not exist, such indicators can serve as proxies to estimate the sectorial use of building stock and determine the exposure of productive assets used by communities for their livelihoods (often agriculture-based, such as exposed cropland).

Catastrophe risk modelling is used by banks, insurance companies, governments and industries to protect their assets. For insurance companies, assessing losses from disaster scenarios is central to ensuring their ability to pay out. Governments have obligations to reconstruct public assets and infrastructure after a disaster. Both have mostly focused on getting adequate physical exposure data. However, governments also have an implicit obligation to offer their populations emergency assistance (such as food and shelter) and to finance recovery/reconstruction activities (e.g. provision of support to poorer households, measures to support the recovery of the private sector) (Alton & Mahul 2017). Implicit liabilities are harder to quantify, and even if quantified, are usually of less absolute financial value for the poorer segment of society (*ibid*.). As Hallegatte et al. (2016) state: 'A flood or earthquake can be disastrous for poor people but have a negligible impact on a country's aggregate wealth or production if it affects people who own almost nothing and have very low incomes'. Consequently, these implicit liabilities are less well covered by Disaster Risk Finance and Insurance. It is of paramount importance for ensuring the well-being of all citizens in a country that disaster risk management interventions are properly designed. Overall, there is less understanding and quantification of the assets that are important to vulnerable and hazard-prone communities (Box 2.1).

2.2.4 Impacts

If risks are left unmanaged, disasters result in a vast array of impacts on people, societies, economies and environment. Impacts from natural hazards include negative, neutral and positive consequences. For instance, floods damage crops, property and infrastructure, but fill reservoirs. Damage to property from a storm may be followed by increased economic activity and rebuilding with healthier and safer homes. A disruption that causes loss to one business may provide an opportunity for other businesses to benefit. The terms 'loss' and 'damage'[1] are typically applied to the negative impacts of a disaster. The ultimate measure of the effectiveness of any disaster risk reduction measure is to assess the reduction in loss and damage. While they are often applied interchangeably, they may be used to differentiate between economic loss and physical damage (e.g. Koks 2016). Alternatively, some analysts distinguish between irreversible loss, e.g. fatalities from heat-related disasters, and recoverable damage, e.g. damages to buildings (Boyd et al. 2017; Mechler et al. 2019). Impacts may also be categorised as tangible or intangible and as direct or indirect. Tangible impacts can be expressed in monetary terms (e.g. disruption to businesses, costs of infrastructure destroyed), whereas intangible impacts cannot be easily expressed in monetary terms (e.g. casualties, impacts to mental health of individuals). Direct impacts can be directly associated with the action of the hazard

[1] Loss and damage is also one of the pillars of climate action in the Paris Agreement and refers to climate impacts which are beyond adaptation.

event where it strikes, whereas indirect impacts can be the result of cascading events and may be remote, e.g. interruptions of supply chains. It is very important for the design of risk reduction and management interventions to have a catalogue that has systematically and uniquely matched hazard information to the loss and damage associated with each historical disaster event. The World Meteorological Organization (WMO) has started an initiative to standardise how to catalogue high-impact events and their associated impact (WMO 2018a). Different approaches, methodologies and tools are used to collect the impact data. Damage and Needs Assessments (DNAs) are usually done at different intervals right after a disaster hits into the recovery phase. These DNAs, if government led, are consolidated into institutional databases where the data are accessible to the public usually at an aggregated level. Most governments have their own procedures for rapid and initial damage assessments. In addition, there are DNA methods that draw upon the capacity and expertise of national and international actors, such as the Damage, Loss, and Needs Assessment (DALA) and the Post Disaster Needs Assessment (PDNA). The PDNA is an inclusive, government-led and government-owned process, where the European Union, World Bank and United Nations provide technical support and facilitation as determined and requested by the government of the affected country for the recovery phase. DALA is a World Bank methodology used mostly for the immediate needs of a country. Table 2.2 provides a non-exhaustive overview of impact data providers, repositories and data collection methods.

Table 2.2 Non-exhaustive overview of impact data providers, repositories and data collection methods

Primary impact data providers	Data repositories per provider
Government	Reinsurance
Environment	Munich RE's NatCatSERVICE
Social welfare	Swiss Re SIGMA Explore
Health	Research centre
Public works	Centre for research on the epidemiology of disasters EM-DAT
Energy	Karlsruhe Institute of Technology CATDAT
Water	UNDRR
Civil Protection Agencies	Preventionweb
National Disaster Management Authorities	Sendai Desinventar
Government international (OFDA, NOAA)	UN OCHA
Humanitarian sector	Reliefweb
UN OCHA and other UN agencies	Humanitarian Data Exchange (HDX)
NGOs	IFRC
IFRC	Disaster Response Emergency Fund appeals, plans and updates
Affected communities	Country-specific, often National Disaster Management Authorities, e.g.
Local knowledge	United States: SHELDUS
Insurance and reinsurance companies	Philippines: DSWD Dromic
MünichRe, SwissRe, LCW, AON	
Media	
Newspapers	
Social media	
TV	
Community radio	

2.3 What Are Available Options to Deal with Disaster Risks?

When it comes to managing disasters and disaster risks, three approaches are often referred to: (i) disaster management (DM), (ii) disaster risk management (DRM) and (iii) disaster risk reduction (DRR). DM refers to the organisation, planning and application of measures preparing for, responding to and recovering from disasters (UNDRR 2016, p.14). DRM refers to the application of disaster risk reduction policies and strategies to prevent new risk, reduce existing disaster risk and manage residual risk, contributing to the strengthening of resilience and reduction of disaster losses (UNDRR 2016, p.15). DRR is aimed at preventing new and reducing existing disaster risk and managing residual risk, all of which contribute to strengthening resilience and, therefore, the achievement of sustainable development (UNDRR 2016, p. 16).

The evolution and application of these approaches mirror the shifts in thinking from hazards towards vulnerability and from top-down to bottom-up approaches (Paul et al. 2018). For instance, it is often emphasised that DM focused more on responding to and recovering from disasters (Jones et al. 2015), whereas DRM and DRR take a more comprehensive approach, including elements of prevention, mitigation and preparedness (Ouriachi-Peralta & Fakhruddin 2014).

An approach to managing and reducing disaster risk is often represented in the form of a disaster cycle, composed of four components:

1. Mitigation[2] encompasses strategies and practices aimed at reducing the likelihood or consequence of a hazard, e.g. levees, land-zoning and building practices (Coppola 2011).
2. Preparation/preparedness refers to strategies and measures for preparing for and reducing the impacts of disasters, e.g. early warning information, contingency planning and evacuation drills (Buckle 2012); more recently preparedness also includes initiatives around early warning early action and forecast-based financing.
3. Response encompasses strategies to reduce negative disaster impacts and avoid further possible implications, e.g. evacuation of people and property (WMO/EHA 2002).
4. Recovery involves aspects such as relief, reconstruction and rehabilitation (Wisner et al. 2012); usually, it refers to 'normalising' and returning to the pre-disaster situation (Coppola 2011), although contemporary thinking encourages the concept of 'building back better' (UNDRR 2015).

Although its prominence still prevails, especially among practitioners, the cycle is not without critics. In reality, these phases will never be so distinct and compartmentalised (Twigg 2015); they are rather in a constant interplay and continuum

[2] Mitigation as used in this chapter differs from mitigation as used in climate change discourse (i.e. used to refer to the cut in greenhouse gas emissions).

(Coppola 2011). This interplay is even more visible for slow-onset than for sudden-onset disasters.

Risk must be viewed in the context of the society in which it occurs. Every aspect of society is open to risk, and every member has a responsibility to respond to certain aspects of risk. Individuals may also have a responsibility on behalf of others as a result of their position in businesses and governmental or non-governmental bodies. Hence reducing disaster risks involves a wide range of both public and private actors. Private actors are individuals, households or communities that take action; for instance, communities are generally the first to respond to a disaster. Public actors are governmental institutions such as the National Meteorological and Hydrological Services (NMHS), disaster management authorities and government ministries responsible for water development and infrastructural works.

Disaster risk governance (DRG) refers to how public authorities, civil servants, media, private sector and civil society are organised at community, national and regional levels to manage and reduce disaster and climate-related risks (UNDP 2020). It is an essential part of DRG that all actors, from private individuals to businesses to the most senior government officials, understand the risks that they are exposed to and the level of responsibility they have for managing those risks. In many countries, domestic laws and policies define these levels of responsibility, e.g. the Philippine Disaster Risk Reduction and Management Act of 2010 (Republic of the Philippines 2010). In addition, international disaster response laws, rules and principles encompass a wide range of both global and regional international law and norms and bilateral treaties and agreements. Where a country has a federal structure, the law will state the conditions under which the provincial government should seek federal assistance. If a disaster caused by a natural hazard surpasses the capacity of a state to respond, the Inter-Agency Standing Committee can decide to initiate a humanitarian system-wide response (IASC 2020). In this case, the sovereign state can ask for and agree to international support. Actors operating at global, national and local levels require intra- and inter-organisational coordination.

A key aspect of DRG is the creation of a shared understanding, backed up by legislation, funding, management and enforcement, of where responsibility for assessing and managing risk lies. Responsibilities typically cascade from government ministries with responsibility for strategic risks to the whole country, to city councils holding the risk for their municipality, to infrastructure operators (often private businesses) having responsibility for risks to their systems and consequent risks to people using them, to businesses needing to protect themselves financially and their customers if their goods or services are interrupted, down to each individual having responsibility for actions to protect themselves. The higher up this chain the responsibility lies, the greater portion of risk is held and the greater the penalty of failure. Along with this shared understanding goes the requirement on each responsible actor to have a risk assessment and a risk management plan for their area of responsibility and to ensure that this is consistent with the plans of their stakeholders – whether higher up the chain, lower down or at the same level.

Often, measures for delivering DRR are classified as structural or non-structural (see, e.g. UNDRR 2016). Structural measures refer to engineering approaches resulting in physical infrastructure (e.g. flood walls), while non-structural measures refer to strategies involving policies, laws and 'soft approaches' (e.g. training, education, awareness-raising). Structural measures are more tailored towards hazard reduction, whereas non-structural measures aim to decrease vulnerability and exposure (Harries & Penning-Rowsell 2011) and increase coping capacity.

A large spectrum of actions can be taken, as part of risk reduction, to reduce, retain, transfer or absorb risk (UNFCCC 2012). Table 2.3 gives examples of Disaster Risk Reduction (DRR) actions and Climate Change Adaptation (CCA) actions and shows where early warning systems (EWS) fit in. At one end of the spectrum are actions that can be taken to protect against infrequent events with minor impacts. While these may be inconvenient, they do not justify major investments, so are best dealt with by early warnings that enable people to prepare for and avoid them and insurance to cover repair costs. Frequent events are best avoided altogether, either by land use planning, e.g. avoiding building on the floodplain; by use of natural protective features, e.g. coastal mangroves and salt marshes; by protective engineering, e.g. river levees, strengthened building codes; or by a combination of these measures. The most difficult to deal with are rare hazards with major impacts. Rarity and scale make engineering solutions unviable. Protection of life demands plans for large-scale evacuation to safe locations, backup for essential services and release of resources for rapid recovery. Insurance is a valuable contributor to recovery for moderately rare events, but for the most extreme, only governments have the necessary resources, supported where necessary by international financial mechanisms.

Table 2.3 Overview of public and private actions that can be taken to reduce, retain, transfer or absorb risk, adapted from van den Homberg and McQuistan, 2019. (DRR, disaster risk reduction; CCA, climate change adaptation; L&D, loss and damage)

Adjustment	Spectrum and *timing*	Private action; Tech level: examples	Public action; Tech level: examples
Incremental	DRR: Preparedness *Short-term* *Ex ante*	*Basic:* Fisherman put fish net around fish pond after receiving early warning	*Basic:* NGO locating relief items closer to the predicted to be affected area. Increase response capacity of communities
	DRR: Risk reduction CCA: Medium-term for next year's floods *Ex ante*	*Basic:* Household raises plinths/floors and diversifies their crops	*Intermediate to advanced:* A NMHS improves their hydro-meteorological modelling so that forecasts with better lead times and spatial resolution become available. Government-led irrigation system, building of dykes
	Humanitarian aid. *Directly after floods* *Ex post*	*Basic/none:* Support from within the community	*Intermediate:* Post-disaster public and donor assistance, such as relief items or cash transfers to households and money to governments for reconstruction of, e.g. roads and embankments

(continued)

Table 2.3 (continued)

Adjustment	Spectrum and *timing*	Private action; Tech level: examples	Public action; Tech level: examples
Fundamental	DRR and CCA (larger scale or intensity). *Long-term over several years* *Ex ante*	*Intermediate:* Access Interactive Voice Response service to get meteorological and agricultural advice	*Intermediate:* Improving access to information through digital inclusion, e.g. making sure early warning services are available in first language of beneficiaries, voice SMS early warning service, nationwide coverage of mobile networks, lower taxation on mobile users
	DRR and CCA (new to a particular region or resource system). *Medium to long-term* *Ex ante*	*Advanced:* Citizens participate in crowdsourcing of water levels	*Advanced:* Dam operator changes its way of releasing water by using advanced forecasting models. Forecast-based financing. A Rice Research Institute develops flood-tolerant rice
		Intermediate: Take a micro-insurance	*Intermediate:* Micro-insurance can be supported by mobile technology and/or public-private partnerships to ensure commercial viability
	DRR and CCA (transform places) *Long term* *Ex ante*	*Intermediate:* Citizens contribute to constructing bio-dykes or ecological corridors	*Intermediate:* Large dams no longer being built, but several smaller ones. Green infrastructure such as bio-dykes; ecological corridors. Use of floodplains instead of building dykes
	L&D Curative: redress and rehabilitation *Short term* *Ex post*	*None:* Involuntary migration or staying put	*Intermediate:* Financial compensation for loss and damage that can be attributed to climate change. Active remembrance (e.g. through museum exhibitions, school curricula). Counselling

Given limited budgets and technological capacities, especially in developing countries, trade-offs and choices have to be made. A straightforward comparison of permanent and temporary or long-term and short-term risk reduction measures is problematic as multiple decision-makers with different mandates and political agendas are involved. For example, government agencies dealing with water development and irrigation are responsible for permanent and structural measures (e.g. building dikes), whereas disaster management and humanitarian agencies take decisions regarding temporary, EWS-informed and non-structural responses (Bischiniotis et al. 2020). It is likely that each agency will apply different evaluation protocols (Mechler 2016). On the one hand, economic valuations such as cost-benefit analysis are typically used to justify large-scale infrastructure expenditures, which often introduces a bias towards wealthier areas with more assets to lose (Hallegatte et al. 2016). On the other hand, EWS-based early actions are typically evaluated in terms of their reduction of human losses and livelihood impacts (Gros et al. 2019, Rai et al. 2020).

A systemic approach to risk management is essential to ensure that policy options and corresponding actions are sustainable in the long-term rather than short-term sticking plasters. It is important to move from silo approaches per individual hazard to multi-hazard approaches. Based on several sources of data, the Red Cross Climate Centre calculated that, of 132 unique extreme weather-related disasters occurring in 2020, of which 92 have overlapped with the COVID-19 pandemic (Walton & van Aalst 2020), 51.6 million people globally were directly affected by an overlap of floods, droughts, storms and the COVID-19 pandemic. Current methods for risk assessment and risk management need to evolve to capture (better) the systemic nature of risk. One can think of tools such as vulnerability and capacity assessments, contingency planning and visualisation techniques (Gill & Malamud 2014). Galasso et al. (2021) propose an approach to risk-based design of new urban settlements in which quantitative predictions of the impact of potential hazard scenarios form the foundation for a policy discussion between stakeholders. The challenges in this transformation to govern systemic risk are related to finding the optimal complexity. How detailed should the approach be, given limited resources and given limited data availability?

One possible way to speed up the transition from managing individual risks and disasters to managing compound and consecutive risks and disasters is to draw on insights from development aid. For example, we already know that poverty tends to increase in both developed and developing economies after a disaster such as a flood or storm (Karim and Noy 2016). Therefore, in the move towards systemic risk reduction, a core component should be a strong social programme to increase people's resilience even in the absence of explicit disaster-related triggers (Deryugina 2017). Adaptive and shock-responsive social protection systems have the potential to help people manage covariate risks comprehensively, including anticipating them, absorbing their impacts and managing future risks (Ulrichs et al. 2019). Examples from different social protection programmes in Latin America, South Asia and parts of Africa have shown that social protection can play an important role in reducing deprivation, increasing food security and avoiding negative risk coping strategies, among others. Moreover, some preliminary experience with adaptive social protection programmes in the Sahel (Daron et al. 2020) has shown the capacity to protect poor households from climate and other shocks before they occur, given their potential to scale up and be flexible, thus contributing to a long-term risk management strategy. Understanding the various cascading risks that increase vulnerability during different life phases can be useful in designing comprehensive social protection systems that are better prepared to handle multiple vulnerabilities and compound risks.

2.4 The Role of Early Warnings Systems in Disaster Risk Reduction

In the previous section, we showed that decision-makers and disaster and emergency managers have a large array of options to reduce disaster risks and their impacts on societies, economies and environment. Yet the dominant approach to dealing with disasters has been skewed towards responding and providing relief after they have happened. Over the years, there has been a shift in policy and practice with an increased understanding that preventing and preparing for disasters yields numerous benefits and contributes to resilient communities and societies. One of the central instruments in being more prepared is the provision of early warning systems (EWS), which we now explore in more detail.

2.4.1 The Emergence of Early Warning Systems

The emergence of EWS in international DRR policy and practice can be tracked through global agreements for disaster risk reduction and beyond. In 1994, during the World Conference on Natural Disaster Reduction held in Yokahoma, Japan, the State Members of the United Nations agreed on the Yokahoma Strategy and Plan of Action for a Safer World (IDNDR 1994). As one of the ten guiding principles, countries agreed that 'early warnings of impending disasters and their effective dissemination using telecommunications, including broadcast services, are key factors to successful disaster prevention and preparedness' (IDNDR 1994, p.6). The Yokahoma Strategy drew attention to a need for establishing and/or strengthening EWS and called for assistance in developing EWS for countries most vulnerable to natural hazards.

However, only limited progress in delivering integrated EWS at scale has been delivered. A greater attention to EWS in international arenas was given only after the devastating impacts of the Indian Ocean Tsunami in 2004 (WMO 2015a). This was reflected in the Hyogo Framework for Action 2005–2015, a global footprint for disaster risk reduction, recognised as a major shift towards focus on prevention and preparedness as opposed to response and recovery (Tozier de la Poterie & Baudoin 2015). As one of its five priorities for action, the Hyogo Framework lays out a need to identify, assess and monitor disaster risks and enhance early warning. In its general considerations, the Hyogo Framework states that EWS are 'essential investments that protect and save lives, property and livelihoods, contribute to sustainability of development, and are far more cost-effective in strengthening coping mechanism than is primary reliance on post-disaster response and recovery' (UNDRR 2005; p.5). Importantly, the Hyogo Framework emphasised a need for people-centred EWS, systems that will account for differentiated vulnerabilities, offer guidance on how to act on warning information and support action by decision-makers. Although the Hyogo Framework raised the profile of EWS worldwide, substantive gaps remained.

The successor of the Hyogo Framework is the Sendai Framework for Disaster Risk Reduction 2015–2030, a global agreement serving as guidance for countries to reduce their disaster risks at the time of writing of this chapter. Unlike the Hyogo Framework, the Sendai Framework does not identify EWS as one of its priority areas, but rather identifies it as one of seven global targets. Target (g) calls for countries to 'substantially increase the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to people by 2030' (UNDRR 2015; p.12). Although multi-hazard early warning systems (MHEWS) was not a new concept, the Sendai Framework is the first global DRR policy blueprint that emphasises the importance of a multi-hazard approach in relation to early warnings. Given that the Sendai Framework is still relatively new and reporting on the targets is not yet fully developed, it remains to be seen to what extent the Sendai Framework has enhanced the delivery of EWS in both developed and developing countries.

In addition to global agreements for DRR, EWS are an important part of global climate action and the sustainable development goals (SDGs), as they are central for reducing vulnerability and enhancing resilience of people and nations. The Paris Agreement, a global document providing a framework for climate action, refers to EWS in Article 7 (on adaptation) and Article 8 (on averting, minimising and addressing loss and damage associated with the adverse effects of climate change) (UNFCCC 2015). One example of the intertwined nature of DRR and climate action at the global level is the establishment of the Climate Risk Early Warning Systems (CREWS) initiative during Conference of Parties 21 (COP21). CREWS is a financial mechanism, implemented by the Global Facility for Disaster Reduction and Recovery, the World Meteorological Organisation and the United Nations Office for Disaster Risk Reduction. It provides funding for least developed countries and small island developing states to implement risk-informed early warning services for weather-related hazards. In their 2019 Annual Report, CREWS states they supported 44 countries and over 10 million people in gaining access to better early warning services (WMO 2020b).

2.4.2 Early Warning Systems: Definition and Components

As explained by Kelman and Glantz (2014), there is no universal definition of EWS, as this is dependent on the context, scale and hazard in question. For the purpose of this chapter, we adopt the latest definition by UNDRR (2016) stating that an EWS is 'an integrated system of hazard monitoring, forecasting and prediction, disaster risk assessment, communication and preparedness activities, systems and processes that enables individuals, communities, governments, businesses and others to reduce disaster risks in advance of hazardous events'.

The World Meteorological Organisation and United Nations Office for Disaster Risk Reduction have published a widely used and internationally recognised checklist for multi-hazard and people-centred early warning systems, outlining four main

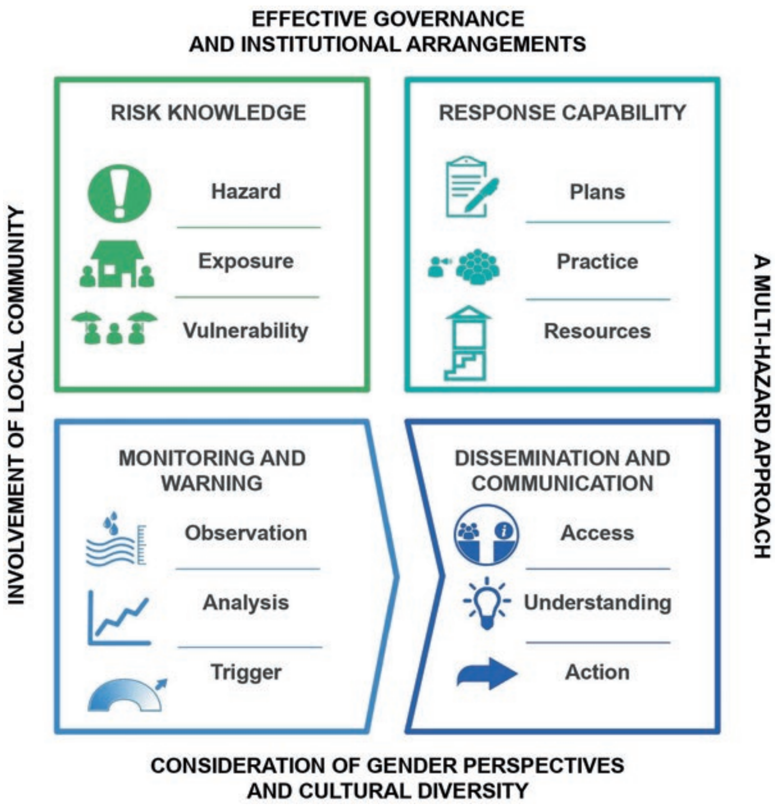

Fig. 2.2 Components of an early warning system. (Adopted from Brown et al. 2019)

elements and four overarching components of any early warning system (UNISDR 2006, WMO 2018b), as presented in Fig. 2.2. For an early warning system to be truly effective, all eight components must be considered and addressed in a holistic approach to ensure accurate, timely, reliable and understandable information reaches everyone in the right way for them to take action.

Risk Knowledge As through EWS there is an effort to reduce risks and prepare for hazards in a specific spatial area (e.g. community, city, region), it is imperative to know the nature of risk in the area. Risk assessments can help to identify the areas prone to hazard occurrences, the location and nature of vulnerable groups and critical infrastructure and assets in exposed locations. For instance, the Zurich Flood Alliance used a combination of digital mapping techniques, based on the OpenStreetMap (OSM) and community-based participatory methods, to map flood risks in Nepal, Peru and Mexico as a basis for risk reduction strategies (Practical Action 2018). In the United States, since 2009, The Federal Emergency Management Agency (FEMA) introduced the Risk Mapping, Assessment and Planning (Risk MAP) programme which provides risk assessment tools, flood mapping products, planning and outreach support in order to facilitate risk-informed decision-making at local levels (FEMA 2021). Risk information is vital in being able to design hazard monitoring systems, to set up appropriate evacuation strategies in response to warnings (including evacuation routes and safe areas) and to ensure warning messages reach the most vulnerable (WMO 2010).

Usually, more emphasis in EWS is given to understanding hazards (e.g. the physical behaviour of a flood or a landslide), while vulnerabilities and exposure are often overlooked (Alcántara-Ayala & Oliver-Smith 2019). However, a holistic understanding requires knowing what elements are at risk (i.e. exposed), for instance, roads that might be damaged during landslides which might impact evacuation efforts or schools that might be inundated in a case of flooding, thus interrupting education – information needed to act early and minimise the impact of natural hazards. On the other hand, information on vulnerability reveals which individuals and groups within a society are marginalised and will be more impacted, as vulnerabilities are shaped by social, political, economic and cultural norms (Wisner et al. 2004). For instance, Hurricane Katrina had a disproportionate impact on those poorest, with no home ownership, poor English language skills and ethnic minorities and those of immigrant status (Zoraster 2010). Similarly, Brown et al. (2019) found that marginalised gender groups in flood- and landslide-prone communities of Nepal and Peru are excluded from DRR policies, strategies and decision-making and that their marginalised role within a society results in decreased access to early warning.

This risk knowledge then needs to be shared with those affected by the risks and those responsible or mandated with dealing with those risks. By sharing this knowledge, awareness is raised not just of the risks themselves but also of the need and advocacy to reduce those risks – this is where the benefits of and engagement in an early warning system come in. Collaboration between stakeholders and sharing of knowledge, information and data are needed so that all are aware of the risks and the opportunities to take action to reduce those risks (WMO 2015a).

Monitoring and Warning Scientific understanding of the natural processes that generate hazards, together with past experience and monitoring of current conditions, enables the likelihood of their occurrence to be forecasted in advance (WMO 2010). The accuracy and reliability of these forecasts at different lead times before a hazard occurs can vary widely and are affected by a range of factors including hazard type, how suddenly the hazard occurs, how good the previous observational data and current monitoring are, how well the underlying processes are understood and how complex and replicable the hazard to be modelled is (WMO 2015a). There is a stark difference in forecasting capabilities for different hazards. While a tornado can only be forecast with certainty a few minutes ahead, the storm that spawned it, along with other severe weather hazards, can often be forecasted a few hours ahead. In contrast, development and movement of the weather system containing this storm and others may be predictable several days in advance. Prevalence of the general conditions favouring such storms may be identifiable months in advance. Using previous observations of hazards and their environmental impacts, and aligning these with capabilities for response, warning levels can be developed, whereby when a level of confidence is reached that a threshold of specific environmental conditions will be passed, a warning is issued. Warning systems vary widely according to the hazard, the nature of its impact and the organisation of response capabilities. Examples include the National Fire Danger Rating System in the United States, the Heat Health warning system in Hong Kong, the typhoon warning system in Japan, the storm surge warning system in the Netherlands, the National Severe Weather Warning Service in the United Kingdom and many others.

In order to ensure that warnings properly reflect the evidence, it is important that the evidence is made available for scrutiny, at least for the more severe events but ideally on a routine basis. A record of all warnings issued must be retained, together with the evidence used to justify each warning. Any event for which a warning was not issued, or was issued very late, should also be retained for scrutiny and analysis so that lessons may be learned for application. Similarly, warnings that were not followed by a hazardous event need to be retained, even if they were issued at very low probability, so that the reliability of the likelihood estimates can be assessed over the long term.

Dissemination and Communication Dissemination and communication refer to processes and procedures for distributing the warning and preparedness information in an understandable format to those with responsibility for taking action and to those at risk including the most vulnerable (Brown et al. 2019, UNDP 2018). In literature on EWS, dissemination and communication components are often clustered together. In short, dissemination is how the information reaches the end-users, while communication refers to its content. Appropriate, tailored communication of warning information is critical to ensure people get the right information in the right way to act in advance of hazards (WMO 2010). To ensure that warnings reach all those who need them, the needs of users must first be identified, and a suitably wide range of dissemination media selected to ensure that all are reached, including the most vulnerable and marginalised.

Communication of the warning information also needs to be carefully considered. The raw forecast information analysed by technical specialists in, for example, an NMHS is not appropriate to be communicated beyond this specialist expert group because it requires specific knowledge and skill to understand and interpret. Therefore, warning information needs to be re-packaged and tailored for different users. For instance, experiences of the Super Typhoon Haiyan in the Philippines in 2013 revealed a discrepancy between expert and lay people's understanding of what ‘storm-surge’ means, leading to higher impacts, as technical jargon got lost in translation and interpretation (Santos 2013). Evaluation of the effectiveness of warning communications is needed to assess whether the information, including the level of risk, was understood by users, whether it was felt to be useful, appropriate to needs and actionable.

Dealing with uncertainties in the forecasts is a challenge, and how to communicate this beyond producers of the warning varies among early warning systems. The majority of research and advice in communicating uncertainty in an operational context for natural hazard early warning encourages transparency and emphasises the importance of education and the development of trust (Morss et al. 2008, WMO 2008).

There have been substantial advancements in how warning and preparedness information is communicated and disseminated, especially with the advancement of technology (e.g. e-mails, text messages, radio broadcasts and mobile applications). For instance, Cumiskey et al. (2015) found that farmers in the low-lying, flash flood-prone district of Sunamganj located in the North-Eastern part of Bangladesh prefer mobile services for receiving flood warnings. This is a new opportunity as up to 85% of people have access to mobile phones. However, failures in EWS still mainly occur due to poor communication and dissemination practices (Basher 2006). This is especially true in developing countries, where many still lack access to the technologies for receiving warning information.

Response Capability Response capability refers to a community's knowledge of their risks, ability to act on warnings and familiarity with what they should do when a warning is issued (e.g. where and how to evacuate). It is important that, given accurate, timely and understandable warning information is available and communicated to appropriate users in advance of a disaster, people and institutions are able to respond and take action. A holistic early warning system not only provides warning information but also enables action to be taken based on those warnings. It should be noted here that 'response capability' refers to the capability of responding *to* the early warning information *before* the hazard event, as well as being prepared to respond effectively *after* the hazard event occurs. Response capability is rooted in resources, skills and networks that stakeholders have (Marchezini et al. 2018). It includes having clear lines of authorities and decision-making processes, organising drills and practice scenarios and clear protocols and procedures developed from national to community levels (WMO 2015a).

The capacity of users to take action before a disaster occurs, based on warning information, needs to be built in longer-term planning and preparedness activities. Preparedness plans based on an understanding of local and national knowledge and capacities are needed. Also, plans of how to respond to warnings have to be developed (WMO 2010). Those plans need to be practiced to develop familiarity through training and education (WMO 2002). People also need to have sufficient resources to respond, such as a safe location to go to, a safe route to that location and any other resources to enable them to take action.

Wherever possible, barriers to being able to take action need to be identified in advance, and measures taken to address them within the planning stages. People make decisions based on their perception of multiple risks (not just the natural hazard risk), their capacities and other circumstances. For instance, Elder et al. (2007) showed that, among other reasons, African American communities in New Orleans decided not to evacuate during Hurricane Katrina due to financial constraints, neighbourhood crime, perceived racism and inequities. Continually reviewing the effectiveness of response and any challenges experienced during disasters, and adapting plans in an iterative manner, ensures response plans are up to date (WMO 2010).

Effective Governance and Institutional Arrangements Effective governance of an EWS and robust institutional arrangements are key features to ensure that it operates smoothly. Mandates, responsibilities and long-term funding are required at national level for government institutions to be able to set up and operate a sustainable EWS (WMO 2010, 2018b). A legislatively underpinned commitment and consistent efforts at national level are needed over a long time period in order to address and develop all aspects. Clear standards must be set to ensure that warnings are issued when required and in a timely manner (e.g. at least 6 hours ahead of the event); that they describe the hazard, its location, timing and impact adequately; that they conform to a specified format (e.g. the Common Alerting Protocol); that a defined level of quality control is applied (e.g. a second person checks the warning before issue); that a record is kept of all warnings issued; and that the outcome is recorded. These standards should be monitored and statistics of conformance reported to stakeholders.

Where government commitment is lacking (e.g. through lack of funds), non-governmental organisations (NGOs) or the private sector have sought to fulfil this role, especially in developing countries. For example, Šakić Trogrlić et al. (2018) described how in Southern Malawi NGOs are supporting the government through delivery of community-based early warning systems for flooding. Similarly, in Nepal the Department of Hydrology and Meteorology based in Kathmandu is officially mandated as responsible for the flood early warning system monitoring and warning components. However, there are gaps in the responsibility for dissemination, communication and response capacity within the government institutional mandates. NGOs in Nepal have rushed to fill this void, setting up and operating local early warning services. In the past, these systems (national and local) have operated mostly independently of each other, providing potentially duplicative or conflicting sources of early warning information for local people (Meechaiya et al. 2019). This is not a sustainable solution, often reaching small segments of the population and prone to termination when funding ceases.

UNEP (2015) states that early warning information is a basic human right as climate change and disasters both contribute to human rights violation. As such the mandate for developing and sustaining an early warning system must rest on government bodies. EWS are considered a public task; they have the economic characteristics of public goods that make them difficult to be privately funded and therefore depend heavily on public funding for their proper functioning. Especially in developing countries where taxation systems do not ensure enough public funding, this poses challenges to the financial sustainability of its provision (Deltares 2015). Not every aspect of an EWS must be government operated, nor must a single organisation operate the whole system. Stakeholders involved in producing and using early warning systems range across institutional disciplines and operate at a variety of spatial scales. Effective governance should encourage communication and coordination between stakeholders.

Importance of governance is especially relevant in the context of cross-boundary aspects of an EWS, as hazards do not follow administrative borders. They can affect neighbouring countries simultaneously, and an aspect of approach to DRR in one country (e.g. land use change, construction of infrastructure) can affect the timing, severity and occurrence of a hazard in a neighbouring country. Therefore, a joint and coordinated approach including well-established governance structures (e.g. policy and planning frameworks and institutional design) and processes (e.g. public engagement and behaviour change, research and partnership with policy and practice) to cross-border EWS is crucial. This can include development of clear guidelines and protocols, sharing of historical and real-time data between the countries, sharing of modelling outputs and risk maps across boundaries, joint monitoring and operations, clear division of responsibilities and sustainable financial mechanisms.

Governance also includes the regular maintenance, evaluation and improvements of all elements of the system and of the system as a whole. A successful EWS meets the objectives it was designed for. With time, it will grow and evolve to meet new objectives. However, capabilities and needs are continually changing, so it is unlikely that any EWS will still be optimally meeting the needs of the community after 5 years of operation. Therefore, a key aspect of EWS management is regular review, based on a robust evaluation. Such reviews must address whether the EWS is successfully delivering the information required by users, whether it is still using the most appropriate technologies, whether it is still reaching those at risk in a timely manner and whether it is using the best information available.

It is essential that all aspects of an EWS are maintained, monitored and exercised, including through automated quality-control, structured reporting by trusted partners; monitoring of response through real-time media including social media, telephone and email; and post-event surveying – preferably including direct interviews. EWS managers need to be aware of the ethical dimensions of their systems, ensuring that users are not disadvantaged by reason of their personal characteristics, but also ensuring that their interactions with the EWS system do not, in themselves, have a negative effect. This requires that particular care is taken over confidentiality of feedback information that might, for instance, be used by credit or insurance agencies, in pressurised selling, or even by criminal groups. A particular challenge arising from the growth of social media is the need to counter false information. This requires constant monitoring of social media and rapid response with corrective information before false information is repeated. Where necessary, action should be taken to remove sources of false information.

Involvement of Local Community Early warning systems are only effective if they inherently and actively put people at the centre – ensuring all elements of the early warning system consider and prioritise those at risk from natural hazards (WMO 2010). Local authorities, non-governmental organisations and communities need to be involved in all aspects of early warning so that the system is designed to be appropriate for community needs and capacities. This way, the responses to warning information will be designed to protect people, households and communities from disasters.

A local, ‘bottom-up’, ‘end-mile’ or ‘first-mile’ approach to early warning, with active participation of local communities, including marginalised groups, enables engagement in and contribution to the system, ensuring reduced vulnerability and leveraging and strengthening of local capacities. Community-based early warning systems are good examples of involving local communities. For instance, Practical Action has been working with communities in Nepal since 2008 in setting up local flood early warning systems, with extensive involvement of local communities across the four components of EWS (Rai et al. 2020). Examples of community involvement in local-level early warning systems can also be found in high income countries. For instance, in Scotland, private developers Scottish Flood Forum and Scottish Environmental Protection Agency jointly implemented the RiverTrack. It is an affordable river level monitoring system providing real-time river levels to displays located in local homes and businesses, thus allowing for continuous monitoring.

The involvement of communities can also be framed in the context of citizen science, where the level of participation can increase from citizens as merely sensors, citizens as basic interpreters, citizens that directly participate in the EWS problem definition and data collection up to fully collaborative science (Paul et al. 2018). In many areas of the world, local communities also have rich local and indigenous knowledge on early warning (Acharya & Prakash 2019, Šakić Trogrlić et al. 2019), and there is an increasing focus on understanding how this type of information can be blended and integrated with scientific knowledge in EWS.

The Importance of Gender and Cultural Diversity Vulnerability to the impact of disasters is increased by gender inequality, gender norms and social marginalisation (Brown et al. 2019, UNISDR 2009). Women and marginalised groups including gender minorities are often excluded from DRR policies, strategies and decision-making (Brown et al. 2019, UNISDR 2009). In contexts of gender inequality, people of different genders access, process, interpret and respond to information in different ways, due to the social and cultural organisation of gender relations and the gendered division of labour (UNISDR 2009). For instance, Tyler and Fairbrother (2018) while researching a role of gender in decision-making at household level on wildfire evacuation found that men and women have differing conceptions on when they should evacuate: while women would prefer earlier evacuation, men prefer later evacuation. However, it is challenging for women to voice their concerns as men are culturally viewed as more authoritative voices in wildfire discussions. Fordham (2001) explored a gender perspective on early warning in DRR. She found that during the 1991 Cyclone in Bangladesh women were less likely to receive the warning; even when they did, cultural norms forbade their movement in public. Cultural diversity and marginalisation affect all elements of an early warning system (Brown et al. 2019). Marginalised people are often those most overlooked by early warning systems. People may be marginalised on the basis of age, sex, disability, race, ethnicity, religion, migration status, socio-economic status, place of residence, sexual orientation and gender identity. These groups require special consideration, focused attention, proactive engagement and sensitive or transformative approaches to ensure no one is left behind. The key consideration should be equity of outcome rather than equality of treatment. Cultural diversity and marginalisation affect all elements of an early warning system (Brown et al. 2019). Early warning systems need to take account of cultural differences in the perception of authority, of the cause of hazards, of the nature of prediction and in the availability and use of communication channels, among other factors.

A Multi-Hazard Approach People are at risk from multiple hazards with each having different likelihoods of occurring. For instance, they might live in a multi-hazardous location prone to both hydrometeorological and geophysical hazards, and different hazards can also interact (e.g., an earthquake triggering a landslide). As such, if we are taking a people-centric approach to early warning, we should develop an early warning system or early warning systems that address all hazards affecting the population in a certain location.

Where possible, early warning systems should link hazard-specific systems together to ensure people are provided with early warning for all hazards they are at risk from (WMO 2018b). Such a multi-hazard early warning system would provide a holistic understanding of forecasted hazards that may occur and their complex, interrelated relationships, such as whether these hazards occur alone, simultaneously, cascadingly or cumulatively (UNDRR 2020a).

For instance, the United Kingdom's Natural Hazard Partnership[3] (Hemingway & Gunawan 2018) publishes the Daily Hazard Assessment, an overview of 21 natural hazards that could affect the United Kingdom over the next 5 days. The hazards covered are air (e.g. aero allergens and air pollutions, hail, rain, lightning), land (e.g. avalanches, earthquakes, landslides), water (e.g. surface water flooding, drought) and space (e.g. space weather, near Earth and space objects). While multi-hazard early warning systems that are truly integrated across hazards are rare, a multi-hazard approach to early warning is achievable, for example: building new hazard early warning systems upon existing systems; coordinating across responsible institutions to share data, forecasts or outputs; and/or developing consistent, coordinated or combined communication materials.

2.4.3 Early Warning Systems as Preparedness and Risk Reduction

As Kelman and Glantz (2014) note, a common misunderstanding in relation to EWS is that they exist only to be activated once a hazard occurs. However, the aim of an EWS is not just to facilitate institutional, community or individual response to an impending hazard, but to (ideally) introduce a long-term risk reduction behaviour as well as instigate anticipatory action. To ensure EWS lead to both long- and

[3] http://www.naturalhazardspartnership.org.uk/

short-term risk reduction behaviour before a disaster arrives, the EWS should be integrated in the community's everyday life, as opposed to being only used when a disaster is imminent.

If designed, implemented and operated in its entirety, taking into account all of the parts described in the previous section (i.e. all eight components), EWS present an opportunity to reduce disaster risks and foster a 'culture' of preparedness. For instance, mapping of disaster risks conducted as a part of EWS can inform spatial development and serve as a basis for policies that would delineate disaster-prone areas and introduce some of the available measures (e.g. limited development, introduction of insurance schemes, disaster prevention infrastructure), in turn reducing risks in these areas. Similarly, paying attention to differentiated vulnerabilities of individuals and members of communities provides an opportunity to design actions that would both decrease their vulnerabilities in the long term (e.g. designing inclusive decision-making processes and increasing access to services) and improve their capacity in terms of EWS (e.g. designing communication practices for people with hearing impairment or evacuation protocols for people with physical disabilities).

Depending on the type of a hazard and the lead time of the warning that is possible, EWS offers a window of opportunity for early actions. Warning information is useless if not followed by appropriate actions that will minimise impacts by reducing risks or increase preparedness for a better response. For instance, this requires moving away from warnings that tell what the weather will be, to warnings that tell what the weather will do. WMO has developed guidelines for how National Meteorological and Hydrological Services can implement 'impact-based forecasting', i.e. providing a forecast of the potential consequences of a hydrometeorological event, in terms of its effects on, e.g. people and infrastructure. It can also be sector specific, such as for agriculture, tourism or humanitarian aid. These types of forecasts and warnings are designed to provide detailed information on who or what is exposed and vulnerable to the particular hazard. For impact forecast and warning services, exposure is explicitly considered along with hazard and vulnerability (WMO 2015b). This requires NMHS to transform and collaborate with other sector-specific government agencies, private sector and humanitarian agencies to be able to provide such impact-based forecasts. It also requires changes in mandates of NMHS as well as other government agencies. If impact-based forecasts are provided, this also brings responsibilities to act on this information. Several agencies involved in humanitarian response such as International Federation of Red Cross, World Food Programme, Food and Agriculture Organization and UN OCHA are working in parallel on mechanisms to release funding based on impact-based forecasts.

In 2008, the Red Cross Red Crescent movement introduced Forecast-based Financing (FbF) for early action and preparedness for response. FbF enables access to a Disaster Response Emergency Fund, a funding source habitually only available for humanitarian response, via an Early Action Protocol (EAP). The EAP is triggered when an impact-based forecast—i.e., the expected (humanitarian) impact as a result of the expected weather—reaches a predefined danger level (IFRC 2018). An

EAP outlines the potential high-risk-prone areas where the FbF mechanism could be activated, the prioritised risks to be tackled by early actions, the number of households to be reached against an expected activation budget, the forecast sources of information, the expected lead time for activation and the agencies responsible for implementation and coordination. Around ten EAPs for mostly sudden-onset disasters and one for slow-onset disasters have been established and approved since the first one in 2018. Early actions are determined in collaboration with to-be-affected communities and need to comply with a number of criteria (IFRC 2018) in order to be able to be executed and to be cost-effective. Very often one of the early actions is the transfer of cash to the to-be-affected communities. Most early action protocols are based on hazards for which the lead time of the warning allows for sufficient implementation time.

However, even if there are only a few hours available to have certainty of a hazardous event (e.g. a flash flood), if EWS is implemented as a preparedness (e.g. clear responsibilities of roles, defined evacuation routes and identified shelters) and risks are reduced (e.g. people trained in alternative livelihood options, existing insurance schemes), impacts could be minimised.

As described by IFRC (2008), in an example of a cyclone, there are multiple preparedness and risk reduction actions available in different timeframes, each with different requirements for dissemination. Given that climate change projections indicate an increased likelihood of intense tropical cyclones (an early warning for years in advance), risk reduction actions could be introducing strict building codes and promoting cyclone-proof housing, while preparedness actions could be raising awareness of cyclone risks and training communities for disaster response. On a seasonal timescale, forecasts of above-average cyclone activity are available, providing an opportunity to revisit contingency plans, replenish stocks and conduct emergency drills. Early warning information of likely development of cyclones in a particular stretch of the ocean can now provide weeks of advance warning, prompting awareness of the potential for storm warnings. Days before the cyclone makes landfall, when forecasts are quite accurate in identifying locations to be hit, evacuation can be prepared, warnings can be sent to communities at risk while housing can be cyclone-proofed. For example, machine learning models trained on historical cyclone events in the Philippines are being used to predict 3 days ahead whether more than 10% of houses in a municipality will be damaged. If this threshold is surpassed, early actions are taken in the form of household strengthening and early harvesting of rice or abaca trees (Wagenaar et al. 2021). Then, just hours before the event, final warnings provide the trigger for evacuation to storm shelters.

2.5 Gaps in Early Warning Systems

Early warning systems for natural hazards have come a long way, facilitated by advances in technology (e.g. monitoring, forecasting and dissemination technology) and science (understanding of the processes involved), by increased policy support (both at global and national levels) and by growth in understanding what integrated and people-centred EWS are (i.e. the components described above). However, there are still large gaps that warrant further research, investments, policy change and practice. In Table 2.4, we summarise the main gaps according to the eight components of EWS.

Substantive gaps remain across all components of EWS. Gaps in the 'technical' aspects of EWS (e.g. quality of monitoring equipment, forecasting capability, dissemination channels) are a hindrance to effective EWS in many parts of the world, especially in developing countries. For instance, observing networks are often inadequate, particularly across Africa, where in 2019 just 26% of stations reported

Table 2.4 Common gaps in EWS

Components of early warning system	Gaps identified in the literature
Risk information	A predominant focus on hazard with a lack of understanding of vulnerability and exposure Lack of integration of risk information in decision-making Data gaps – especially in developing countries Difficult access to data for risk information – particularly open access/sharing across disciplines or organisations
Monitoring and warning	Uncertainty in forecasting and climate change influencing forecasting capability Varying skills of forecast information: accuracy, reliability, resolution Lead time Spatial and temporal resolution Varying quality of historical data records limits prediction skill Lack of validation/evaluation of forecast skill Lack of monitoring infrastructure, technical and human capacity, especially in developing countries Lack of sustainability of monitoring and forecasting systems Inadequate monitoring Prediction capabilities for rapid-onset hazards (e.g. flash floods and landslides) and lack of systems for some hazards (e.g. dust and sandstorms, flash floods)
Dissemination and communication	Dominance of experts at the expense of user-focused communication Top-down dissemination takes time, reducing lead time Lack of feedback mechanisms between users and producers Lack of access to warning information, especially for the most vulnerable groups Inadequate communication systems to provide timely, accurate and meaningful warning information to those at risk Underdeveloped dissemination infrastructure in developing countries Lack of impact-based warning information Inadequately standardised nomenclature, protocols and standards Ineffective engagement of media and private sector Fragmented monitoring responsibilities Communication content/message not adapted for specific user needs/capabilities

(continued)

Table 2.4 (continued)

Components of early warning system	Gaps identified in the literature
Response capability	Weak public response to warnings Lack of risk awareness and understanding – lack of outreach/education and practice Lack of post-event reviews and poor incorporation of lessons learned Unclear authorities and decision-making processes hindering the response Lack of simulation exercises and evacuation drills Lack of inducing long-term risk reduction behaviour Lack of adequate safe spaces, concerns over safe spaces, lack of safe routes Barriers to taking action even if would want to, e.g. caring responsibilities or insufficient lead time Concerns over leaving assets/possessions (guarding and staying put) Behavioural reasons for not responding (e.g. risk perception based on previous experience of hazards and staying put)
Effective governance and Institutional arrangements	Inadequate multi-agency and institutional collaboration and clarity of roles and responsibilities Lack of funding (i.e. disaster finance still heavily focused on response) Weak budgetary and political support in some countries Inadequate coordination between local, national and regional levels Gaps in legal, institutional and coordination frameworks, especially in developing countries Political failures to take action (e.g. timing, lack of resources, fear of litigation) Weak integration of EWS in national plans Inadequate recognition of links between disaster risk reduction, climate change adaptation and sustainable development Insufficient coordination among actors responsible for EWS
Multi-hazard approach	Most countries report warning systems for single hazards (i.e. lack of multi-hazard EWS) Very few countries have all hazards covered. And rarely are they integrated (sharing data, risk analysis, interactions, one-communication channel/method, synthesised SOPs for response)
Involvement of local community	Lack of engagement of those at risk is the design and operation of EWS Practical challenges of community engagement (e.g. physical distance, funding, timeframes) Lack of using participatory approaches Lack of inclusion of local, traditional and indigenous knowledge
Gender perspectives and cultural diversity	Gender incorporation in EWS rarely considered Lack of consideration of cultural diversity and linguistic barriers Marginalised people not included or considered in a meaningful way in assessment of risk and unable to participate meaningfully in DRR/DRM/EWS preparedness plans, etc.

Based on Basher 2006, Grasso 2014, UNDP 2018, WMO 2015b, Zommers and Singh 2014 according to the WMO requirements (WMO 2020a). Good monitoring and forecasting depend on high-quality data. Yet, data quality and preservation of long-term records remain a challenge. Moreover, hazard data remain the focus of most EWS, with data on vulnerabilities and exposure sidelined. This results in an inability to provide impact-based and tailored warning information.

The ‘social’ component of EWS also remains marginalised in comparison to the technical aspects. Despite a rhetoric of importance of community involvement, consideration of gender and marginalised groups and differentiated vulnerabilities, these often remain box-ticking exercises, given inadequate attention. EWS are a long way from being considered as social processes, and a ‘culture’ of preparedness is rarely achieved in practice. For instance, inadequate attention is given to public awareness and training on how to respond to warning information, while systems in place continue to favour relief over early action. Furthermore, in many parts of the world, information fails to reach those at the sharpest end of natural hazards. Research on transboundary EWS in Bangladesh, India and Nepal showed, for example, that access to EWS technology is not distributed fairly (van den Homberg & McQuistan 2019). Overall, there is an insufficient capacity worldwide to translate early warning into early action (WMO 2020a).

Good governance remains a significant challenge in many parts of the world. Early warning systems remain unfunded and politically unfavoured, with inadequate policies and institutional structures in place. For instance, gaps remain in legal frameworks for EWS. A recent review of the role of national laws in managing flood risk by Mehryar and Surminski (2020), focusing on 139 national laws from 33 countries, found that national laws have a prevailing focus on the response and recovery strategies while placing less emphasis on proactive risk reduction and preparedness, including EWS. Taking legal responsibility for warnings and their dissemination remains one of the key issues in operationalisation of a flood EWS (Parker 2017). Responsibilities for different aspects of early warning largely remain scattered across departments and institutions, resulting in an uncoordinated and unsustainable approach. There is a plethora of reporting frameworks for the Global Agreements (i.e. Sustainable Development Goals, Sendai Framework and Paris Agreement), with indicators that relate to (parts of) EWS. However, these are often high-level, based on (too optimistic) self-reporting and not harmonised. As a result, there is also a lack of high spatial and temporal resolution data on whether early warnings are received, understood and acted upon.

As mentioned previously, despite multi-hazard frameworks being a target of EWS, they remain underdeveloped and rarely, if ever, achieved in practice. With a global push for multi-hazard EWS, it remains worrying that in many countries, EWS are inadequate or non-existent even for single hazards.

In addition to gaps across the eight components of an EWS, there are other significant gaps. For instance, in evaluating the performance of an EWS (Sättele et al. 2016). As suggested by WMO (2018a, 2018b), the checklist developed around the four core components of an EWS (i.e. risk knowledge, monitoring and warning, response capability, dissemination and communication) offers a series of practical actions and initiatives which should be considered when evaluating EWS. An EWS needs to be continuously reviewed and assessed in order to incorporate the learnings, adapt needed improvements and create an effective EWS. This is across all areas including (among others) evaluating forecast skill, data collection/monitoring accuracy and logistics, lead time, effectiveness of access to and understanding of warning information and people's abilities to act based on warnings. Furthermore, there are significant differences between countries in the availability of skills for EWS. For instance, in developing country contexts where resources are limited, the government departments responsible for EWS are often extremely restricted, both in terms of number of staff available to the department and in terms of the range of skills hired. Naturally, physical science skills are the most urgent types of skills needed in, for example, NMHS, but there are a range of skills and specialties required for a fully operational EWS (e.g., skills in social sciences, science communication, public relations). Without them, robust monitoring and warning thresholds may be developed, but they will not be effective in enabling early action. In contexts where these perceived 'softer' skills are not recruited or resourced within the EWS-mandated government department, it leaves gaps either (1) where those mandates are perceived as beyond the institution's capacities and therefore not attempted or (2) where NMHS staff are required to act beyond their training, experience, skills and knowledge in areas outside their expertise.

2.6 Summary

- Disaster risks arise from a complex interplay between physical hazards and the exposure of vulnerable people, assets and systems to them. Understanding disaster risk, and its distribution in time and space, is fundamental for management and reduction of these risks.
- We have presented the ingredients of disaster risks and available options to deal with them, with a specific focus on the role of early warning systems. We presented an eight-component framework of people-centred EWS, highlighting the importance of an integrated and all-society approach.
- If designed, implemented and operated in its entirety, such an EWS can reduce disaster risks, foster preparedness and early action and build resilience of populations at risk. In order to realise these benefits, warnings must be received, understood and acted on: they must be useful, usable and used.
- Successful operation of an EWS requires assured long-term funding and involves a vast array of stakeholders, including local communities, government departments at different levels, private sector, media and regional players.
- Equal importance should be given to the social components (e.g. community involvement, communication) as to the technical aspects of an EWS.
- EWS need to account for the occurrence of multiple hazards.
- Realising the full potential of EWS requires systematic changes in the current status quo, including (but not limited to) increased funding and prioritisation of EWS, improvements in horizontal and vertical governance arrangements, development of new technologies with corresponding capacity development and enhanced involvement of communities at risk.

References

Acharya A. and A. Prakash, 2019. When the river talks to its people: Local knowledge-based flood forecasting in Gandak River basin, India. *Environmental Development,* **31,** 55–67. DOI: https://doi.org/10.1016/J.ENVDEV.2018.12.003

Alcántara-Ayala I. and A. Oliver-Smith, 2019. Early Warning Systems: Lost in Translation or Late by Definition? A FORIN Approach. *Int. J. Disaster Risk Science,* **10**(**3**), 317–331. DOI: https://doi.org/10.1007/s13753-019-00231-3

Alton M. L. and O. Mahul, 2017. *Assessing Financial Protection against Disasters: A guidance note on conducting a disaster risk finance diagnostic*. Washington, DC: World Bank Group, 60. https://documents1.worldbank.org/curated/en/102981499799989765/pdf/117370-REVISED-PUBLIC-DRFIFinanceProtectionHighRes.pdf (Accessed 2/9/2021)

Basher R., 2006. Global early warning systems for natural hazards: systematic and people-centred. *Phil. Trans. Roy. S., A: Mathematical, Physical and Engineering Sciences*. Royal Society **364**(**1845**), 2167–2182. DOI: https://doi.org/10.1098/rsta.2006.1819

Bischiniotis K., H. de Moel, M. van den Homberg, A. Couasnon, J. Aerts, N. G. Guimarães, E. Zsoter and B. van den Hurk, 2020. A framework for comparing permanent and forecast-based flood risk-reduction strategies. *Sci. Tot. Environ.*, **720,** 137572. DOI: https://doi.org/10.1016/j.scitotenv.2020.137572

Boyd E., R. A. James, R. G. Jones, H. R. Young and F. E. L. Otto, 2017. A typology of loss and damage perspectives. *Nature Climate Change,* **7(10**), 723–729. DOI: https://doi.org/10.1038/nclimate3389

Brown S., M. Budimir, A. Sneddon, D. Lau, P. Shakya and S. Upadhyay, 2019. *Gender Transformative Early Warning Systems: Experiences from Nepal and Peru.* Rugby, Warwickshire, United Kingdom: Practical Action. Available at: https://floodresilience.net/resources/item/gender-transformative-early-warning-systems-experiences-from-nepal-and-peru/ (Accessed 01/03/21).

Buckle P., 2012. Preparedness, warning and evacuation. In: Wisner B., J. C. Gaillard and I. Kelman (eds) *The Routledge Handbook of Hazards and Disaster Risk Reduction*. Abingdon: Routledge, 481–492. ISBN 9780415523257

Cardona O. D., M. G. Ordaz, E. Reinoso, L. E. Yamín and A. H. Barbat, 2010. CAPRA - Comprehensive Approach to Probabilistic Risk Assessment: International Initiative for Risk Management Effectiveness. *14th European Conference on Earthquake Engineering*. paper presented at the European Conference on Earthquake Engineering. Ohrid, Macedonia, 10. https://www.researchgate.net/profile/Alex-Barbat/publication/259598259_CAPRA_-_Comprehensive_Approach_to_Probabilistic_Risk_Assessment_International_Initiative_for_Risk_Management_Effectiveness/links/0c96052cd8a91e18b3000000/CAPRA-Comprehensive-Approach-to-Probabilistic-Risk-Assessment-International-Initiative-for-Risk-Management-Effectiveness.pdf (Accessed 2/9/2021)

Coppola D. P., 2011. *Introduction to international disaster management* (2nd edition). Elsevier. ISBN 978-0-12-382174-4. https://doi.org/10.1016/C2009-0-64027-7

Cumiskey L., M. Werner, K. Meijer, S. H. M. Fakhruddin and A. Hassan, 2015. Improving the social performance of flash flood early warnings using mobile services. *Int. J. Disaster Resilience in the Built Environment* **6**(**1**), 57–72. DOI: https://doi.org/10.1108/IJDRBE-08-2014-0062

Daron J., M. Allen, M. Bailey, L. Ciampi, R. Cornforth, C. Costella, N. Fournier, R. Graham, K. Hall, C. Kane, I. Lele, C. Petty, N. Pinder, J. Pirret, J. Stacey and H. Ticehurst, 2020. Integrating seasonal climate forecasts into adaptive social protection in the Sahel. *Climate and Development*, 1–8. DOI: https://doi.org/10.1080/17565529.2020.1825920

Deltares, 2015. *Mobile services for flood early warning in Bangladesh*: *final report*. Delft, The Netherlands: Deltares. https://www.deltares.nl/app/uploads/2015/11/Deltares-Mobile-Services-for-Early-Warning-in-Bangladesh-Final-Report_web.pdf. (Accessed 2/9/2021)

Deryugina T., 2017. The Fiscal Cost of Hurricanes: Disaster Aid versus Social Insurance. *Amer. Economic J.: Economic Policy,* **9**(**3**), 168–198. DOI: https://doi.org/10.1257/pol.20140296

Elder K., S. Xirasagar, N. Miller, S. A. Bowen, S. Glover and C. Piper, 2007. African Americans' Decisions Not to Evacuate New Orleans Before Hurricane Katrina: A Qualitative Study. *Amer. J. Pub. Health. Amer. Pub. Health Assoc.* **97,** S124–S129. DOI: https://doi.org/10.2105/AJPH.2006.100867e

FEMA, 2021. *Risk Mapping, Assessment and Planning (Risk MAP) | . Risk Mapping, Assessment and Planning (Risk MAP).* https://www.fema.gov/flood-maps/tools-resources/risk-map (Accessed 03/03/21).

Fordham M., 2001. *Challenging boundaries: a gender perspective on early warning in disaster and environmental management.* United Nations Division for the Advancement of Women. https://www.unisdr.org/files/8264_EP52001Oct261.pdf (Accessed 2/9/2021)

Gaillard J. C., J. R. D. Cadag and M. M. F. Rampengan, 2019. People's capacities in facing hazards and disasters: an overview. *Nat. Hazards,* **95(3**), 863–876. DOI: https://doi.org/10.1007/s11069-018-3519-1

Galasso, C., J. McCloskey, M. Pelling, M. Hope, C. J. Bean, G. Cremen, R. Guragain, U. Hancilar, J. Menoscal, K. Mwang'a, J. Phillips, D. Rush and H. Sinclair, 2021. Editorial. Risk-based, Pro-poor Urban Design and Planning for Tomorrow's Cities. *Int. J. Disaster Risk Reduction*, **58**, 102158. https://doi.org/10.1016/j.ijdrr.2021.102158

GFDRR, 2021. ThinkHazard. Available at: https://thinkhazard.org/en/ (Accessed 28/02/21).

Gill J. C. and B. D. Malamud, 2014. Reviewing and visualizing the interactions of natural hazards. *Rev. Geophys*. **52(4**), 680–722. DOI: https://doi.org/10.1002/2013RG000445

Grasso V. F., 2014. The State of Early Warning Systems. In: Singh A and Zommers Z (eds) *Reducing Disaster: Early Warning Systems for Climate Change.* Dordrecht: Springer Netherlands, 109–125. https://doi.org/10.1007/978-94-017-8598-3_6

Gros C., M. Bailey, S. Schwager, A. Hassan, R. Zingg, M. M. Uddin, M. Shahjahan, H. Islam, S. Lux, C. Jaime and E. Coughlan de Perez, 2019. Household-level effects of providing forecast-based cash in anticipation of extreme weather events: Quasi-experimental evidence from humanitarian interventions in the 2017 floods in Bangladesh. *Int. J. Disaster Risk Reduction,* **41,** 101275. https://doi.org/10.1016/j.ijdrr.2019.101275

Hallegatte S., A. Vogt-Schilb, M. Bangalore and J. Rozenberg, 2016. *Unbreakable: Building the Resilience of the Poor in the Face of Natural Disasters.* The World Bank. http://elibrary.worldbank.org/doi/book/10.1596/978-1-4648-1003-9 (Accessed 06/02/19).

Harries T. and E. Penning-Rowsell, 2011. Victim pressure, institutional inertia and climate change adaptation: The case of flood risk. *Global Environmental Change,* **21(1**), 188–197. https://doi.org/10.1016/j.gloenvcha.2010.09.002

Hemingway R. and O. Gunawan, 2018. The Natural Hazards Partnership: A public-sector collaboration across the UK for natural hazard disaster risk reduction. *Int. J. Disaster Risk Reduction,* **27**, 499–511. https://doi.org/10.1016/j.ijdrr.2017.11.014

van den Homberg M. and C. McQuistan, 2019. Technology for Climate Justice: A Reporting Framework for Loss and Damage as Part of Key Global Agreements. In: Mechler R., L. M. Bouwer, T. Schinko, S. Surminski and J. Linnerooth-Bayer (eds) *Loss and Damage from Climate Change: Concepts, Methods and Policy Options*. Cham: Springer International Publishing, pp513–545. https://doi.org/10.1007/978-3-319-72026-5_22 (Accessed 05/02/19).

IASC, 2020. *What does the IASC humanitarian system-wide level 3 emergency response mean in practice?* New York, USA: Inter-Agency Standing Committee. https://interagencystandingcommittee.org/system/files/l3_what_iasc_humanitarian_system-wide_response_means_final.pdf (Accessed 2/9/2021)

IDNDR, 1994. *Yokahoma strategy and plan for action for a safer world.* Yokahoma, Japan: United Nations. https://www.ifrc.org/Docs/idrl/I248EN.pdf (Accessed 2/9/2021)

IFRC, 2008. *Early Warning > Early Action*. Geneva, Switzerland: IFRC. https://media.ifrc.org/ifrc/document/early-warning-early-action/ (Accessed 03/03/21).

IFRC, 2018. *Forecast-based Financing Practitioners Manual*. Geneva, Switzerland: IFRC. https://manual.forecast-based-financing.org/. (Accessed 2/9/2021)

Jones S., B. Manyena and S. Walsh, 2015. Chapter 4 - Disaster Risk Governance: Evolution and Influences. In: Shroder JF, Collins AE, Jones S, Manyena B and Jayawickrama J (eds) *Hazards, Risks and Disasters in Society*. Boston: Academic Press, 45–61. http://www.sciencedirect.com/science/article/pii/B9780123964519000044 (Accessed 03/04/19).

Karim A. and I. Noy, 2016. Poverty and Natural Disasters: A Regression Meta-Analysis. *Rev. Economics Institutions,* **7(2)**, 26. DOI:10.5202/REI.V7I2.222

Kelman I. and M. H. Glantz, 2014. Early Warning Systems Defined. In: Singh A and Zommers Z (eds) *Reducing Disaster: Early Warning Systems For Climate Change*. Dordrecht: Springer Netherlands, 89–108. https://doi.org/10.1007/978-94-017-8598-3_5

Lindersson S., L. Brandimarte, J. Mård and G. D. Baldassarre, 2020. A review of freely accessible global datasets for the study of floods, droughts and their interactions with human societies. *WIREs Water,* **7(3)**: e1424. DOI: https://doi.org/10.1002/wat2.1424

Marchezini V., F. E. A. Horita, P. M. Matsuo, R. Trajber, M. A. Trejo-Rangel and D. Olivato, 2018. A Review of Studies on Participatory Early Warning Systems (P-EWS): Pathways to Support Citizen Science Initiatives. *Frontiers in Earth Science*. Frontiers 6. https://www.frontiersin.org/articles/10.3389/feart.2018.00184/full (Accessed 20/11/20).

Marin-Ferrer M., K. Poljansek and L. Vernaccini, 2017. *Index for risk management - INFORM: concept and methodology, version 2017*. Joint Research Centre (European Commission). http://op.europa.eu/en/publication-detail/-/publication/b1ef756c-5fbc-11e7-954d-01aa75ed71a1/language-en/format-PDF (Accessed 28/02/21).

Mechler R., 2016. Reviewing estimates of the economic efficiency of disaster risk management: opportunities and limitations of using risk-based cost–benefit analysis. DOI https://doi.org/10.1007/s11069-016-2170-y

Mechler R., E. Calliari, L. M. Bouwer, T. Schinko, S. Surminski, J. Linnerooth-Bayer, J. Aerts, W. Botzen, E. Boyd, N. D. Deckard, J. S. Fuglestvedt, M. González-Eguino, M. Haasnoot, J. Handmer, M. Haque, A. Heslin, S. Hochrainer-Stigler, C. Huggel, S. Huq, R. James, R. G. Jones, S. Juhola, A. Keating, S. Kienberger, S. Kreft, O. Kuik, M. Landauer, F. Laurien, J. Lawrence, A. Lopez, W. Liu, P. Magnuszewski, A. Markandya, B. Mayer, I. McCallum, C. McQuistan, L. Meyer, K. Mintz-Woo, A. Montero-Colbert, J. Mysiak, J. Nalau, I. Noy, R. Oakes, F. E. L. Otto, M. Pervin, E. Roberts, L. Schäfer, P. Scussolini, O. Serdeczny, A. de Sherbinin, F. Simlinger, A. Sitati, S. Sultana, H. R. Young, K. van der Geest, M. van den Homberg, I. Wallimann-Helmer, K. Warner and Z. Zommers, 2019. Science for Loss and Damage. Findings and Propositions. In: Mechler R., L. M. Bouwer, T. Schinko, S. Surminski and J. Linnerooth-Bayer (eds) *Loss and Damage from Climate Change: Concepts, Methods and Policy Options.* Cham: Springer International Publishing, 3–37. https://doi.org/10.1007/978-3-319-72026-5_1

Meechaiya C., E. Wilkinson, E. Lovell, S. Brown and M. Budimir, 2019. *The governance of Nepal's flood early warning system: opportunities under federalism.* London: Overseas Development Institute. https://odi.org/en/publications/the-governance-of-nepals-flood-early-warning-system-opportunities-under-federalism/ (Accessed 2/9/2021)

Mehryar S. and S. Surminski, 2020. *The role of national laws in managing flood risk and increasing future flood resilience.* London, UK: Grantham Research Institute on Climate Change and Environment. https://www.lse.ac.uk/granthaminstitute/publication/the-role-of-national-laws-in-managing-flood-risk-and-increasing-future-flood-resilience/ (Accessed 03/03/21).

Morss R. E., J. L. Demuth and J. K. Lazo, 2008. Communicating Uncertainty in Weather Forecasts: A Survey of the U.S. Public. *Wea. Forecast*, **23(5),** 974–991. https://doi.org/10.1175/2008WAF2007088.1

Ouriachi-Peralta T. and S. H. M. Fakhruddin, 2014. Integrating local knowledge in disaster risk reduction: a case study for Indonesia. *Asian J. Environ. Disaster Management*, **6**. DOI:https://doi.org/10.3850/S1793924014000297

Parker D. J., 2017. Flood Warning Systems and Their Performance. In *Oxford Research Encyclopedia of Natural Hazard Science*. https://oxfordre.com/naturalhazardscience/view/10.1093/acrefore/9780199389407.001.0001/acrefore-9780199389407-e-84 (Accessed 03/03/21).

Paul J. D., W. Buytaert, S. Allen, J. A. Ballesteros-Cánovas, J. Bhusal, K. Cieslik, J. Clark, S. Dugar, D. M. Hannah, M. Stoffel, A. Dewulf, M. R. Dhital, W. Liu, J. L. Nayaval, B. Neupane, A. Schiller, P. J. Smith and R. Supper, 2018. Citizen science for hydrological risk reduction and resilience building. *Wiley Interdisciplinary Reviews: Water,* **5(1)**: e1262. DOI:https://doi.org/10.1002/wat2.1262

Practical Action, 2018. *Participatory digital mapping: building community resilience in Nepal, Peru, and Mexico*. Rugby, Warwickshire, United Kingdom: Practical Action. https://infohub.practicalaction.org/bitstream/handle/11283/620791/Digital+Mapping_web.pdf?sequence=1 (Accessed 03/03/21).

Rai R. K., M. J. C. van den Homberg, G. P. Ghimire and C. McQuistan, 2020. Cost-benefit analysis of flood early warning system in the Karnali River Basin of Nepal. *Int. J. Disaster Risk Reduction,* **47,** 101534. DOI:https://doi.org/10.1016/j.ijdrr.2020.101534

Republic of the Philippines, 2010. *Philippine Disaster Risk Reduction and Management Act of 2010*. https://www.ifrc.org/PageFiles/100077/Philippines_2009_Philippine%20Disaster%20Risk%20Reduction%20and%20Management%20Act%20of%202010.pdf. (Accessed 2/9/2021)

Ruiter M. C. De, A. Couasnon, M. J. C. Van Den Homberg, J. E. Daniell, J. C. Gill and P. J. Ward, 2020. Why We Can No Longer Ignore Consecutive Disasters. *Earth's Future,* **8(3)**: e2019EF001425. https://doi.org/10.1029/2019EF001425

Šakić Trogrlić R., G. B. Wright, A. J. Adeloye, M. J. Duncan and F. Mwale, 2018. Taking stock of community-based flood risk management in Malawi: different stakeholders, different perspectives. *Environ. Hazards,* **17(2),** 107–127. https://doi.org/10.1016/j.pdisas.2021.100171

Šakić Trogrlić R., G. B. Wright, M. J. Duncan, M. J. C. van den Homberg, A. J. Adeloye, F. D. Mwale and J. Mwafulirwa, 2019. Characterising Local Knowledge across the Flood Risk Management Cycle: A Case Study of Southern Malawi. *Sustainability,* **11(6),** 1681. DOI:https://doi.org/10.3390/su11061681

Santos L. A., 2013. *Storm surge: Lost in translation and interpretation*. Devex. https://www.devex.com/news/sponsored/storm-surge-lost-in-translation-and-interpretation-82311 (Accessed 01/03/21).

Sarkar S., 2021. Rapid assessment of cyclone damage using NPP-VIIRS DNB and ancillary data. *Nat. Hazards,* **106(1)**, 579–593. DOI:https://doi.org/10.1007/s11069-020-04477-9

Sättele M., M. Bründl and D. Straub, 2016. Quantifying the effectiveness of early warning systems for natural hazards. *Nat. Hazards Earth Syst. Sci*., **16(1),** 149–166. DOI:https://doi.org/10.5194/nhess-16-149-2016

Sun Q., C. Miao, Q. Duan, H. Ashouri, S. Sorooshian and K.-L. Hsu, 2018. A Review of Global Precipitation Data Sets: Data Sources, Estimation, and Intercomparisons. *Rev. Geophys*., **56(1),** 79–107. https://doi.org/10.1002/2017RG000574

Tozier de la Poterie A. and M.-A. Baudoin, 2015. From Yokohama to Sendai: Approaches to Participation in International Disaster Risk Reduction Frameworks. *Int. J. Disaster Risk Science,* **6(2),** 128–139. DOI https://doi.org/10.1007/s13753-015-0053-6

Twigg J., 2015. *Disaster Risk Reduction* (2nd edition). London, UK: Overseas Development Institute. https://odihpn.org/wp-content/uploads/2011/06/GPR-9-web-string-1.pdf (Accessed 2/9/2021)

Tyler M. and P. Fairbrother, 2018. Gender, households, and decision-making for wildfire safety. *Disasters,* **42(4),** 697–718. DOI:https://doi.org/10.1111/disa.12285

Ulrichs M., R. Slater and C. Costella, 2019. Building resilience to climate risks through social protection: from individualised models to systemic transformation. *Disasters,* **43(S3),** S368–S387. DOI:https://doi.org/10.1111/disa.12339

UNDP, 2018. *Five approaches to build functional early warning systems*. United Nations Development Programme. https://www.eurasia.undp.org/content/dam/rbec/docs/UNDP%20Brochure%20Early%20Warning%20Systems.pdf (Accessed 2-9-2021)

UNDP, 2020. *Issue Brief: disaster risk governance*. https://www.undp.org/content/dam/undp/library/crisis%20prevention/disaster/Issue_brief_disaster_risk_reduction_governance_11012013.pdf (Accessed 03/05/21).

UNDRR, 2005. *Hyogo Framework for Action 2005-2015: Building the resilience of nations and communities to disasters.* Geneva, Switzerland: United Nations Office for Disaster Risk Reduction, 25. https://www.unisdr.org/2005/wcdr/intergover/official-doc/L-docs/Hyogo-framework-for-action-english.pdf (Accessed 2/9/2021)

UNDRR, 2015. *Sendai Framework for Disaster Risk Reduction 2015-2030*. Geneva, Switzerland: United Nations Office for Disaster Risk Reduction, 37. https://www.preventionweb.net/files/43291_sendaiframeworkfordrren.pdf. (Accessed 2/9/2021)

UNDRR, 2016. *Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction*. New York: United Nations. https://www.unisdr.org/we/inform/publications/51748 (Accessed 08/05/19).

UNDRR, 2020a. *Early warning system*. http://www.undrr.org/terminology/early-warning-system (Accessed 03/03/21).

UNDRR, 2020b. *Hazard definition & classification review.* https://www.undrr.org/publication/hazard-definition-and-classification-review (Accessed 08/06/21)

UNEP, 2015. *Early warning as a human right: building resilience to climate-related hazards*. UNEP. https://wedocs.unep.org/xmlui/handle/20.500.11822/7429 (accessed 03/03/21).

UNEP, 2021. *Global Risk Data Platform*. https://preview.grid.unep.ch/index.php?preview=data&events=floods&evcat=3&lang=eng (Accessed 28/02/21).

UNFCCC, 2012. *A literature review on the topics in the context of thematic area 2 of the work programme on loss and damage: a range of approaches to address loss and damage associated with the adverse effects of climate change*. UNFCCC. https://unfccc.int/resource/docs/2012/sbi/eng/inf14.pdf. (Accessed 2/9/2021)

UNFCCC, 2015. *Paris Agreement*. Paris, France: United Nations Framework Convention on Climate Change. https://unfccc.int/sites/default/files/english_paris_agreement.pdf (Accessed 2-9-2021)

UNISDR, 2006. *Developing early warning systems, a checklist: third international conference on early warning (EWC III)*, 27-29 March 2006, Bonn, Germany. Geneva, Switzerland: UNISDR. http://www.undrr.org/publication/developing-early-warning-systems-checklist-third-international-conference-early-warning (Accessed 01/03/21).

UNISDR, 2009. *Making disaster risk reduction gender-sensitive: Policy and practical guidelines*. Geneva, Switzerland: UNISDR. https://www.unisdr.org/files/9922_MakingDisasterRiskReductionGenderSe.pdf (Accessed 2/9/2021)

Wagenaar D., T. Hermawan, M. J. C. van den Homberg, J. C. J. H. Aerts, H. Kreibich, H. de Moel and L. M. Bouwer, 2021. Improved Transferability of Data-Driven Damage Models Through Sample Selection Bias Correction. *Risk Analysis,* **41(1)**, 37–55. DOI: https://doi.org/10.1111/risa.13575

Walton D. and M. van Aalst, 2020. *Climate-related extreme weather events and COVID-19.* IFRC Climate Centre. https://climatecentre.org/downloads/files/Extreme%20weather%20events%20and%20COVID%2019%20IFRC2020(1).pdf. (Accessed 2/9/2021)

Wamsler C. and E. Brink, 2014. Moving beyond short-term coping and adaptation. *Environ. Urbanization* **26(1),** 86–111. DOI:https://doi.org/10.1177/0956247813516061

Wisner B., J. C. Gaillard and I. Kelman, 2012. *The Routledge handbook of hazards and disaster risk reduction.* (1st edition). London: Routledge. ISBN 9780415523257

Wisner B., P. Blaikie, T. Cannon and I. Davis, 2004. *At risk: natural hazards, people's vulnerability and disasters* (2nd edition). London: Routledge. ISBN 978-0415252164

WMO, 2002. *Guidelines on Improving Public Understanding of and Response to Warnings*. Geneva: WMO. https://library.wmo.int/doc_num.php?explnum_id=9222 (Accessed 2/9/2021)

WMO, 2008. *Guidelines on communicating forecast uncertainty*. Geneva, Switzerland: World Meteorological Organisation. https://library.wmo.int/doc_num.php?explnum_id=4687 (Accessed 2/9/2021)

WMO, 2010. *Guidelines on early warning systems and application of nowcasting and warning operations*. Geneva: WMO. https://library.wmo.int/doc_num.php?explnum_id=9456 (Accessed 2/9/2021)

WMO, 2015a. *Synthesis of the Status and Trends with the Development of Early Warning Systems. A Contribution to the Global Assessment Report 2015 (GAR15)*. Geneva, Switzerland: WMO. https://www.preventionweb.net/english/hyogo/gar/2015/en/bgdocs/WMO,%202014a.pdf (Accessed 2/9/2021)

WMO, 2015b. *WMO Guidelines on multi-hazard impact-based forecast and warning services*. Geneva, Switzerland: World Meteorological Organisation. https://library.wmo.int/doc_num.php?explnum_id=7901. (Accessed 2/9/2021)

WMO, 2018a. *Cataloguing high-impact events and associated loss and damage*. https://unfccc.int/sites/default/files/resource/Excom%207%20submission%20from%20WMO%20(002).pdf (Accessed 2/9/2021)

WMO, 2018b. *Multi-hazard Early Warning Systems: A Checklist, Outcome of the first Multi-hazard Early Warning Conference, 22-23 May 2017, Cancun, Mexico*. Geneva, Switzerland: World Meteorological Organization, 20. https://etrp.wmo.int/pluginfile.php/21553/mod_page/content/18/MultihazardChecklist.pdf (Accessed 2/9/2021)

WMO, 2020a. *2020 State of Climate Services*. Geneva: WMO. https://library.wmo.int/doc_num.php?explnum_id=10385 (Accessed 2/9/2021)

WMO, 2020b. *CREWS Report Series Annual Report*. Geneva: WMO. https://library.wmo.int/doc_num.php?explnum_id=10226 (Accessed 2/9/2021)

WMO/EHA, 2002. *Disasters and emergencies: definitions*. Addis Ababa, Ethiopia: WMO/EHA. http://apps.who.int/disasters/repo/7656.pdf.

Zommers Z. and A. Singh, 2014. Introduction. In: Singh A and Zommers Z (eds) *Reducing Disaster: Early Warning Systems for Climate Change*. Dordrecht: Springer Netherlands, 1–19. https://doi.org/10.1007/978-94-017-8598-3_1

Zoraster R. M., 2010 Vulnerable Populations: Hurricane Katrina as a Case Study. *Prehospital and Disaster Medicine,* **25(1),** 74–78. https://doi.org/10.1017/S1049023X00007718