The evolution and state-of-the-art of weather and climate warnings

Deliverable D2.1

DEVELOPED WITHIN
WP2 Human Behaviours, T2.1 Overview of existing knowledge

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3. Summary

This report assesses aspects of the historical evolution and current state of weather and climate warnings, drawing on a range of global case studies to provide illustrative examples. The evaluation allows for a better understanding of how weather and climate warnings have been used over time, what has been improved, what has been neglected, and insights available to avoid reinventing the wheel without repeating known mistakes. Recommendations are provided to consider for The HuT project's demonstration sites to contribute warning processes to the ongoing efforts to build a safe environment for coping with climate extremes:

1. Augment communication and exchange.
2. Integrate with other systems and sectors.
3. Cultivate engagement in warnings by integrating multiple warnings types.
4. Implement multi-sectoral, multi-vulnerability, multi-hazard warnings.
5. Account for legalities.
6. Start with and use scientific baselines.

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4. Introduction

Warnings are a core component of Disaster Risk Reduction (DRR) strategies, and an early warning system is a key tool within DRR practices that is designed to reduce the impact of a hazardous event and, if effective, can substantially increase the numbers of survivors, and reduce the societal and environmental impact (Maskrey, 1997; United Nations, 2006; Grasso and Singh, 2011). Weather hazards have been conveyed in warnings for thousands of years, permeating human history, usually in the form of lore. The Met. Office (2023) from the UK analyses lore, tracing it back through history and validating its warning worth. One well known lore is the aphorism and its variations “Red sky at night, shepherd’s delight. Red sky in the morning, shepherd’s warning.” First used in the Bible in the book of Matthew, it signifies the changing sky to help the shepherds prepare for the next day's weather. For parts of the UK, there appears to be meteorological truth to the statement, as a red sky at sunset means high pressure is moving in from the west, so the next day will most likely be dry and pleasant. However, lore must be used with caution as its geographical transferability is usually limited, and any sign may not always be accurate.

Similarly, older people claim that their joints tell them the chance of rain due to arthritis responding to humidity. Scientific investigations have long sought to corroborate or refute this reality (Aikman, 1997). While there might be some potentially relevant biomedical mechanisms, sometimes people’s behaviour influences calculated correlations as much or more than the physical connections (Xie et al., 2020). Consequently, people’s feelings about their body or actual physical responses require significant work–and are an important area of examination–to determine their value for weather warnings (Xie et al., 2020). Whether using observations in the world around us, or how we as individuals respond to observations have been a key component of weather and climate warnings (Zschau and Küppers, 2013).

As our understanding of global patterns of weather and climatic changes, and anthropogenically enforced climate change, warnings for climate have evolved to become highly sophisticated computer data processors and modelers to help sift through vast quantities of data to produce as accurate a forecast and warning as possible. The role of statistical sciences is playing an ever-broader role in establishing warnings, with percentages acting as tipping points for alerts or warnings. But warnings are not just about the hazard, and its likelihood to occur. Warnings are inherently about people and how they communicate, prepare, act, and process warnings, as seen by the UNDRR definition of an early warning system (2023, online):

“*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 take timely action to reduce disaster risks in advance of hazardous events*”.

Human interaction with weather and climate has evolved as our world and behaviours have developed, enabling warnings with increasing understanding and accuracy (Glantz, 2009). Fundamental to this relationship has been the ability to observe our surrounding

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environment, take appropriate action, and embed warnings into everyday life (Kelman and Glantz, 2014). This report assesses aspects of the historical evolution and current state of weather and climate warnings, drawing on a range of global case studies to provide illustrative examples. The evaluation allows for a better understanding of how weather and climate warnings have been used over time, what has been improved, what has been neglected, and insights available to avoid reinventing the wheel without repeating known mistakes. Recommendations are provided to consider for The HuT project's demonstration sites to contribute and enhance warning processes to the ongoing efforts to build a safe environment for coping with climate extremes.

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5. Methodology

This report draws on examples, without being comprehensive or systematic, of weather and climate warnings from human history and around the world. No time limit or geographic constraints were imposed on documents or examples used. This report is thus an expert, critiquing overview, illustrating what ought to be considered, focused on informing partners in The HuT how to adopt state-of-the-art approaches for their own weather and climate warnings, within the project's context.

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6. An overview of the evolution of warnings

Warning systems have evolved significantly over time, especially as technology and technology have advanced. In many cases, there has been a shift from lore, religious, and traditional warnings to dependence on highly sophisticated models, data sets, and technologies (Fearnley et al., 2018). Effectively, 'common sense' elements of warnings have been reduced, creating dependency on a system that is black boxed and often not transparent even to the wider public, and reduced redundancy in the warning process (Mileti & Sorenson, 1990).

This situation does not mean that the warnings are necessarily better or worse in any way. After all, 'common sense' is not always fully accurate, precise, useful, or usable. It is more about recognising the changes, with any system having advantages and disadvantages. The key to successful warnings is combining the best of everything available to overcome the limitations of each. In this regard, warnings can be examined using three key lenses:

- Design and management processes.
- Engagement with people and institutions.
- Roles of technologies.

6.1 Designing and managing warning systems

Contemporary warning systems might have been given significant recognition in the 1960s, although they were largely viewed as linear (Gillespie & Perry, 1976), assuming a clear relationship between a hazard occurring and the generation of a warning for one-way dissemination. Warning systems were regarded as linear processes based on a cause-and-effect relationship, driven by scientific knowledge. Barton's (1969) work on disaster classification generated a paradigm shift from the descriptive to the analytical, by developing four classifying variables in his typology of disasters: scope of impact, speed of onset, duration of impact, and social preparedness and this shifted perceptions of a warning to a warning 'system'. Rather than showing an EWS as a linear progression through the different stages of disasters in chronological order (which do not really exist anyway), EWS models comprised subsystems (in this case evaluation-dissemination and response) that have inputs, outputs and feedback between them (see figure 1).

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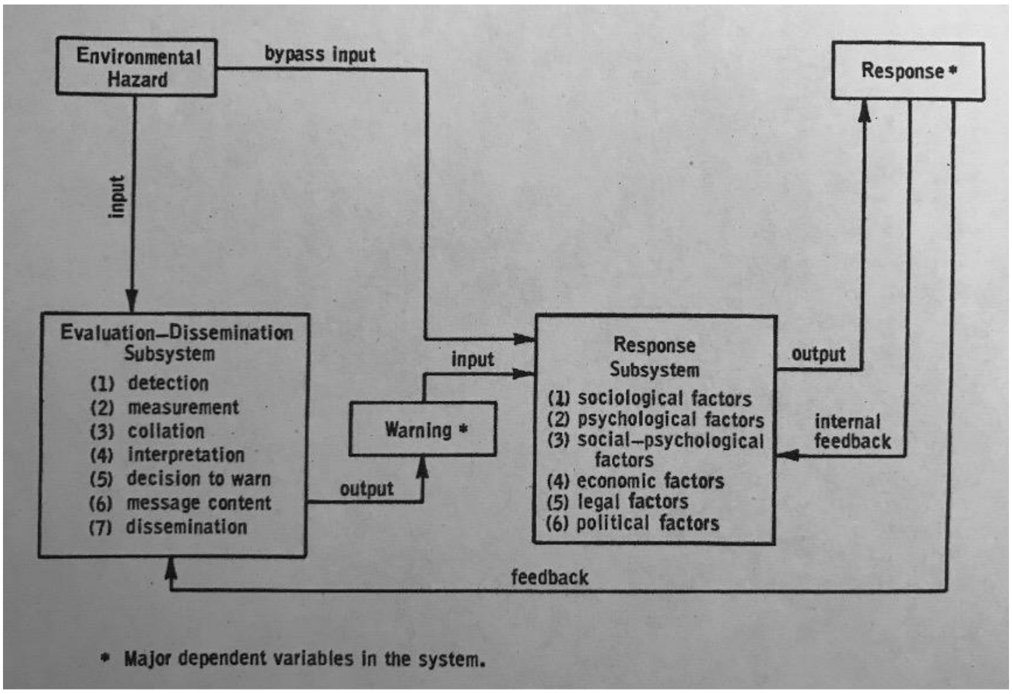

Figure 1: Systems model of a warning system (White & Haas, 1975, p.185)

The term 'systems' has many definitions, although the one adopted here is of a group of interacting, interrelated, or interdependent elements forming a complex whole, which is nearly always defined with respect to a specific purpose (Kim 1994).

Adopting a systemic approach enabled the development of models for the prediction of individual, group and organisational behaviours, going beyond the simplistic cause and effect relationships within an early warning. Foster (1980) identified that decision-making and communication processes between different actors in EWS were non-linear and could be understood better within the context of systems theory as a dynamic system. Foster (1980) states that 'every warning system should be designed to facilitate a two-way flow of information' (Foster 1980, p.203; see figure 2).

The warning models adopted struggled to view EWS as a system because they fail to 'identify emergent properties arising from interacting elements and because it does not consider that the behaviour of systems is due as much to their external environment as to their internal mechanisms' (White, 1995, p.41). White argued that disaster studies tools that provide a holistic approach, by considering how human behaviour and context can affect the management of risk, should be used. Therefore, by the 1990s a complex systemic approach was adopted that 'focuses on interaction among the elements of a system and on the effects of its interactions; it examines a variety of factors at one time; it integrates time, feedback, and uncertainty' (Mileti, 1999, p.107).

Early warning systems have therefore ended up with a range of classifications:

- **Traditional knowledge warning systems:** These systems incorporate traditional knowledge and observations, often through storytelling, songs, and regular conversations about the local environment.

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- **Oral or visual warning systems:** Early warning systems have been around since ancient times, with people using simple methods such as ringing bells, blowing horns, or lighting signal fires to warn others of impending danger. Visuals such as light or smoke. In some cases, people relied on environmental signs, such as changes in animal behaviour or weather patterns, to presume impending weather hazards. These early systems were often crude and not very effective, but they laid the foundation for more advanced warning systems in the future.
- **Community-based warning systems (CBEWS):** These systems empower people by involving them in the data collection and analysis processes, with communities leading and operating them (see more at: https://www.ifrc.org/document/community-early-warning-systems-guiding-principles)
- **Community-driven warning systems (CDEWS):** These systems empower people as they are developed, operated, and managed by a community, including monitoring the indicators.
- **Integrated warning systems:** These systems bring together data, analysis, warnings, and response in one system as seen in the Global Information and Early Warning System on Food and Agriculture (GIEWS) (see https://www.fao.org/giews/en/)
- **Multi-hazard early warning systems (MHEWS):** These systems facilitate co-ordination and consistency of warnings for multiple hazards occurring simultaneously or in succession, as differing actions may be required (see WMO, 2018).
- **Information Technology and Indigenous Knowledge with Intelligence (ITIKI)**: this warning system integrates indigenous and scientific drought forecasting approaches via a novel integration framework that ensures indigenous knowledge is relevant, acceptable and resilient, and employs three ICTs (mobile phones, wireless sensor networks and artificial intelligence) to enhance the system's effectiveness, affordability, sustainability and intelligence.

One of the key issues is that warnings from different hazards and threats often operate in isolation and lack the capacity to identify and manage concurrent and cascading crises, whereby an initial event's impact can generate a sequence of subsequent failures and disruptions, often worse than the initial event. MHEWS attempt to align the challenges of issuing multiple hazard warnings and preparing for the negative/contradicting, or positive/reinforcing actions that can emerge. Several hazards and/or impacts of similar or different types can occur alone, simultaneously, cascading or cumulatively over time, and the interrelated effects need to be accounted for. Yet, for MHEWS to be able to warn of one or more hazards, co-ordinated and compatible mechanisms and capacities are needed across agencies and government at national, regional, and local levels with vulnerable groups (Golnaraghi, 2012). This requires an integrated and comprehensive framework that clarifies the roles, responsibilities, and relationships of all stakeholders within the system.

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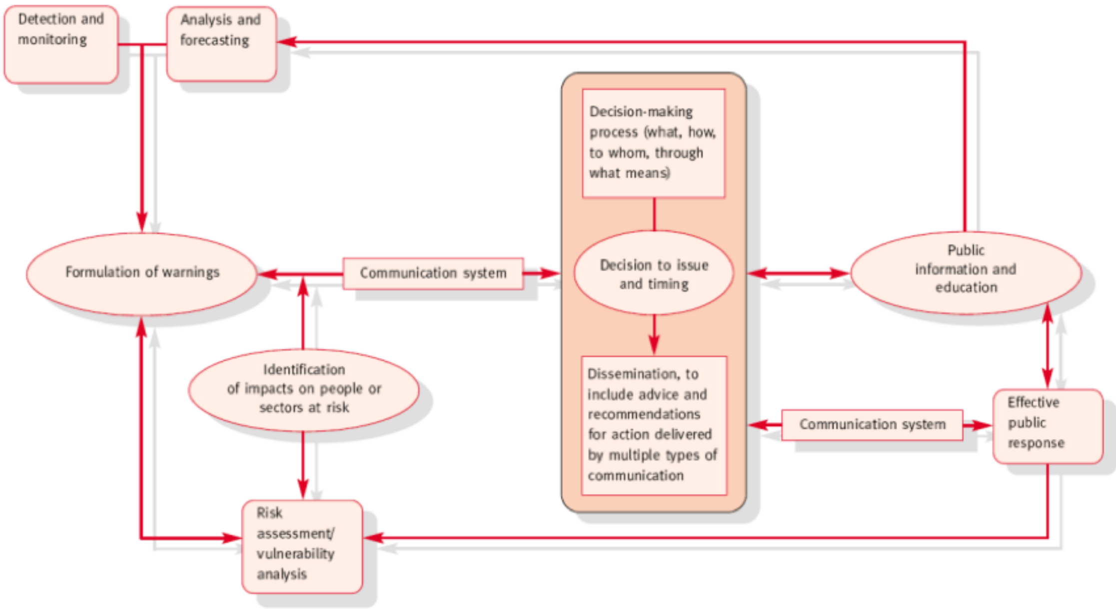

Figure 2: Systems model of a warning system Figure 2: Systems: Generic model of forecasting / warning systems developed by Schlosser, C (Twigg, 2004, p.301).

It is the reciprocal interactions or feedback amongst variables or subsystems, as well as time delays in seeing the results, that create complexity, making the system difficult to understand (Senge 1990). Therefore, it is important that analyses of complex systems are not left solely to scientists, since these systems are transdisciplinary, involving human agents, science and society (Nowotny, 2005). Theoretically, the framing of EWS has evolved through systems thinking throughout the last fifty years with growing recognition of the social systems involved in an EWS, and the role complexity plays (Sandström and Juhola 2017). At the core of The HuT, human behaviour is recognised as integrating social systems within the complexity of warnings, as ultimately warnings are by, from and for people.

6.2 Engagement within warning systems to create action

Engaging with stakeholders is vital to generate actions from warnings. All too often, warnings are issued, but not actioned, resulting from poor integration with society, inadequate engagement by the public and stakeholders, and a lack of clearly defined roles and responsibilities (Garcia & Fearnley, 2012). After several unsuccessful warnings resulting in unnecessary deaths (such as Nevado del Ruiz eruption in Colombia, 1985 that killed over 23,000 people (Barberi et al., 1990; Voight, 1990), the focus was shifted from the scientists issuing the warnings, to making sure the vulnerable people were made aware. This became known as the ‘last mile’, in other words, making sure warnings actually get to the people who are vulnerable so they can take action, as often warnings get ‘lost’ in the pipeline from the scientists or government agencies to the ‘public’ (Stanciugelu, Bilanici, and Stal 2017). However, following a broader movement within science communication shifting from the public being passive receivers of

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information to active stakeholders of the process (Bodmer, 1985; House of Lords 2000; Bauer 2009), it was thought that the public needed to be more engaged in the process of science, and that the key people affected by scientific knowledge should have a say in how they receive information, and what information they should receive. This became known as upstream engagement (Wilsdon, Wynne, & Stilgoe, 2005; Wilsdon & Willis, 2004). A range of tools and approaches have been used around the world to enhance public engagement and leadership for warnings that enables the public, i.e., those vulnerable to be part of the system and warnings, from the start of the process; this is commonly referred to as the 'first mile' (Gaillard and Kelman, 2018).

Engagement with the public has evolved over time and can take various forms, using a range of tools and approaches to enhance public engagement and leadership for warnings. Typically, tools occur via two key approaches, from the top down (i.e., government led), and from the bottom up (i.e., community led) (table 1).

Table 1: List of public engagement tools commonly adopted in sciences globally, where there is uncertainty, risk, ambiguity, and ignorance involved (Rowe & Frewer, 2000 p.8-9).

Government led	Community led
Public opinion surveys: These provide a large sample response to gather information and viewpoints.	Citizen science: Collect, process, and analyse data for people-powered and people- led research.
Focus groups: Small groups representing the public to provide free and open discussion about an issue.	Public activism: Campaigns and lobbying, and Community Based and Driven Early Warning Systems.
Citizen juries / panels: Public panels with independent questions to review.	Grassroots campaigns: People leading themselves to influence wider policy and practice, this includes Community Based Early Warning Systems championed by NGOs and other civil agencies.
Responsible Research and Innovation: Works to listen to and account for public perspectives, also scrutinising the values and actions of science.	

There has been an evolution in the way that the public have been involved in warnings systems, from warnings being rooted in a community and society based on traditional knowledge, through to community-based warning systems. However, increasingly technology has removed people from warning systems, regressing to focusing on the vulnerable as the 'last mile'. Additionally, the lines are increasingly being blurred as the public can be a source of data collection, analysis, and solutions (Bultitude, 2014) providing value information in the warning process. There are new hybrid systems being put in place that attempt to integrate indigenous knowledge with technology (ITIKI) and also Community Driven EWS. Core to all these concepts is that warnings are 'people-centred' (UNDRR, 2023).

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6.3 Technology: a revolution in data and communication

As communication technology developed, so did warning systems. Telecommunication systems were developed to provide quick and efficient communication of warnings, including the telegraph, landline telephones, radio, television, and mobile telephones. Reliance on technology also created problems when the technology failed or disseminated incorrect information, from official or unofficial sources. Radio and television broadcasts, in particular, were used as important means of disseminating warnings to large populations. Even as technology has developed, many people remain reliant on them, with NOAA Weather Radio in the US remaining an example (https://www.weather.gov/nwr/).

With the advent of computer technology, automated warning systems became possible via mediums such as pop-up messages, email, mobile phones, and social media (Calhoun, 2021). These systems often collect and analyse data in real-time, sending out warnings automatically. For weather, examples are bots on social media and apps with push notifications also indicating shelter locations. Automated mobile phone warnings continue to evolve, whether using text messages, audio files, or video files, sent by different networks from standard SMS to internet-based applications such as WhatsApp. Reverse emergency calling (e.g., reverse 911 for Canada and the US or reverse 112 for much of Europe) also involves defining the polygon (spatial area) in which the warnings should be received.

In recent years, the use of Wireless Emergency Alerts (WEA) and Cell Broadcasting (CB) has become increasingly common (UCL WRC, 2022; UCL WRC 2023). These alerts are sent to mobile phones in a specific geographic area, although each technological system is shaped by the cultures and policies of the locations in which they are operating (Bean et al. 2021). Social media platforms such as Twitter and Facebook have also become important for quickly disseminating information to a large audience during emergencies (Bui, 2019). Privacy concerns are raised about tracking people's locations via their phone and sending them information without consent. Another concern is changing priorities and credibility as the ownership and mandate of a specific social media company change. All these technological advantages, however, can be offset by misinformation, hacking, outages or other failures, lack of credibility or transparency, and contradicting other sources in a specific crisis context.

In summary, principal data and communication for warnings have been:

- **Sirens and alarms:** The development of sirens and alarms in the early 20th century greatly improved the effectiveness of warning systems. These devices could be heard over long distances and were used to warn (Bennett, 2021). Many sirens were integrated following post-war periods where sirens were re-purposed from war sirens to hazard sirens.
- **Radio and television broadcasts:** The advent of radio and television broadcasting allowed for more widespread and timely dissemination of warnings. Emergency alerts could be broadcast to a large audience, providing people with important information about impending danger.

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- **Computerised warning systems:** With the development of computers, warning systems became even more sophisticated. Computerized warning systems could track weather patterns, seismic activity, and other data to provide more accurate and timely warnings.
- **Automated warning systems:** Once established these technologically based systems operate without human input to provide warnings based upon pre-assigned criteria and may trigger automated responses (e.g., bridge closures).
- **Social media**: Social media platforms such as Twitter and Facebook have also become an important tool for warning systems. Emergency officials can use social media to quickly disseminate information to a large audience, helping to keep people safe during emergencies.
- **Wireless Emergency Alerts (WEA):** In recent years, the use of Wireless Emergency Alerts (WEA) has become increasingly common. These alerts are sent to cell phones in a specific geographic area, warning people of imminent danger such as severe weather or terrorist attacks.
- **Cell broadcast:** As with WEA this is a technology similar to SMS text messages that simultaneously delivers messages to all phones using a cell tower instead of individual recipients.

Weather and climate warnings have drawn on more data and more sources, with the capability to provide increased differentiation among recipients and the information provided. Whether or not useability, usefulness, engagement with intended audiences, and people's responses have all improved remains an area of much research. Göber et al. (2023) advocate for expanding the use of integrated weather and society approaches to help fill in gaps within weather warnings. This is a key challenge for The HuT, remaining integral to WP2 especially engagement with and support for the demonstration sites within the context of their specific hazards and especially vulnerabilities.

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7. Weather and Climate Warnings

Official weather warnings have existed for centuries, if not millennia. They have evolved considerably, although many core issues remain the same, partly due to the focus on the science, rather than the humans in warning systems. The latest frameworks and models of warnings are demonstrating that those systems that integrate and engage the public are more successful.

7.1 Learning from the past

One of the earliest mentions of an early warning system in literature may be attributed to weather forecasting, specifically the "Observatory" founded by Robert Fitzroy in 1861, which later became the UK Met Office (UK Met Office, 2023). Fitzroy's system was among the earliest recorded examples of a system for predicting weather and included a network of coastal stations that communicated via telegraph to gather observations of weather conditions at sea. Using data collected from thermometers, barometers, and other meteorological instruments, Fitzroy's system issued storm warnings to ships. It could also be considered an early example of the use of citizen science in warning systems, as it involved arranging for mariners, captains, and fishermen to provide information, with tested instruments being loaned for this purpose, and for computation of the collected data (Fitzroy, 1963). In addition, Fitzroy distributed barometers at every port for crews to consult before setting out to sea, famously stating "In winter the rise of the barometer presages frost." The storm signals developed by Fitzroy in 1861 were even used as a model temporarily in Hong Kong to alert of storms, typhoons, and hurricanes, further highlighting the impact and influence of Fitzroy's early warning system. The dissemination of storm warning information to the public was also a crucial aspect of Fitzroy's system, with the use of telegraphs and newspapers as channels for spreading the alerts. Fitzroy's early warning system underscored the value and significance of effective communication and public engagement, not only as end-users of the system, but stakeholders involved in the design, implementation and evaluation, allowing for continuous improvement, as well as tailoring the information to its specific recipient (Burton, 1986). These are key principles still relevant in modern warning systems.

By 1883 bespoke warnings had emerged, including for rapid-onset and highly destructive hazards. Holden (1883) discusses the development of a warning system for tornadoes to local communities in the United States, based on the use of weather observation stations and telegraph communication. Holden's system proposed the establishment of a network of weather observation stations across the country, which would report their observations to a central office where meteorologists would analyse the data and issue tornado warnings to local communities via telegraph. The warnings would include information about the location, intensity, and direction of the tornado, as well as advice on how to take shelter. Holden's system was based on the recognition that tornadoes were a common and often deadly natural hazard in the United States, and that there was a need for better ways to provide warnings to communities in their path. The paper reflects the growing interest in meteorology and weather forecasting in the late 19th

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century, as well as the increasing awareness of the importance of public safety and disaster preparedness (Coleman and Pence, 2009).

Gaster (1896) addressed topics relating to the use of instruments at the individual as well as collective level for the creation of synoptic weather charts, alongside a brief history of weather observing and forecasting in the UK. The lecturer also mentions the difficulties around creating storm warnings using these surface charts, and how a trial of receiving weather information from the United States a few years prior was abandoned because many of the systems moving off the U.S. did not end up directly impacting the U.K. and was essentially "useless as a direct warning... [and] because the knowledge that a storm was prevailing over the Western Atlantic often caused those on the side to issue warnings prematurely. To cry "Wolf! wolf! too often, is sufficient to ruin the reputation of any system of warning" (Gaster, 1896, pp. 226). Gaster (1896) notes the value of credibility and accuracy needed in warnings, but also accepts alternative proposals by others of how better forecasts could be created and their potential limits. He was keen to support the process of disseminating information to the public, including simple communication issues like telegraphic errors that can lead to unnecessary or missed warnings. This was warning public engagement at an early stage of the scientific revolution–and some ideas have been borne out in more recent work demonstrating how the "Cry Wolf" syndrome occurs yet could be avoided through people's involvement and engagement (Atwood et al., 1998; Barnes et al., 2007).

Warnings evolved rapidly with the integration of technology, alongside global development resulting in large populations at risk of hazard events. Table 2 provides a summary of case studies from 1970 to today, demonstrating successes and failures related to people-centred approaches and EWS stakeholder partnerships. It is clear failures frequently occur where there are gaps between making warnings end-to-end (i.e., the system covers the entire range, from hazard detection to action, which includes providing understandable and actionable warning messages), and successes are seen when an integrated approach that bring the four elements of warnings together is implemented (Garcia and Fearnley, 2012).

Table 2: Case study evidence showing examples of success and failure related to people-centred approaches and EWS stakeholder partnerships (adapted from Budimir and Fearnley, 2022).

Linking Issue	**Example**	**Lesson**	**Key References**
Increase participation / engagement	Bangladesh Cyclone Preparedness Programme (CPP), 1970s, (success)	1) Following over a million deaths from cyclones in the 1970s, massive reduction in death toll was effected by engraining cyclone warning and response within the local culture and linking it to day-to-day life via the Cyclone Preparedness Programme (CPP); 2) education and basic trainings resulted in people receiving local warnings, knowing where to evacuate to, and are confident that much of their livelihoods and services will remain viable while rebuilding; 3) the warning process has improved daily life and livelihoods	Khan, 2008 Haque et al. 2022 Kelman et al., 2018

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Risk education and availability of scientific knowledge	Nevado del Ruiz, Colombia, 1985 (failure)	1) Human error in misjudgement, indecision, and bureaucratic short-sightedness around the scientific evidence provided of the lahar risk from the increasingly active volcano, resulted in over 23,000 deaths in Armero, most of which could have been saved if warnings had been issued; 2) doing better science often does not translate into a reduction of loss of life and social and economic losses; 3) information was not publicly available due to concerns of panic.	Barberi et al., 1990 Voight, 1990
Define accountability and responsibility	Fiji Woman's Weather Radio 2004 (success)	1) The programme supported women to become leaders in improving the warning situation for everyone.; 2) Fijian women know how to manage crops when drought hits, and teach each other skills to survive and provide food for the families; 3) the value of supporting the people who can best help their community, and work within technological constraints is enormous; 4) focusing on the first mile has resulted in long-term improvements, the development of a highly effective network, and gender inclusion benefiting everyone.	UNDRR, 2022 Rahmani-Shirazi, 2018
Good governance effective decision-making	Hurricane Katrina, USA 2005 (failure)	1) Long-term warnings were ignored, and government officials failed to maintain levees and floodwalls; 2) government officials took insufficient actions or made poor decisions immediately before and after landfall; 3) the systems on which officials relied to support their response efforts failed, and 4) government officials at all levels failed to provide effective leadership.	American Society of Civil Engineers Hurricane Katrina External Review, 2007 Katrina, 2006
Define accountability and responsibility	L'Aquila, Italy, 2009 (failure)	1) The L'Aquila commission members made contradictory and historically inaccurate statements regarding the possibility of earthquake precursors; 2) they provided the townsfolk the false impression that there was nothing to fear by describing the swarm as "normal" and by incorrectly stating that the swarm discharged energy; 3) poor risk communication was the result of not having clearly defined roles, and protocols.	Alexander 2010 Imperiale and Vanclay, 2019 Imperiale and Vanclay, 2020
Considering multi-hazard scenarios	Tohoku, Japan 2011 (failure)	1) Underestimating the scale of the earthquake, and subsequent tsunami, landslides, and liquefaction resulted in insufficient warnings resulting in larger death tolls; 2) sensible land planning and ignorance of ancestral knowledge led the Fukushima Daiichi Nuclear Power Plant being built in a high-risk area resulting in a global nuclear crisis.	Day and Fearnley, 2015 Ozaki 2012 Suppasri et al., 2021
Integrating science	The establishment of	1) Collaborative, interdisciplinary research project bringing in expertise across subject	Ogra, Donovan, and Adamson, 2019

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research into practice	GSI's National Landslide Forecasting Centre through the research-into action LANDSLIP project, 2021 (success)	areas, including physical science disciples, social scientists, practitioners, and implementers; 2) equality of partnerships and sustainable stakeholder engagement – Geological Survey of India as project partners for longer term legacy of learning; 3) flexibility in project workplans to adapt to contextual needs; 4) time and resources spent establishing common goal; 5) championing from within context for an operational forecast centre; 6) leadership within LANDSLIP project to channel efforts towards a common, useful and applied goal.	Phengsuwan 2020
Effective and continuous communication networks	Nepal floods, 2022 (success)	1) Multiple dissemination channels for sending out warning information, including: real-time data published on a government online portal, daily bulletins to institutional decision makers, dissemination of warning messages to the local community via radio, SMS messages and social media, and formal (media, local authorities, military etc) and informal (volunteers, neighbourhood etc) community dissemination; 2) training and awareness raising at local level; 3) improved feedback loops between local NGOs and national HydroMet services; 4) recognition there is still room for improvement to reach the most marginalised.	Budimir et al., 2020 Pandey and Basnet 2022
Bringing these together:	Argentina's social science team within the Met Service (success)	1) Dedicated social science team within the Met Service tasked with understanding local, user needs and developing an iterative approach to improving forecast information quality – with a specific focus on dissemination and communication to support early action; 2) social science team were integrated within the forecasting team and provided an expert bridge to local community and stakeholder needs; 3) iterative and reflective development and improvement; 4) ongoing efforts to continue joining up local to national stakeholders through expert intermediary group.	See: https://www.smn.gob.ar/

The linking issue in table 2 relates to a point of failure or success in a warning system that is not considered in the UN model warnings that comprise four elements, as seen in figure 3. These cross-linking issues demonstrate warnings typically fail or succeed due to the processes that link the four components of the EWS, rather than the four individual components themselves.

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Figure 3: Graphical presentation of an effective Multi-Hazard Early Warning System (MHEWS) as proposed by the Early Warning for All Initiative (WMO, 2022, p.7).

Today many international early warning systems operate via a common alerting protocol (CAP) (see: http://docs.oasis-open.org/emergency/cap/v1.2/CAP-v1.2-os.html) and include earth observation systems that use sensors and satellites to track changes in the environment, down to more national and local scales. Such systems seek to integrate huge data sets (for example the Famine Early Warning System https://fews.net), or are required to activate emergency management systems (i.e., raising barriers against floods or cutting off power and gas). Whilst such technology can provide opportunities for remotely monitoring meteorological hazards, it is argued that community-based early warning mechanisms, that have been hard-wired into the country's risk reduction governance structures, provide a more cost-effective and efficient early warning mechanism for impending hazards, impacts and loss. These systems can also capture more than biophysical data, which can sometimes simplify the complexity of the situation (Sandström et al. 2020).

For example, the Africa Multi-Hazard Early Warning and Early Action System for Disaster Risk Reduction validated in October 2021 is a community-based early warning system that empowers local communities in the warning process, in some cases embodying traditional tribal knowledge rather than modern science (African Union Commission, 2022). The Red Cross has implemented a community-based surveillance program in Indonesia, Kenya, Sierra Leone, and Uganda to detect and report public health events by community members, selected based on diversity criteria. Volunteers are trained to submit reports using SMS applications and other electronic forms, which are cross-checked by supervisors and entered into a real-time database triggering appropriate response activities. The program has demonstrated high levels of accuracy and timeliness in ensuring early detection and response to outbreaks, though adapting to local contexts is important for optimal effectiveness.

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Overall, warning systems have evolved to become faster, more accurate, and more efficient at providing information to people during emergencies. The development of technology has played a significant role in this evolution, allowing for automated systems that are able to analyse data and provide warnings in real-time (telecommunication, radio and tv, social media, mobile phone alerts, automated warning systems). Yet, despite these advances there are still issues resulting in failures, such as people not acting (Nikkanen et al. 2021).

In July 2021, over 240 people were killed in western Europe in flash floods. The floods seemed to have hit without warning, even though the European Flood Awareness System (EFAS) had given days of warning that intense floods were expected with many updates as the seriousness of the situation became increasingly apparent. This is another example of the science, monitoring, technology, and information being successful, yet still the warnings failed to avert a disaster, for a slew of complex social reasons that are still being analysed–including the apparent lack of awareness in many places that they had long histories of flooding (Fekete and Sandholz, 2021; Thieken et al., 2023).

To address such circumstances, traditional weather forecasts and warnings that give an indication of what the weather will likely have been shifting toward impact-based forecasting (IbF) that considers the vulnerability of people and property to the weather and warns of the associated impacts, as well as the likelihood of them occurring (Merz et al., 2020). This involves integrating data about potential hazards with information about vulnerabilities of populations, assets, and infrastructure. Guidelines for implementing IbF across a range of applications for specific sectors, users, or areas have been developed (Red Cross Red Crescent Climate Centre, 2020; WMO, 2021) reflecting the different types, purposes, and uses. This trend will accelerate as lessons are learned and user feedback from around the world is received. Impact based forecasting intends to relay a message to those at risk to take the appropriate actions as it contains:

- Information about level of confidence in the forecast for better decision-making.
- Post-event analysis of multi- hazard impacts to assist in planning, response and mitigation of impacts.
- Coordinated process to address disaster response and preparedness.
- Common situational awareness.

Impact-based forecasts use a risk matrix to determine the warning level. National Meteorological Services, disaster managers and local communities work together using impact data from previous extreme weather events to determine and agree the warning levels on a case-by-case basis (see figure 4).

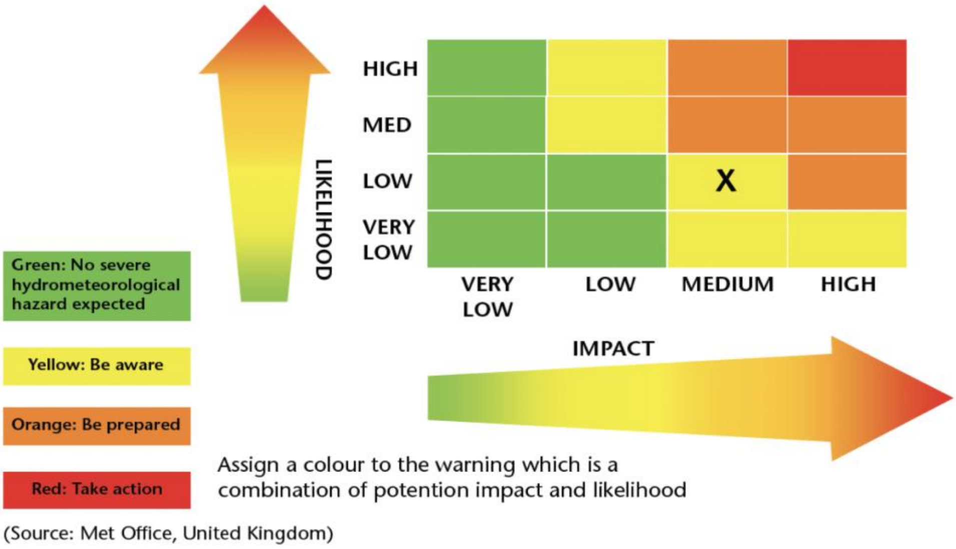

Figure 4: An example of a risk matrix for warnings (UK Met. Office).

As part of the WMO funded *Hi-Weather project* (see: http://www.hiweather.net) over the last decade a warning value chain was developed as an approach to understand the different relationships, processes, inputs, contributions, outcomes, and operational contexts of each stakeholder in the warning chain. The warning value chain can be represented as a sequence or network of different disciplines reprocessing information from previous segments and adding additional, unique information, as in figure 5: 'In a perfect warning chain, the warning received by the end user would contain precise and accurate information that perfectly met their need, contributed by each of the many players in the chain' (Golding et al., 2022 p. 3). One of the main criticism remains that this should be represented as a cycle rather than a chain to reflect the end-to-end nature of warnings, this model does in fact try to capture the need to communicate across stakeholders, work across disciplines, and adopt a 'first-mile' approach.

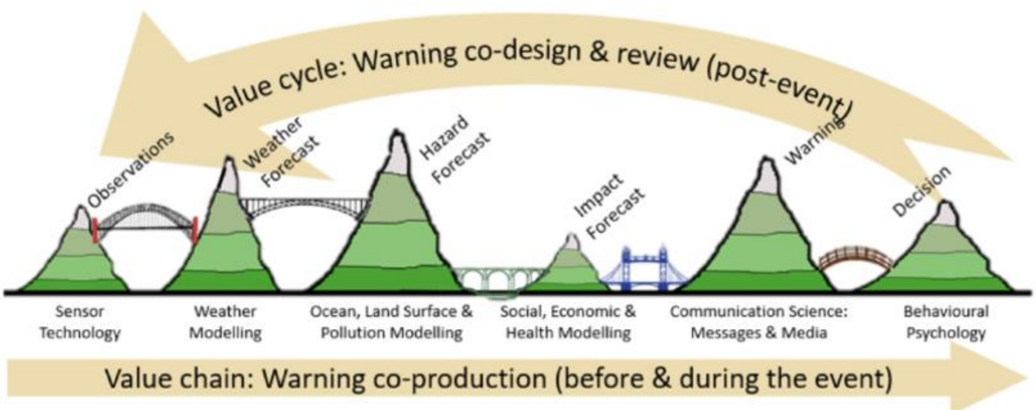

Figure 5: Schematic value chain for high impact weather warning showing the capabilities and outputs (green "mountains") and information exchanges (bridges) linking the capabilities and their associated communities (Golding et al., 2022, p.17).

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Whilst historical warning systems may appear less sophisticated, many of the issues identified in the 1800s remain issues with the warnings of today. Technology arguably has added in further layers of complexity that detach the end user from the warning. Yet, the meteorological sector is working hard to bridge this gap by generating warnings based on impact, and understanding the whole value chain is needed to make warnings work. This reinforces the concept that it is the linking processes that typically cause failures in warnings (table 2).

7.2 Various Knowledges

7.2.1 Traditional knowledges

Indigenous communities have a wealth of traditional knowledges and observation systems that allow them to detect and act on natural hazards such as earthquakes, volcanic eruptions, floods, droughts, and wildfires. This knowledge is derived from a deep understanding of the behaviour of plants, animals, and ecosystems and can be used to predict and manage natural hazards. Traditional indicators such as animal and plant behaviour, weather patterns, and changes in the environment are relied upon by indigenous communities to predict impending hazards and take appropriate actions to protect themselves and their communities.

An analysis of indigenous knowledge and warnings in the Lower Shire Valley in Malawi, highlights the value of such knowledge in detecting and responding to natural hazards (tables 3 and 4). Local communities in the area have developed a range of indicators based on their extensive experience of being impacted by natural hazards and a long history of living in the area. These indicators are used to inform traditional forms of warning and response systems to both forecast impending hazards and develop actions to minimise their impacts.

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Table 3: Overview of the indigenous drought and dry spell forecasting indicators in the case study communities. In italic the vernacular names are given. (Trogrlić, Homberg, and Cross, 2018, p.37)

Indigenous drought and dry spell forecasting categories	Example indicators	Indicated period of occurrence
Ecological	**Plants behaviour**	
	Mfuma and *ntoyo* trees shed all their leaves. Bush grass withers.	
	Increased mangoes, sunbird tree (*mtondo*) fruits and Baobao production.	
	Cassava gives lower yields than usually. Nyika plant.	
Ecological	**Animal behaviour**	
	Birds make a camp there where there is a plot of maize.	September
	Kanyimbi comes out of the bush to villages.	
	Worms (*Anyimbiriko)* seen in *Nyamtombozi* tree.	
	Foxes are moving into the village.	
	The hole of the Spider (*Buwe*) is covered with a web (but opening not sealed according to other)	
	A lot of big tortoise near the river.	
	Antelope come out of the bush and move to villages to drink water.	Starting in July
	Pangolin (*Nkhaka/Khaka*) falls down (meaning this very oily animal that normally lives in a cave comes out during the day. *Kamba* or porcupine *chisoni* falls?.	
	Nkhaka (pangolin	
	Wolves produce funny sounds	
	Bird makes its nest door facing heaven. Unknown (*Mpherenga*) bird comes out.	
	More elegant grasshoppers (*Nabobo)* or bigger grasshoppers (*katchokotcha*), which produces crying sound like "khetchekhetche" audible up to 100 m.	
Meteorological	Fog	September
	Wind blows frequently from all directions (or south to north, especially morning and evening), taking away clouds that give rain and brings some coldness.	
	Low temperatures persist in period when higher temperatures are expected.	August/ September
	Very scattered rains instead of heavy downpours than dry spell.	
Riverine	Rapid drying up of dams and the river	
Celestial	Sun with circles, easy to look at. Sun gets dim.	
	Moon with circles (but also no ring surrounding the moon), moon with very small halo.	
	A group of stars make a long line (*Nkhwasa*); stars shine more brightly at night	
	Sun at sunset appears to have coincided with the moon	
	Red horizons at sunrise and sunset	

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Table 4: Indigenous early warning signs for Flooding: Meteorological indigenous warning signs for flooding (Trogrlić, Homberg, and Cross, 2018, p.68).

INDICATOR	CHICHEWA NAME	DESCRIPTION	PERIOD OBSERVED
Very hot temperatures	Kutentha kwamibri/ Ng'amba	Very hot temperatures, beddings are not needed when sleeping. People will sleep outside, and they sweat a lot during the day and at night. When it is hot, more rains come.	October to January
Heavy blowing of wind	Mphepo/ Bangula/ Mwera	Wind blowing heavily causing damages to houses (blowing off the loafs of the houses). Winds bring dust.	September to January
Northern wind	Mbalu/ Mpoto	Wind blowing from north to the south	December
Whirlwinds	Kavuluvula	The whirlwinds will occur increasingly	August to December
Fog occurrence	Nkhungu	Heavy fog on the mountain, especially the top part	November to December
Dark clouds	Mitambo yakuda	Dark clouds appear in the sky	November to January
Frequent blowing of winds	Kuzizila	Winds will blow frequently bringing some coldness	September to December
Rainfall intensity	Not specified	A lot of rainfall every day, rains come evenly distributed	December to March
Southern winds	Not specified	Not specified	
Changes in rainfall	Not specified	Men go to check and see how the rain is coming. They alert each other and if the rain starts in the morning they do not sleep and stay awake to see the water running.	December to March
White clouds	Not specified	White clouds that look like hills	October to March
Thick clouds	Not specified	When it is about to flood, clouds come out in large numbers and are thick	December to March
Stable clouds	Not specified	If the clouds are stable and settled in one place	Not specified

Similar practices and traditional warning systems exist all over the world. For example, indigenous communities in fire-prone regions, such as the Aboriginal people in Australia, have developed traditional practices for detecting and managing wildfires (Smith et al., 2021). They use their traditional ecological knowledge to monitor weather conditions, vegetation patterns, and animal behaviours, which can serve as early warning signs for potential wildfires.

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7.2.2 Art and storytelling

In addition, indigenous artists also have a long history of creating paintings that depict traditional knowledge and stories about the natural environment including the occurrence of natural hazards. Indigenous artists may depict these signals in their artwork as forms of warnings, guiding people in their interactions with nature and helping them navigate the environment safely.

"Indian Legends of the Pacific Northwest" written by Ella E. Clark, published in 1953, is a notable example that underscores the power of stories and illustrations as warnings in indigenous cultures. Clark's book presents a collection of indigenous legends from the Pacific Northwest, including some that could be seen as warnings about natural hazards that previous generations had lived through and passed down their knowledge and experiences. One legend in the book describes the Thunderbird, a large bird with feathers as long as canoe paddles that makes the thunder and great winds when it flaps its wings and creates lightning when it opens and shuts its eyes. In this context, the Thunderbird can be viewed as a symbolic representation of natural forces and the power of weather phenomena, which could be considered as an early form of warning, as it is associated with the observation and interpretation of natural signs. Through storytelling, indigenous communities in the Pacific Northwest shared their observations, experiences, and teachings about the natural world.

Moreover, indigenous artists may also use their art to raise awareness about environmental changes and their impacts on their communities. For example, Jaune Quick-to-See Smit, an enrolled Salish member of the Confederated Salish and Kootenai Nation, is an artist, activist and educator that used visual language to address environmental destruction, critiquing the influence if Native American culture (Kastner, 2013).

The transmission of indigenous stories, art and illustrations related to their environment, natural hazards, animal behaviour etc, over generations is a testament to their effectiveness in being able to create engagement in maintaining and acting upon traditional forms of warning and response systems. In contrast, the crucial aspect of fostering engagement and motivation to take action is often overlooked in more technical, data-driven warnings from official sources. By recognizing and learning from these different traditions and knowledge systems, warning systems can be made more effective at safeguarding local communities.

7.2.3 Integrating community and context specific knowledge with official and/or more technological forms of warning response

The integration of community and context-specific knowledge into official and/or more technological forms of warning response systems is a critical step towards improving the effectiveness of disaster risk reduction and humanitarian interventions in disaster-prone regions.

For example, the drought early warning system called ITIKI (Information Technology and Indigenous Knowledge with Intelligence) integrates indigenous and scientific drought forecasting approaches (Masinde and Bagula, 2012). The incorporation of indigenous

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knowledge ensures that the system is both relevant and acceptable to local communities, while the use of three information and communication technologies (mobile phones, wireless sensor networks, and artificial intelligence) enhances its effectiveness, affordability, sustainability, and intelligence.

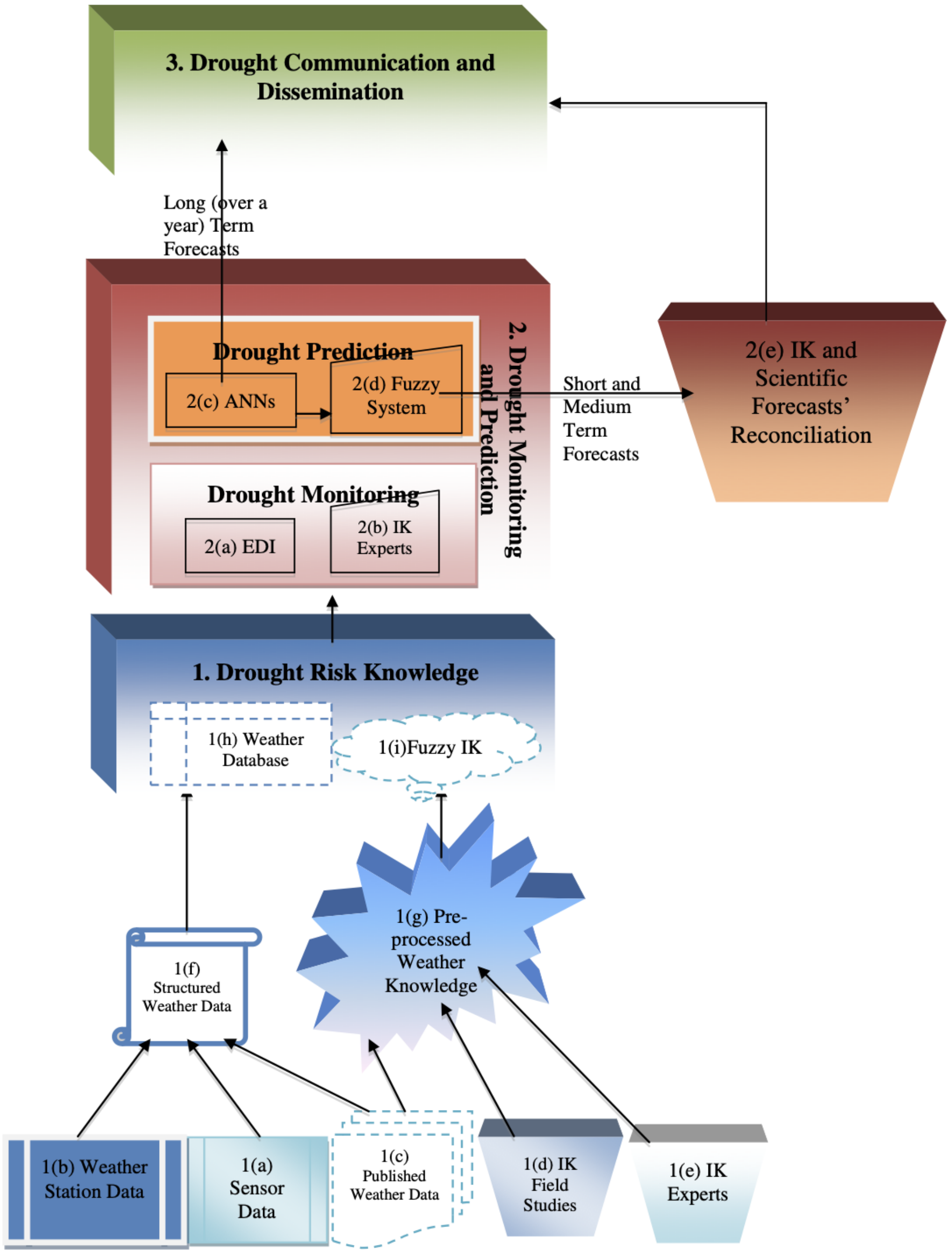

Figure 6: Integrated Drought Early Warning System (Masinde, 2012, p.72)

By incorporating community and context-specific knowledge, warning response systems can be customized to address the specific needs of affected populations, increasing their relevance, acceptability, and resilience. Integrating community and context-specific knowledge can promote community engagement and encourage greater

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uptake of disaster risk reduction measures. This can help create more cost-effective interventions by leveraging the resources and knowledge of local communities. Furthermore, the inclusion of traditional forms of warnings and new technological warnings can enhance the accuracy and effectiveness of disaster risk reduction measures. Finally, by integrating traditional forms of warnings with new technological warnings, warning response systems can take advantage of the accuracy of modern technology while also benefiting from the resilience of indigenous knowledge that can function independently of technological failures.

7.3 Climate change warnings

Human caused climate change has been a pressing scientific concern for decades with efforts towards international policy action since the 1970s. However, despite long-standing warnings about its adverse impacts, effective international action has been elusive. Factors such as disinformation, misinformation, intransigent countries, and corporations have contributed to this challenge. Additionally, inaccurate warnings, such as exaggerated predictions about climate change causing disasters, conflicts, and migration, have also hindered progress. In the mid-1990s, warnings about millions of “environmental refugees” and “climate refugees” gained popularity, with subsequent variations predicting 50 million such refugees by 2010 and 2020.

Reality has not aligned with these dire warnings, undermining the alleged correlations between climate change and migration. Despite the absence of scientific evidence supporting these warnings and numerous scientific analyses providing fewer alarming conclusions, warnings about “climate (change) migrants” persist. Caution is necessary when attributing migration, as well as disasters from hurricanes or conflicts like the wars in Syria and Darfur, to human-caused climate change. While heat-humidity is projected to be a significant exception, and other catastrophic scenarios exist, scientific accuracy should be maintained in warning about the adverse impacts of human-caused climate change (Glantz, 2009).

In Europe, the European Commission established the European Climate Adaptation Platform (Climate-ADAPT) in 2013, which aims to support the development and implementation of early warning systems for climate change. The platform provides a range of tools and resources to support adaptation planning and decision-making.

7.4 Multi-hazard, multi-vulnerability, multi-sectoral warning systems - climate and disease

The integration of climate data and warning systems with health and epidemiological systems has become increasingly important in forecasting and detecting infectious and vector-borne disease outbreaks. This interdisciplinary approach enables a

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comprehensive understanding of the interdependencies and feedback mechanisms between hazards, improves risk mapping, and enhances preparedness and response.

One illustrative example of this is the European Environmental Epidemiology Network (E3 Network see: https://geoportal.ecdc.europa.eu/e3-network/generaldescription), which employed geo-referenced climatic and environmental information, along with other data sources, to develop a disease risk map for malaria emergence and transmission in Greece. The produced map enabled targeted entomological and epidemiological surveillance, vector control activities, and raised awareness among the public and health workers of areas that are environmentally suitable for transmission. Consequently, this approach helped to disrupt malaria transmission in 2013, exemplifying how interdisciplinary collaboration can reduce spill over events and prevent the continuous rise of emerging infectious diseases (EIDs).

Another example is the Malaria Early Warning System (https://iridl.ldeo.columbia.edu/maproom/Health/Regional/Africa/Malaria/System.html) developed by Columbia University, which utilizes seasonal climate forecasts, weather monitoring, and case surveillance to predict malaria epidemics. By leveraging climate data, they helped to provide early warnings of impending epidemics, enabling proactive interventions to prevent or mitigate the spread of the disease.

Finally, the ID Alert project, under Horizon Europe (https://idalertproject.eu), aims to develop indicators that track past, present, and future impacts of climate change on the human-animal-environment interface. This initiative will provide innovative tools and early warning systems that integrate the environment, social, and animal domains, following the Intergovernmental Panel on Climate Change (IPCC) frameworks of climate change impacts and adaptation needs.

Interdisciplinary collaboration between climate, meteorological and environmental sciences is essential to effectively estimate future health risks and develop preventative approaches that account for the complex relationships between social, climate, and environmental drivers of emerging infectious diseases. For example, EWS need to capture the complexity of famines' causes (Sandström and Juhola 2017).

8. Some legal aspects

The responsibility to provide warnings depends on laws. In the UK, scientists typically assess vulnerabilities and hazards, with government officials making decisions around suitable responses to the data presented or absent. In some instances, such as in the Philippines, Indonesia, and in some processes such as Climate Outlook Forums (e.g. https://www.icpac.net/climate-outlook-forums/), this process is combined, working together to interpret the information and to generate decisions although legal aspects including enforceability and liabilities depend on specific contexts.

The EU provides a number of early warning and information systems are part of the EU's Copernicus programme to support member states:

- **Global Disaster Alert and Coordination System:** provides alerts and estimates impacts of earthquakes, tsunamis, tropical cyclones, floods, volcanos, and droughts worldwide (https://www.gdacs.org).
- **European and Global Flood Awareness Systems (EFAS):** give notifications on floods up to 15 days in advance in Europe and worldwide (https://www.efas.eu/en).
- European and Global Forest Fire Information Systems: forecast dangerous weather conditions up to 10 days ahead and provide near-real-time information on active fires and burnt areas. The systems analyse the severity and risk that each forest fire poses for the local population and the environment. This allows informed decisions on the deployment of the rescEU firefighting capacity (https://effis.jrc.ec.europa.eu).
- European and Global Drought Observatories: give information on droughts risks in Europe and worldwide, including meteorological indicators, soil moisture anomalies, vegetation stress and river low flows (https://edo.jrc.ec.europa.eu/edov2/php/index.php?id=1000).

The Intergovernmental Panel on Climate Change (IPCC) provides metrics to measure greenhouse gas emissions, on which some policymakers rely to develop regulations and set emissions targets. These metrics influence the UNFCCC negotiations for agreements on addressing human-caused climate change, although disparities often arise between the science, the science from the IPCC, and the text of UNFCCC agreements. Legalised metrics for measuring emissions and their impacts could play a much more prominent role in determining both warnings and responses to climate change, although these metrics are always evolving as new scientific insights emerge. Understanding the evolution of metrics and legal implications helps in interpreting and acting upon climate change warnings. It underscores the dynamic nature of climate change science, of warning and response systems for climate change, and of the need for continued refinement to enhance their accuracy and effectiveness.

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9. Conclusion: key interpretations for building warnings for the future

(a) Augment communication and exchange

Effective communication and exchange are fundaments for warnings. Warning messages need to be clear, accessible, and tailored to the needs of different audiences, as seen by impact-based warnings. There is also a greater recognition of the importance of community engagement and participation in the design and implementation of early warning systems.

(b) Integrate with other systems and sectors

Warnings are now being integrated with other systems and sectors, including land-use planning, water management, and health systems. This helps to ensure that warning messages are tailored to the specific needs and concerns of different sectors, and that response efforts are coordinated and effective.

(c) Cultivate engagement in warnings by integrating multiple warnings types

While there have been significant efforts toward improving the accuracy, precision, and timeliness of warnings through advancements in scientific methods and technology, efforts to ensure warnings are engaging and relatable to their intended audience need to continue. Traditional forms of warning, such as stories, oral traditions, and artistic expressions, may not be seen as meeting the precision standards that modern technological warnings strive to achieve. However, not only can they provide contextual knowledge and insights into the local environment, but they can also create engagement and captivate people's attention in a way that current technical warning approaches often lack.

Communities are instrumental in shaping people's perceptions, beliefs, and actions, and warnings presented in a way that resonates with their values, beliefs, and cultural context are more likely to motivate action. Art and illustrations as part local and traditional knowledge can also play a significant role in capturing people's attention and driving action. The incorporation of traditional knowledges and traditional warning systems (e.g. indigenous knowledge, local histories, oral traditions, artistic expressions) ensures that the system is both relevant and acceptable to local communities. Whereas technological warnings and communication technologies (mobiles phones, wireless sensor networks, cell broadcast, etc) can help to increase the precision, intelligence and effectiveness of warning and response systems. Combining technical accuracy with cultural relevance, can help to ensure that warnings are not only effective at detecting and alerting of a threat, but also at creating engagement and action to respond to it.

(d) Implement multi-sectoral, multi-vulnerability, multi-hazard warnings

Further research is needed to explore how to develop and enact multi-sectoral, multi-hazard warning systems that account for the risks, cascading impacts, and feedback loops between sectors and hazards.

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(e) Account for legalities

Legalities of warnings–aspects of promulgated and enforceable rights, obligations, and duties–must always be considered. Both vertical and horizontal governance apply to many aspects of warnings, with legal precedents including both warnings and failures to warn. Some jurisdictions legislate explicitly; others are based on precedent; and others use a combination of both. Anyone operationalising warnings must always examine their legal contexts, to ensure that they are fulfilling their mandates without exceeding them–even if fulfilling their legal mandate means a less useful or usable warning than would be preferred. For The HuT, each demonstration site would need to indicate their legal contexts directly and it could be useful to compare them.

(f) Start with and use scientific baselines

Scientific baselines from warnings that are often neglected are:

- Focusing on the first mile rather than the last mile, in order to start with people who need and use warnings, rather than ending with them.
- Highlighting end-to-end-to-end-to-end… warnings rather than end-to-end warnings to emphasise that warning is a non-linear, looping, feedback-based social process, not a unidirectional algorithm with clear start and finish points.
- Accepting the need for not-always-early warnings, such as late warning systems and medium warning systems, rather than assuming that early warning systems are the only task.

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