Value Chain Approaches to Describe, Improve, Value and Co-Design Early Warning Systems

v0.1

WWRP WORLD WEATHER RESEARCH PROGRAMME

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Forewords

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Executive Summary

An early warning system can be described as an “information value chain” in which a sequence of actors (organizations, communities and individuals) produce and share information that helps people to take actions to protect themselves against loss from hazardous events. More broadly, the value chain concept is a useful framework for characterizing the processes, inputs, contributions, contexts, and relationships of actors who, together, produce and deliver critical information to support decisions that lead to beneficial outcomes. Value chain studies provide useful insights and a “chain of evidence” on how value is generated, thus supporting a variety of managerial decisions.

This document, *Value Chain Approaches to Describe, Improve, Value and Co-Design Early Warning Systems*, provides a framework to analyze and optimize early warning systems, ensuring they are both effective and inclusive. It promotes a holistic view of early warning systems driven by users' needs for information to respond to hazards and take protective action. These systems integrate weather and hazard knowledge, technological capabilities for observing and modelling the hazard and its impacts, forecast and warning production, communication and decision support, delivered through a partnership of experts and the community. The approaches described here can be applied to any service delivered in partnership.

The primary audience for this framework is service providers involved in hazard monitoring, warning, dissemination and communication, such as national meteorological and hydrological services and their delivery partners in emergency management, governments and media. It aims to help organizations maximize the effectiveness of early warning systems by identifying key components, actors, and processes that contribute to their overall value and impact. It offers practical tools and methodologies to describe, evaluate, and improve early warning services, addressing the gaps and barriers that often hinder their effectiveness.

Chapter 1 sets the stage by emphasizing the critical role of early warning systems in mitigating the impacts of natural hazards. It discusses the intrinsic value of early warnings, linking them to broader social, economic, and environmental benefits. The chapter introduces the concept of the information value chain, explaining its relevance in understanding and enhancing early warning systems. It argues that a value chain approach provides a systematic way to dissect and analyze the components and processes involved in early warning systems, offering a structured path toward improvement. This chapter also outlines the basic steps involved in conducting a value chain study.

Chapter 2 on describing an early warning service using a value chain, delves into the methodology for mapping the value chain of an early warning service. This chapter emphasizes the importance of visual tools, such as value chain tables and diagrams, in characterizing the components, actors, and information flows within an early warning system. It provides detailed guidance on the steps for collecting and organizing information necessary to describe a service comprehensively. Examples of structured value chain diagrams illustrate how early warning services can be conceptualized as sequences, cycles, or networks of information generation and propagation, demonstrating the approach's flexibility to emphasize different aspects of warning service organization, operation and improvement.

Chapter 3 provides a framework for evaluating the performance of early warning services and identifying improvements. This chapter focuses on establishing a baseline for the current service and conceptualizing value through the value chain approach. It offers methodologies for identifying gaps and barriers that prevent the full realization of value and guides the development and prioritization

of improvement options. A key concept is the theory of change, which helps in mapping out how specific interventions (changes) within the warning value chain can lead to desired outcomes. The chapter includes practical steps and additional resources, helping practitioners to systematically assess and enhance their services.

Chapter 4 addresses the crucial task of quantifying the benefits of enhancements to early warning systems to support decisions on options for improvement, or to measure the value of enhancements after they have been implemented. This chapter outlines the process from scoping improvements to their valuation, outlining techniques for measuring the economic and social value of service enhancements. The Value of Information Characterization and Evaluation (VOICE) framework is introduced, offering a structured approach to valuation. Weather Service Chain Analysis targets information decay, which can be useful in identifying where improvement could most enhance value. The chapter concludes by discussing sources of uncertainty, the propagation of uncertainty through the value chain, and methods to quantify it.

*C*hapter 5 emphasizes a collaborative approach to co-designing and co-developing new early warning systems. It highlights the importance of engaging stakeholders, particularly user communities, in the design process to ensure that the services meet their needs and expectations. The co-design process is outlined in several phases, including problem definition, ideation, conceptual design, development, implementation, and monitoring. By involving users throughout these stages, the co-design approach ensures that the resulting services are user-centric, effective, and sustainable.

Each chapter provides real-world examples, detailed steps, and additional reading materials to support the application of value chain concepts.

The annexes provide valuable resources for practitioners seeking to apply the value chain framework to their early warning systems. Annex 1 includes several value chain tools and activities, offering detailed descriptions and methodologies for describing, improving, and valuing early warning services. Annex 2 elaborates on economic valuation methods, discussing techniques such as contingent valuation, conjoint analysis, and benefit transfer methods. Annex 3 presents further examples of value chain analysis in different hydrometeorological and hazard contexts, while Annex 4 provides a glossary of terms to aid in understanding the framework.

This document is an output of the project on *Value Chain Approaches to Evaluate the End-to-End Warning Chain*, a joint project of the High Impact Weather (HIWeather) research project and the Societal and Economic Research Applications (SERA) Working Group of the WMO World Weather Research Programme (WWRP).

Value Chain Approaches to Describe, Improve, Value and Co-Design Early Warning Systems

Contents

Box 1. Context for this framework

This framework stems from a collaboration of experts who are working, like so many others, to improve the operation and effectiveness of early warning systems worldwide. It lays out the principles and practices of the value chain approach for systematically creating, analysing, and improving these warning systems. Our goal is to help accelerate progress in early warning systems, in line with Target "G" of the *Sendai Framework for Disaster Risk Reduction 2015-2030,* and the UN-led *Early Warnings for All* initiative announced by the United Nations Secretary-General in March 2022. Early warnings are a key part of improving societal outcomes, preserving lives and strengthening communities, in the face of the risks posed by hazards of all kinds. The Sendai Framework has been committed to by all United Nations members.

The project on "Value Chain Approaches to Evaluate the End-to-End Warning Chain" (hereafter the Value Chain Project) was created under the umbrella of the WMO World Weather Research Programme (WWRP) as a joint project of the High Impact Weather (HIWeather) research project and the Societal and Economic Research Applications (SERA) Working Group. It commenced in 2020 with a planned completion in 2024.

The Value Chain Project has four main objectives:

1. To review value chain practices used to describe and understand weather, warning and climate services;
2. To assess and provide guidance on how they can be best applied in a weather warning context that involves multiple users and partnerships;
3. To generate an easily accessible means for scientists and practitioners involved in researching, designing, and evaluating weather-related warning systems to review relevant previous experience and assess their efficacy using value chain approaches.
4. To analyse the warning chain data to understand, revise and extend best practice in warning processes.

Describing, Improving, Valuing and Co-Designing Early Warning Systems using Value Chain Approaches: A Framework for Practitioners has been produced in support of these objectives.

How to use this framework

Purpose

An early warning system is an example of an information value chain, where information is created, transformed, and communicated by actors in value-adding processes (observation, modelling, hazard prediction, impact prediction, warning generation and dissemination), ultimately providing value by enabling people to make decisions that affect their well-being. More broadly, the value chain concept is a useful framework for characterizing the processes, inputs, contributions, contexts, and relationships of actors who, together, produce and deliver critical information to support decisions, including for hazardous events. Value chain studies can provide useful insights and a “chain of evidence” on how value is generated and can support many types of managerial decisions.

This document provides a framework and tools for using value chain studies and approaches to describe, evaluate, improve and co-design early warning services. It brings together process-oriented “top-down” perspectives and people-centred “bottom-up” perspectives, drawing on expertise from researchers in the natural and social sciences and practitioners in the broader warning community.

Intended audience

Service providers such as national meteorological and hydrological services (NMHSs) and their partners in emergency management, government, non-governmental organizations (NGOs) and community-based organizations (CBOs), and media are the primary audience for this framework. They are responsible for providing effective early warning services that incorporate all relevant information and reach the desired user communities to help them decide whether and how to act in a high impact situation. Service providers have a strong stake in understanding and improving the warning value chain because it directly affects their activities. They want to know what investments in service improvements are likely to be most successful, to help them manage their resources and apply for additional resources.

Authorities such as political leaders, government ministries, other administrative departments, and funding bodies need to ensure that early warning services are operated according to agreed regulations and service commitments and that they represent value for the community. When a warning service is perceived to have failed to protect the community, authorities may call for an audit or inquiry to understand what went wrong. Authorities may dictate or monitor a program of continuous improvement for the service providers. Funding bodies are interested to learn how their investment in resources for new services or service improvements leads to greater benefits for users.

User communities such as the general public, industries and local businesses, critical sectors such as transport and healthcare, and local NGOs and CBOs are often thought of as “end users”. User communities need to receive useful warning information that assists them to take appropriate action at the right time. As well as receiving information, users provide feedback on how the services could be made more effective in meeting their requirements. It is especially important for user communities to be involved in the design of new services. If they are paying customers, as may be the case for industries receiving bespoke services, they want assurance that they are receiving value for money. Community members want confidence that they are being "looked-after" and that the government is serving them well.

Framework content

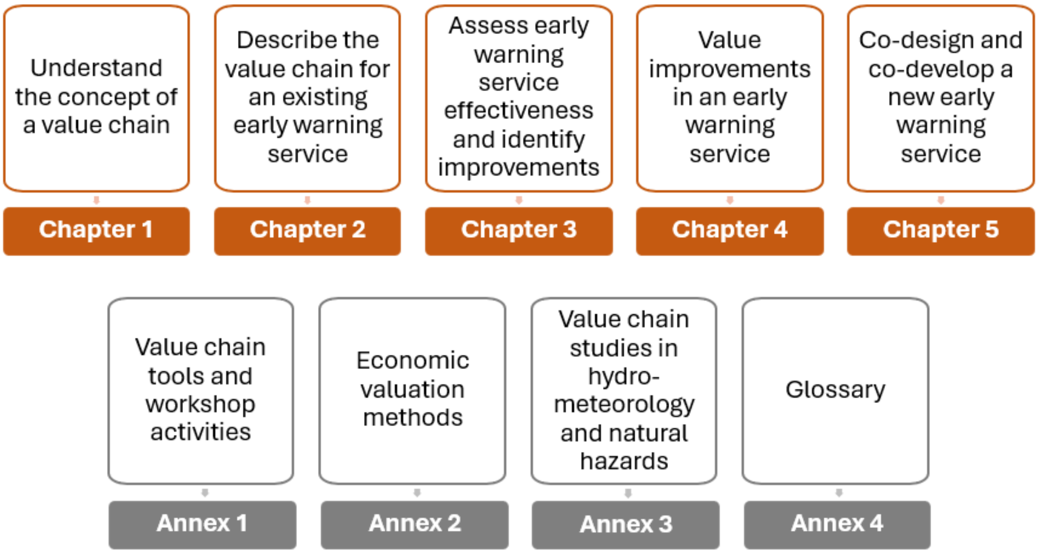
This framework provides practical guidance for how to apply value chain approaches for such purposes as describing an early warning service including its components, actors, and information flows; monitoring and improving the effectiveness of a warning service; valuing improvements to a service; and co-designing a new warning service from scratch. Flowcharts at the end of each chapter summarize the steps for conducting a value chain study for each of these purposes. The framework gives many examples of value chain usage in hydrometeorology and offers several practical tools for applying value chain approaches.

Although the context for this framework is early warnings, the approaches described here can be applied more broadly to any kind of information service delivered in partnership.

The value chain framework was developed within the High Impact Weather project of the WMO World Weather Research Programme (see Box 1 for details). It complements the open source book, *Towards the "Perfect" Weather Warning: Bridging Disciplinary Gaps through Partnership and Communication* (Golding 2022), which examines in detail the communication, translation and interpretation of information between partners involved in the warning value chain.

The focus of the framework is on early warnings for hydrometeorological hazards such as heavy rain, flood, extreme wind, heatwave, and so on, but the concepts can easily be extended for slow-onset hazards such as drought, for other geophysical hazard types, and for complex and compounding hazards that may contain multiple hazard types. The framework does not specifically address linked weather and hazard models (readers interested in that topic are referred to Golding 2022). While the details of the warning value chain will change according to the situation, the framework supports a common approach and language across hazard disciplines. This is essential for ensuring that multiple early warning systems can be integrated and operate with maximum efficiency and transparency. The concepts also apply to services relevant for normal weather conditions.

The structure of this document shown below highlights the main applications of value chain approaches in an early warning service context. The chapters may be read in any order, according to needs and interests. However, readers who are new to the concept of value chains are recommended to start with Chapters 1 and 2 to get a grounding in the basic concepts before proceeding to later chapters.


Understand the concept of a value chain
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1. Introduction to the warning value chain

> "*Risks are being created and accumulating faster than our ability to anticipate, manage and reduce them, and when those risks are realized as shocks or disasters, they bring increasingly dire consequences for people, livelihoods, society and the ecosystems on which we depend."*
>
> Mami Mizutori, Special Representative of the Secretary-General, mid-term review of the Sendai Framework for Disaster Risk Reduction 2015-2030, May 2023.

The importance of early warnings in helping communities to protect themselves from the impacts of hazards is indisputable. Warnings systems around the world vary in terms of coverage, sophistication, hazards warned for, and even their existence. All warnings can be improved to be more effective, but to do that requires understanding how the many elements that go into producing and communicating warnings fit together into an integrated system, namely the warning value chain, that leads to better outcomes for its users.

This chapter lays the foundation for the use of value chain concepts and approaches to characterize an early warning system in detail, identify and value improvements in a warning system, and co-design new early warning systems. It starts by highlighting the crucial importance of early warning systems in reducing the effects of natural hazards. It describes the outcomes of effective warnings and connects them to wider social, economic, and environmental value.

The concept of the information value chain concept is introduced next, including its fundamental parts: nodes, actors, and information flows. Considering an early warning system as a value chain offers a systematic method for breaking down and analyzing its key components and processes, providing a clear roadmap for enhancing its effectiveness. Organizations can use value chain analyses for a wide range of purposes, including organizational understanding, monitoring performance, post-event analysis, investment decisions, comprehensive service renewal, new service co-design, and comparative studies. The fundamental steps for carrying out a value chain study are described at the end of the chapter.

1.1. The value of early warnings

A key mandate of national meteorological and hydrological services is to provide early warning services that enable people to protect themselves and their property and go about their business safely.

The *Early Warnings for All* (EW4All) initiative of the United Nations and WMO is a global driver of development of early warning services. It asserts that warnings are a cost-effective tool that saves lives, reduces economic losses and provides a nearly ten-fold return on investment (WMO 2022a). The outcomes of effective warnings include fewer fatalities, injuries and illnesses; preservation of property; reduced disruption and economic impact; enhanced resilience, preparedness, and emergency response; and improved public trust and confidence (Table 1.1). As will be discussed in later chapters, effective warnings depend on having a fully functional early warning system that includes risk knowledge, monitoring and warning service, dissemination and communication, and response capability (WMO 2018).

Table 1.1 Outcomes of effective warnings

Outcome	***Description***
Reduced loss of life	The reduction in the number of lives lost due to timely warnings. This may be indicated by effective evacuation planning and responsive emergency services which contribute to the avoidance of harm that would have occurred had the warning system not been in place.
Minimized injuries and illnesses	The reduction in injuries and illnesses, both frequency and severity, resulting from the hazard event. Decreased numbers indicate the effectiveness of warnings and emergency response in minimizing harm to individuals.
Preservation of property and environment	The reduction in extent of physical damage to properties, infrastructure, cultural resources, and the natural environment caused by the hazard event. This depends on the capacity of public organizations and emergency services to protect property and the environment or remove physical assets from harm's way, and the responsiveness of individuals and institutions.
Reduced disruption	The reduction in the degree of disruption to normal activities in the affected area, including business closures, transportation interruptions, and school closures, as well as individuals forced to evacuate their homes or relocate temporarily due to the natural hazard. Monitoring the duration of disruptions provides insights into the system's efficiency in facilitating rapid recovery and safe sheltering or evacuation.
Reduced economic impact	The reduction in monetary losses incurred as a result of the hazard event. This includes both direct costs such as infrastructure repairs and indirect costs such as business interruptions, healthcare expenses, and environmental restoration. Furthermore, non-monetary effects, such as avoided damages to nature, can have monetary implications regarding, for example, preservation of associated leisure and tourist services.
Enhanced resilience and preparedness	The increase in the community's ability to respond to and recover from the hazard event. This considers factors such as community engagement, preparedness, and the effectiveness of local response efforts in the face of the disaster.
Enhanced emergency response	Improved ability of emergency responders to mobilise resources, implement response and evacuation plans, establish emergency shelters, coordinate efforts, thereby reducing response times and saving lives.
Improved public trust and confidence	Enhancement of public trust and confidence in the reliability and credibility of the early warning system and the institutions responsible for issuing and disseminating warnings. Trust increases the likelihood that individuals will respond to warnings.

The **value** of an early warning system is the *change* in outcomes that can be attributed to having effective warnings as opposed to not having them. The value of a warning to an individual or community depends on their capacity to take action, which is variable and depends on a range of social, economic, behavioural and institutional factors, as well as on having access to accurate weather and hazard information as part of the warning service. Value is often couched in positive terms if the benefits exceed the costs. Metrics and indicators for warning outcomes can be measured for individual hazard events and monitored over many events to assess the effectiveness of the warnings in reducing harm and generating value (discussed further in Chapter 3).

The primary types of value affected by high impact natural hazards include social, economic, and environmental value (see Box 1.1). Early warning systems are typically evaluated in terms of their reduction of human losses and livelihood impacts (Šakić Trogrlić et al. 2022), which are elements of social value. The value of the warning service is realized when the warning respondents take protective actions that mitigate the potential impacts of the hazardous event (thus enhancing the outcomes in Table 1.1), or if the warning clarifies that they are not in danger.

Economic perspectives are commonly used to define the value of weather forecasts and warnings. For example, Lazo *et al.* (2009) estimated the annual value of weather forecast information to be approximately $286 per household, based on a survey of more than 1,500 respondents in the United States. Approaches to determining the total economic value of a service which includes the estimated benefit of the service less the cost of the service are discussed in Chapter 4.

Box 1.1. Value affected by high impact natural hazards

Social value

Social value impacted by high impact hazards can be both at personal and community levels and include death, injury, impacts on health, wellbeing and community connectedness. Social impacts can be short-lived and recoverable such as education disruption or long term, for example, permanent unemployment and exacerbation of chronic disease. Social value is difficult to price and poses significant ethical challenges in attempting to do so. However, efforts have been made to better quantify the social costs of disasters, such as the work undertaken by the Australian Business Roundtable (Figure 1.1) which estimated the financial and social impacts of asset losses on affected communities.

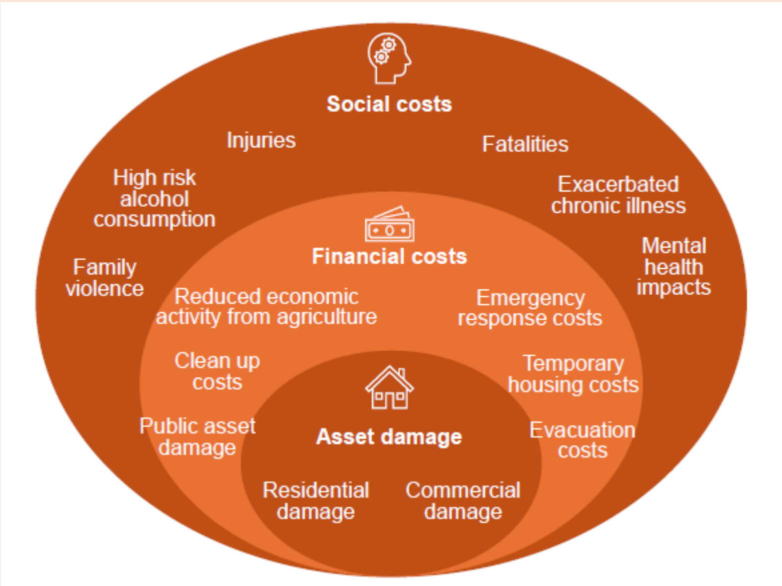


Figure 1.1. Asset losses associated with disasters have flow-on financial and social impacts on affected communities.

Source: Deloitte Access Economics (2021)

Economic value

Economic costs associated with severe events encompass both direct and indirect costs incurred as a result of damage to property and critical infrastructure, business disruptions, injury-related employment losses, and other impacts. Repairing critical infrastructure such as roads, bridges, railways, airports, power plants, water treatment facilities, and communication networks can be costly and result in extended disruptions, further exacerbating economic losses. Crop and livestock losses can lead to economic hardships for farmers and rural communities. Disasters can cause financial strains on healthcare providers, insurers, and governments. Economic cost is often reported as insured losses since that data is available. However, the actual economic losses resulting from a disaster are much higher due to other non-insured costs (for example, public sector costs) and secondary and indirect effects.

Environmental value

Significant environmental costs can result from high impact events, including habitat destruction and fragmentation, loss of biodiversity and species extinctions, loss of ecosystem services (for example, water purification, flood regulation, carbon sequestration), soil erosion and degradation, air and water pollution, and harm to marine ecosystems. Neglecting the environmental impacts of high impact events can undermine the long-term sustainability of ecosystems and human societies. Protecting the environment reduces these costs as well as enhancing human health and well-being and preserving the cultural and spiritual values that symbolize the intrinsic worth of nature, the interconnectedness of all living beings, and the responsibility to take care of the Earth's resources for future generations. Estimating environmental costs is difficult but the System of Environmental Economic Accounting may be useful (United Nations 2024).

A market economic perspective may not apply when monetary costs are difficult to allocate for both practical and ethical reasons. This is particularly the case for social and environmental impacts. The field of economics has methods for deriving values for non-market benefits and costs (including social and environmental) which, when “monetized”, can help put them on a better footing to compare to “market” costs and benefits. The relative importance of environmental value, compared to societal and economic value, can vary depending on the specific circumstances of the high-impact weather event and the perspectives of stakeholders involved. Most early warning systems within NMHSs prioritise protecting human life above economic and environmental considerations.

Early warning systems play a critical role in reducing the costs of disasters by enabling proactive risk management, enhancing preparedness and resilience, and facilitating timely response and recovery efforts. Anticipatory action based on early warnings (for example, led by the International Federation of Red Cross and Red Crescent Societies, IFRC) allows resources to be put in place before an event occurs, enabling communities to be better prepared with emergency shelters, food, and other supplies, thereby reducing the social and economic impacts (IFRC 2024).

Even a perfect warning system will generally prevent only some of the loss that occurs. Reducing the costs associated with high impact events also requires effective risk management strategies, investments, and actions. Many of these involve long-term planning and infrastructure investment, which have the triple dividend of not only avoiding losses but also creating economic/development benefits and other non-market social/environmental benefits (Heubaum *et al.* 2022). However, that still may not be enough, and the better the protection against hazards, the more serious the impact of failure is likely to be (Mileti 1999).

1.2. Early warnings and the information value chain

Knowledge about weather and other hazards, exposure, and vulnerability provides critical advance information to inform decision-makers to take immediate protective actions, prepare for hazards, and implement longer-term risk mitigation policies.

The **value of information (VOI)** refers to a change in benefit to a decision maker resulting from the use of the information (Lazo and Mills 2021). Macauley (2006) provides a useful discussion on the value of information in earth sciences, offering a comprehensive and common approach for conducting evaluation studies.

Value-generating processes can be represented and analyzed using an **information value chain** (IVC). An information value chain describes the value resulting from a chain of processes for creating, transforming and exchanging knowledge and data (information). It consists of a web of “nodes” where information is produced, interpreted, and used by “actors” operating at each node in the chain (these terms are explained in greater detail in Box 1.2) Early warning systems combine information from observations, modelling, hazard prediction, warning generation and dissemination. These are produced, augmented and exchanged by NMHSs, hazard agencies and other service providers, media, community and local actors, to support warning recipients to decide to take action to reduce their losses (or to be assured that there is no threat or that it has passed).

Box 1.2 Components of an information value chain

Nodes represent centres or occasions of information processing (production, translation, transformation, dissemination, and use). The nodes (sometimes called “stages”) are the fundamental building blocks of the information value chain that set the actors’ roles and responsibilities. Examples of nodes are weather forecasting, warning communication and decision-making.

Actors include the full assortment of individuals, enterprises, organizations, agencies, communities, and other entities that engage in the activities described by the nodes. Other common terms to describe actors are agents, experts, enablers, users, stakeholders, and producers. Actors typically involved in early warning systems include NMHSs, local and national governments, regional institutions and organizations, international bodies as well as non-governmental institutions and communities (REAP 2024b). Most actors in the warning value chain are both producers and users of information and are frequently involved in several nodes. Different actors have their own values, perceptions, objectives, resources, constraints, capabilities, cultural context and practices which may influence their ideas about the relative importance and roles played in generating value.

Flows describe the communication and movement of data, knowledge, resources and relations among actors and nodes. These are the “links” in the chain. Flows can be both internal and external to an organisation or node. Information and resource flows can be defined in terms of their content, volume, frequency, duration, medium, and format. Relations among actors and nodes govern the flow of information and resources. It is vital to clarify the responsibilities associated with each relation so that actors and nodes operate in coordinated strategies and structures to ensure the effectiveness of the flow, which can be challenging (Garcia and Fearnley 2012, Potter *et al.* 2021).

Figure 1.2 depicts the high level value chain. NMHSs represent a key actor and provide much knowledge and information through their service production and delivery systems. Further information (value) is added (or lost) in "downstream" communication and value-adding processes that often involve other actors. This approach is consistent with many hazard communication and response frameworks such as for health hazards, geological hazards, chemical and nuclear hazards, and so on (WHO 2024). Societal value is the ultimate outcome.

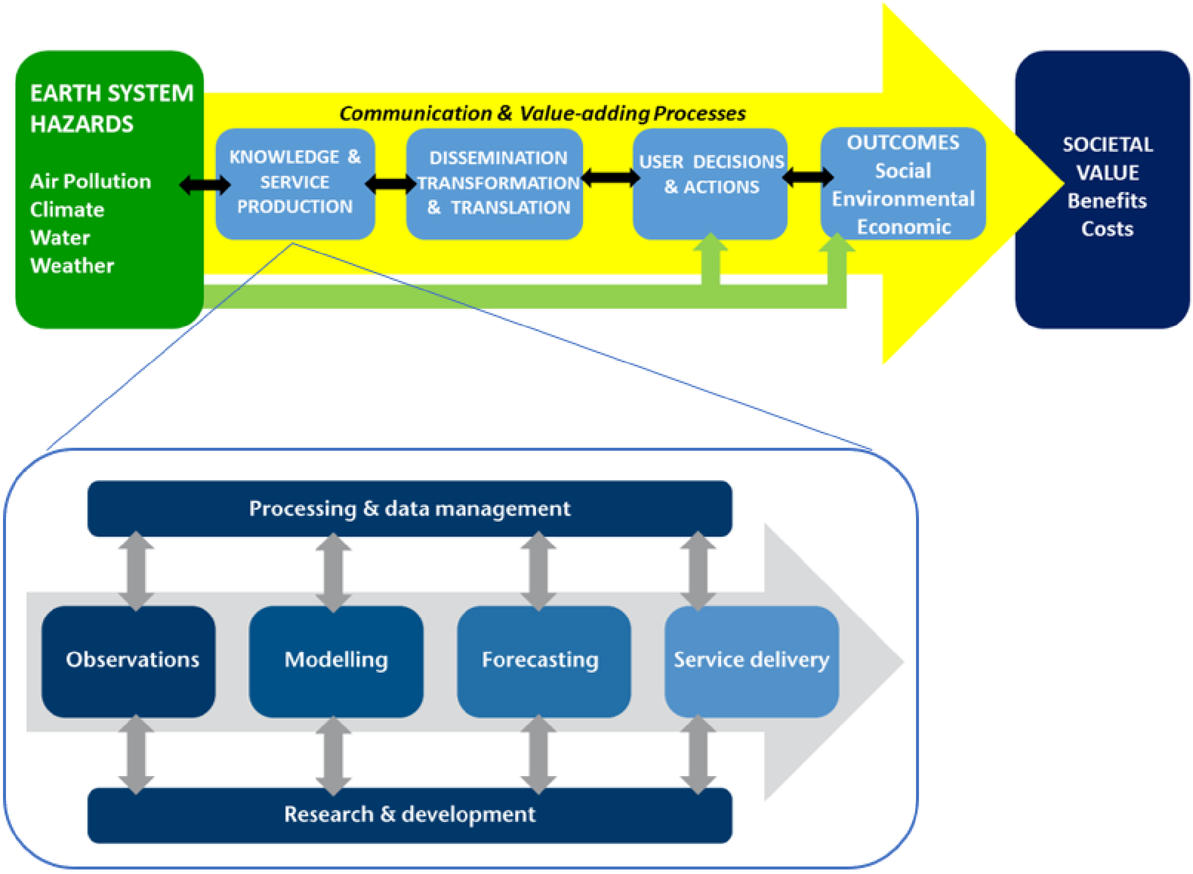


Figure 1.2. High level value chain for forecast and warning services, expanded to show the main components of the service production and delivery system of NMHSs

Source: Adapted from WMO *et al.* (2015)

The links in the chain symbolize the interactions between the nodes, that is, the communication of information, movement of resources, and nature of relationships among actors. Most actors in the value chain are both producers and users of information. Importantly, an IVC measures the user benefit resulting from the chain of information processing.

In recent years the term "value chain" has come into common usage in the hydrometeorological community with a meaning more akin to "production chain" or "value-adding steps". This aligns with the concept of an industrial value chain (Porter 1985), where products pass through a chain of activities in order, and at each activity the product gains some value (for example, raw materials progressing through a series of steps to become a delivered, finished product). Indeed, the warning information value chain described above features value-adding processes.

However, it is incorrect to assume that improving an information process in one part of the chain will automatically lead to enhanced user benefits. For example, improving the accuracy of forecasts at short lead times may not be effective if people do not have enough time to change their decisions and take a different action based on the new information. More informative graphical warnings disseminated online will not benefit users who have no access to the internet. Therefore, it is crucial that user outcomes – value – be considered explicitly in a value chain, rather than implicitly.

Two seminal publications promote the use of IVCs in the field of hydrometeorology. WMO *et al.* (2015) introduced the concept of IVCs for understanding and assessing the economic value of weather, climate and hydrological services. Lazo and Mills' (2021) paper on weather-water-climate value chains builds on that earlier work by discussing how to operationalize the value chain concept and apply the broad set of social sciences (including economics) to study and improve the process, providing several illustrative case studies.

Even though an early warning system is complex, it is often represented sequentially to emphasize the key aspects. The flow of information is also intricate, dynamic, and multi-directional. The terms "value cycle" or "value ecosystem" are sometimes used to reflect that complexity. Here the term "value chain" is used because the vast majority of existing work has used that terminology.

This framework uses the following terminology:

Value chain - any linked set of processes, nodes, actors, and information that combine to produce actual or potential value for end users. "Value chain" is used as shorthand for "information value chain" in this framework.

Service chain - the linked set of processes, nodes, actors, and information within a value chain, without explicit consideration of the end user value. This corresponds to the "production chain" concept mentioned above.

Warning value chain - the value chain for an early warning system. It can also refer to the realization and outcomes of an early warning system for a hazardous event that occurred.

Value chain approach - a methodology for framing, characterizing, or evaluating a value chain. This framework describes several value chain approaches and gives tools in Annex 1.

Value chain study - application of one or more value chain approaches to produce a result (for example, a valuation report). "Value chain analysis" is sometimes used to emphasize the analysis aspect.

In practice, it is only possible to capture static snapshots of the core elements of processes represented in the value chain. A warning value chain can represent the operational or routine production and dissemination of a warning ("fast" or "event" mode), the details of which depend on the nature of the event and how far it is in the future. The same value chain, perhaps flowing in a different direction, can represent the evaluation, continuous improvement, and even the design of a warning system ("slow" mode).

Activity: What's in the value chain? Introductory activity where individuals and groups think about who is involved in the value chain, what information they produce and use, and their decisions and actions.

Annex 1

When conducting a value chain analysis of an early warning system it is important to consider the broader context in which it operates (Figure 1.3), which affects the success of the warnings. The Sendai Framework, the EW4All initiative, international protocols, national commitments to international agreements, and national governance of risk management (including a clear definition of who is responsible for what risks) frame the early warning systems in a global context.

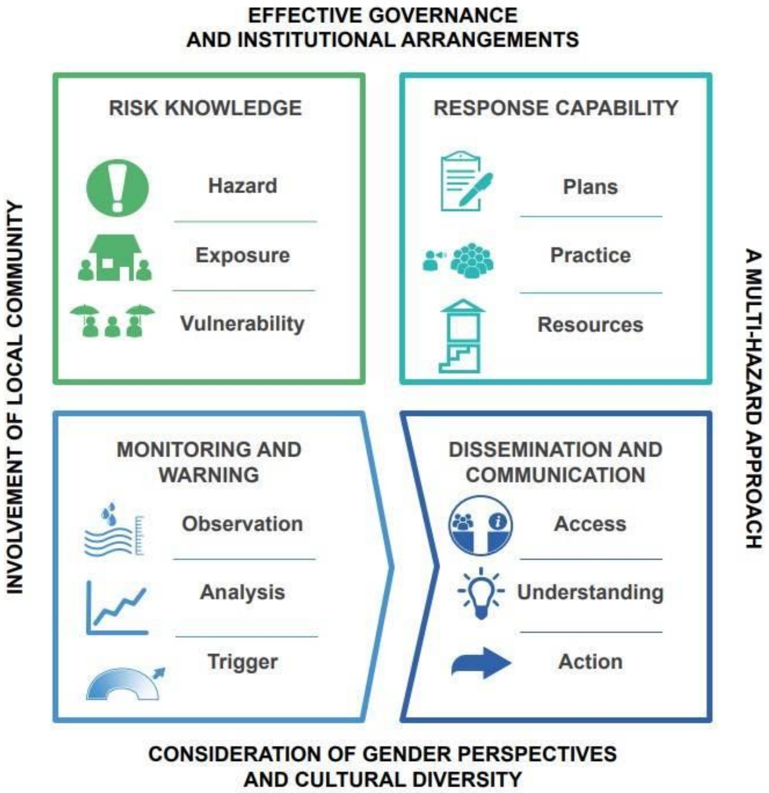


Figure 1.3. The four main elements, and four overarching components required for an early warning system to be effective

Source: Practical Action (2020)

The need for early warning systems is ubiquitous but the contexts for their development and application vary widely around the globe and among hazards. Conceiving a new warning system as a value chain makes it easier to tailor processes to specific contexts and needs and take into account the many societal factors which influence the effectiveness of early warnings, such as governance and institutional arrangements, preparedness, response, and recovery capacity (Figure 1.3). By considering all potential hazards within a warning value chain, communities and authorities can better prepare for complex and compound events, and organizations involved in producing and responding to warnings can optimize their resources and efforts. People-centred warnings are considered best practice because they focus on (and indeed should start with) the users' needs and contexts. Accordingly, warning system design should account for gender and cultural diversity factors as well as individual or household factors such as risk tolerance, attitudes, norms, personal efficacy, resources/income, and social capital.

1.3. Reasons to use a value chain approach

The information value chain offers a holistic view of how different parts of a system, including previously ignored or understudied aspects, collaborate to create value. Information value chains operate on all time and space scales and adapt to fit a range of situations.

Value chain analysis is a practical way for those involved in creating social and other benefits to understand how the value is generated. It integrates technical weather model or forecast accuracy assessment with social science concepts such as behaviour, decision-making, equity, and socio-economic outcomes. It shares many similarities with other methods such as theory of change and logic models (described in Chapter 3), offering insights into *how* value is generated through the people, organizations, processes, linkages, and resources involved in the value chain. In the case of NMHSs, a value chain approach sheds light on how the complex act of producing and communicating early warnings influences the responses of others to save lives, prevent injury, protect property, and reduce disruption.

Value chain analysis can support many types of managerial decisions of NMHSs and other organizations involved in early warning systems. A hierarchy of purposes for value chain studies is described below in order of increasing complexity. The first few are typically internal to an organization and may be conducted frequently or routinely. Subsequent purposes for value chain analysis are often also internal, but larger in scope and involving more external partners, frequently driven by external mandates. Value chain analysis is also ideally suited for comparing warning systems across time, hazards, locations, and jurisdictions. When selecting the approach to match the scale and objectives of the study, is it crucial to consider the target audience.

Strategic awareness - Value chain analysis can be used to help create an overarching strategic vision of how warning services facilitate the smooth, safe and efficient functioning of society. In practice it means awareness raising and training of staff about this important function and the consequent need to nurture and monitor interactions with users both within and outside of an organization. This vision is communicated to the different user groups and service partners. *Application: Existing or new strategy that includes internal and external engagement.*

Operational management support - Value chain analysis can be cast as an operational management toolbox for monitoring and judging performance of the value chain and of its constituent parts in terms of accuracy, user effectiveness, access, uptake, resource efficiency, affordability, and other indicators. The monitoring can be both quantitative and qualitative, automatic or decision dependent, standardized and/or flexible. It can span the entire value chain or support managerial questions pertaining to fairly simple service improvements in a few sections of the chain. *Application: Evaluation of recent (for example, last year's) performance, possibly in conjunction with plans for incremental improvements (for example, based on user satisfaction surveys).*

Post-event analysis - As part of a reflective debriefing exercise, value chain analysis can provide insight into the relative significance of different value chain segments and actors regarding warning performance for events. If earlier post-event assessments are available, the relative performance of the entire chain and its constituent parts can be assessed. Active involvement of external actors is essential, which makes the value chain analysis more demanding to conduct. Value chain analysis for events can also be used to build a database of parameter values which can be used in economic modelling or other analyses. *Application: Review and assessment of reasons for success and failure following occurrence of high impact events.*

Investment decision – Value chain analysis can be used to support larger investment decisions, such as renewal of radar systems and satellites or extensive in-situ networks. Such cost-benefit analyses are often mandated by governments to evaluate new investments. *Application: Planning for significant renewal or extension of observation equipment or other technology in order to improve preparedness for extreme weather conditions.*

Comprehensive service renewal - Value chain analysis is essential for strategic review of more comprehensive service innovation decisions which may involve new stakeholders and co-producers, new user interfaces, etc., and usually new processes and procedures. Presenting the value chain for the service renewal can facilitate communication with all stakeholders. *Application: Major renovation of a warning service (including, for example, new data sources and warning equipment, citizen observations, new distribution channels and user interfaces, new organizational information pathways and responsibilities).*

New service co-design – When a service does not yet exist and must be created, value chain analysis can assist in defining why, who, what, how, etc. Value chain analysis for service co-design can complement an investment decision evaluation or can be used in an exploratory fashion to support plans for comprehensive service renewal. *Application: Cases where emerging needs, government mandates (for example, following a disaster), or new opportunities (advanced capabilities, new partnerships, resources) can only be met with development of a new warning system.*

Comparative studies - Value chain analysis can be used in support of policies and in international comparisons. International organisations such as WMO, multilateral development banks, and sustainability organizations, as well as academia and large consultancy companies, are often interested in comparative studies over time and across countries in order to revise their benchmarks and promote sharing of experiences of best-in-class approaches. *Applications: Comparison of preparedness for particular hazards across countries or regions; comparison of preparedness for different hazards in the same jurisdiction; comparison of emerging service models, such as in connection with smart cities.*

1.4. Conducting a value chain study

Any value chain study should comprise the following basic steps:

Preparation phase:

1. Define the purpose of the value chain study. Who is the audience and what do they want to know?
2. Determine the level of ambition for the study. What resources are available? What is the timeframe for the study? How will the user community be involved?

During the study:

3. Describe who is involved in the value chain and why.
4. Describe what information moves between the actors in the value chain.
5. Apply data collection and analysis methods appropriate to the purpose of the study.
6. Report the results.

The details of each step, especially the data collection and analysis methods, will depend on the intention of the study. For example, applying a value chain approach to improve an early warning service would include identifying how the value of an improvement in the chain could be assessed, and appropriate methods of measuring or evaluating the benefits of the changes, among other things.

The size of the value chain study should be proportionate to the issue at hand. An internal study may often yield valuable insights. Getting professional assistance (workshop facilitators, economic experts, etc.) may result in a better study. However, the NMHS or other organization interested in the study will still need to provide much of the relevant information.

The chapters to follow elaborate on how value chain concepts can be useful in describing, evaluating and improving, measuring the value of improvements, and co-designing early warning systems.

1.5. Further reading

Golding, B., Mittermaier, M., Ross, C., Ebert, B. Panchuk, S., Scolobig, A., & Johnston, D. (2019). A value chain approach to optimizing early warning systems. *Global Assessment Report on Disaster Risk Reduction*, 1-30.

Lazo, J. K., and Mills, B. (2021). *Weather-Water-Climate Value Chain(s): Giving VOICE to the Characterization of the Economic Benefits of Hydro-Met Services and Products*. American Meteorological Society.

WMO, WBG, GFDRR, and USAID (2015). Valuing weather and climate: Economic assessment of meteorological and hydrological services. *WMO-No. 1153*, 286 pp.

2. Describe an early warning service using a value chain

Describing an existing service is the first step in almost any value chain study. This chapter introduces relevant concepts used in value chain analysis such as the primary value chain components: nodes, actors, and flows; and how to organize connected information into a visual or conceptual structure such as a sequence, cycle or network. Approaches for gathering information about the value chain and characterizing it in greater depth are also given.

The purpose of applying a value chain approach to describe an existing early warning system is to understand it better, perhaps as a first step to improving the service. The aim is simply to understand what exists. This type of analysis enables stakeholders to reflect on why the service is being provided, who it is for, what it looks like, and whether it is having any effect.

By describing the value chain for an existing service it is possible to identify where significant value is being generated. In addition to describing how the “end user” benefits, it can tease out the nature and benefits of information exchange to the participants in intermediate stages of the value chain. When analyzed in a group setting, the process helps people to deconstruct the complexities of the service delivery, consider different perspectives on value generation, and identify the issues they have in common. For example, describing the warning value chain can enable people to work through a particular problem in an existing early warning system. It could also be used to help formalize what may be only tacit agreements between the actors.

A descriptive value chain study often does not require very much in the way of time or resources to produce a useful outcome.

2.1 Organization of a value chain

The information value chain is versatile. It can take many forms, representing different perspectives, actor relationships, time scales, and modes of operation (for example, warning for an approaching hazard event, reviewing the warning service, planning improvements, etc.). This adaptability allows people to visualize and understand the value chain in ways that are most meaningful to their particular roles or interests.

Depicting the value chain in a diagram is an excellent way to gain understanding. There are various ways of presenting the value chain that suit different purposes, with many of them actually reflecting a service chain rather than the full information value chain with user benefit shown explicitly. This chapter shows several ways to visualise service and value chains but is by no means exhaustive.

The service chains for two early warning systems are illustrated in the case studies below. The first example highlights the many activities and groups who are involved in producing, communicating, and using riverine flood warnings in Australia. The primary flow is downward, suggesting a sequence of activities, but many arrows flow both directions to represent the feedback loops on short (flood event) and long (review and improvement) time scales.

The second case study depicts the workflow within the Tanzania Meteorological Authority for preparing information, advisories and warnings for severe weather, involving staff from across the agency. This service chain diagram is especially useful for internal understanding and management.

Case Study 1: Australia's warning system for riverine floods

Following major floods in Brisbane, Australia during summer 2010-11, a panel of technical experts constructed the flood warning value chain shown in Figure 2.1 to summarize the processes, organizations (actors) and activities involved in a flood warning system in Australia.

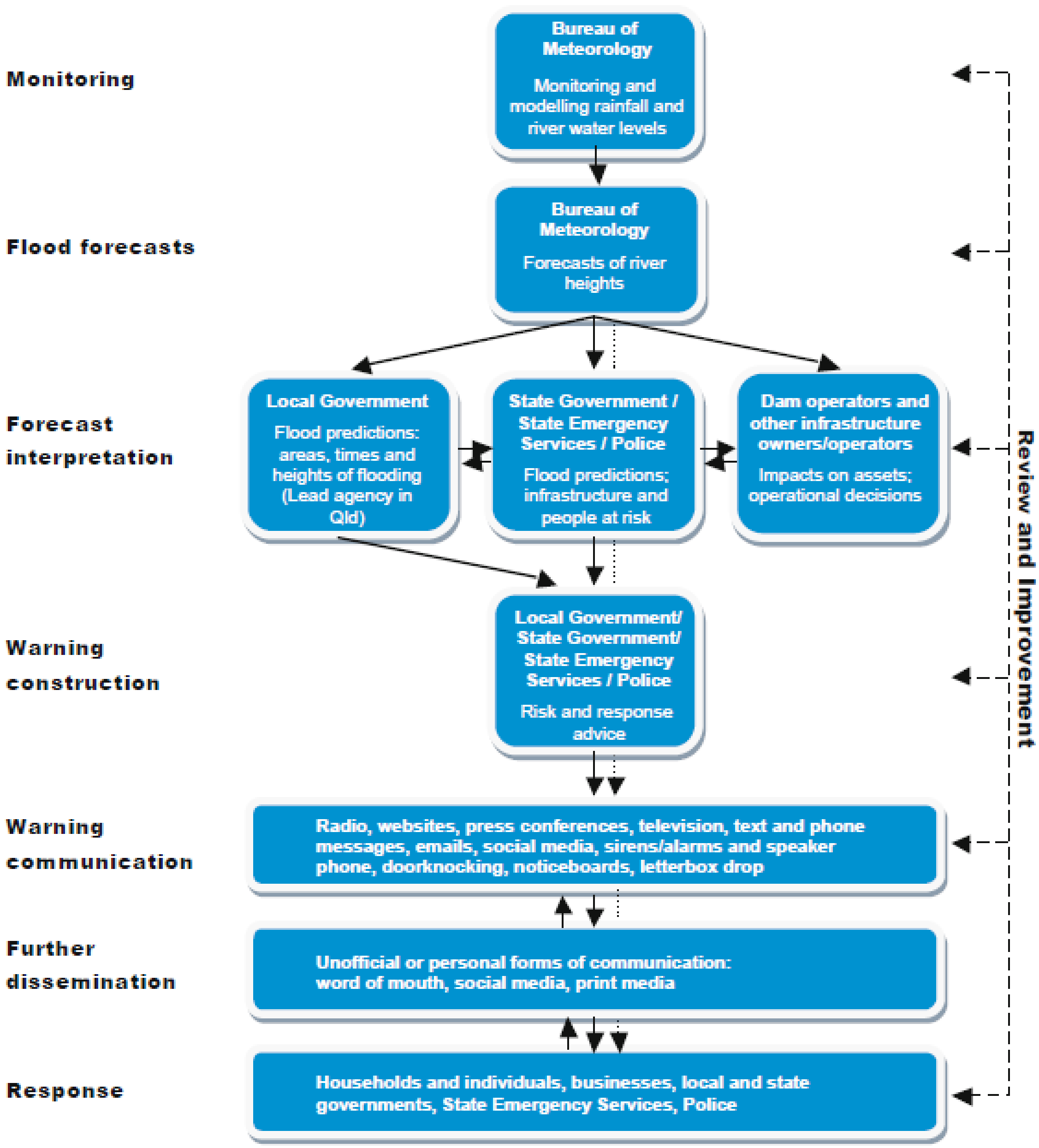


Figure 2.1. Components of a flood warning system in Australia.

Source: Queensland Government (2011)

Case Study 2: Tanzania's early warnings

Tanzania is particularly vulnerable to the impacts of extreme weather, including severe floods, frequent and prolonged droughts, and to coastal storm surges. To address these challenges, the Tanzania Meteorological Authority (TMA), which is the authoritative source of weather and climate information and warnings in Tanzania, collaborated with the UK Met Office and users from various sectors including disaster management, media, agriculture, fisheries, gas and oil, to co-design Standard Operating Procedures (SOPs) for preparing and issuing severe weather warning information through TMA's internal service chain. The SOPs, shown in Figure 2.2, delineate hazard identification, impacts, likelihood of the event to occur, decision-making for issuing warnings, and information dissemination, with the relevant teams and individuals (actors) identified.

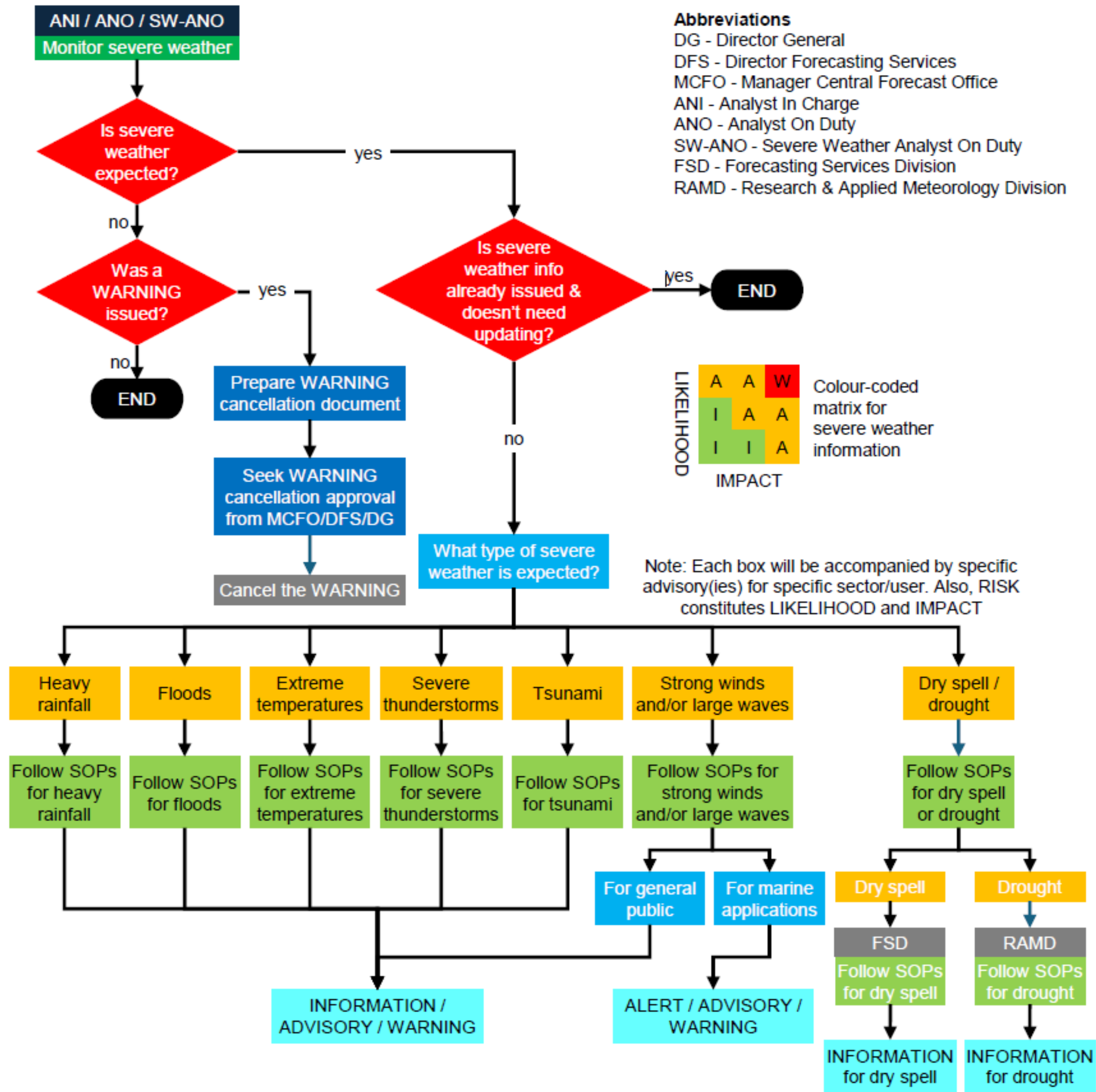


Figure 2.2. Service chain showing standard operating procedures for early warnings issued by the Tanzania Meteorological Authority.

More information: Msemo et al. (2021)

Warning value chains are rarely static. Many of the qualities of nodes, actors, and flows operate dynamically as the social, cultural, political, physical, technological and economic context evolve. It can change over time as the warning system improves, or during a hazardous event as early signs of a hazard evolve into a full-blown event. This could be critical for mitigation actions, protective actions, or anticipatory actions. It may be necessary to identify the context for the warning value chain (for example, how it operates during a certain phase of an event, or for a certain set of users), or consider linked versions that cover multiple contexts.

To successfully describe and evaluate the entire warning value chain it is important first to identify all of the nodes, actors and flows. Some tools that can assist with this are a value chain table and a value tree.

Tool: Value chain table - An easy way to start describing the value chain for a specific service is to list the nodes, actors, and flows in columns of a table.

Annex 1

Tool: Value tree - When multiple services depend on the same information produced upstream in the value chain, a value tree enables better understanding of economies of scale and scope and other synergies between closely related services.

Annex 1

Structure

To aid in describing and discussing the service or value chain for an early warning service it is useful, perhaps even necessary, to visualize the nodes, actors, and flows in a schematic diagram or table. Some examples were shown earlier in Figures 1.1, 2.1, and 2.2.

There is no one "best" way to depict a value chain for an early warning system. The conceptual configuration or structure should reflect the perspectives of the participants involved and support the goal of the value chain study. The visualization is always a simplification of what is in reality a highly complex network of data and information flows between multiple nodes and actors.

The Risk-informed Early Action Partnership has produced an excellent compendium of value chain visualizations for early warning early action (REAP 2024a). Visualizations were categorized into models of early warning delivery, early action delivery, and bridging gaps across actors. They make a useful distinction between visualizing "fast" processes associated with a risk event when warning information must be produced and communicated quickly and efficiently, and "slow" processes such as planning, implementation, review, and improvement, which are often more cyclical. Many value chain structures can accommodate both.

A few of the most common service and value chain structures found in hydrometeorology are presented below; many others can be found in the decision theory and other literature.

Sequential - Service and value chains are frequently drawn as a linear sequence of steps, each representing a process that adds or transforms value. The flood warning service chain in Figure 2.1 is an example. Another is the generic warning value chain of Golding *et al.* (2019) (Figure 2.3), where the bridges represent flows of information across the "valleys of death" between nodes (mountains), where value can be lost. Strong bridges are essential for successful warnings.

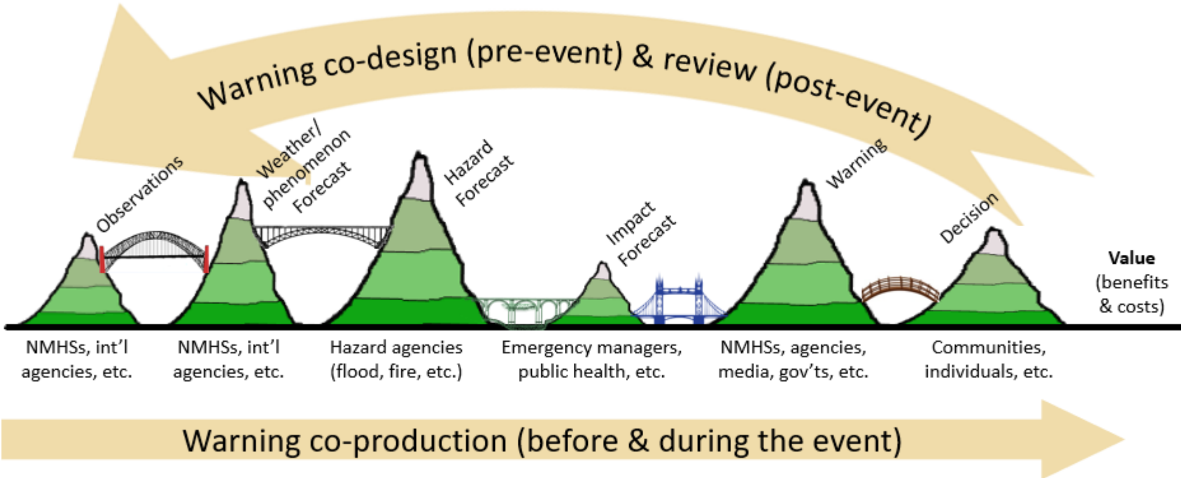


Figure 2.3. Schematic representation of the warning value chain as a sequence of information nodes (mountains) and associated actors who exchange flows of data, knowledge and resources (bridges)

Source: Adapted from Golding *et al.* (2019)

Figure 2.4 emphasizes the actors in the value chain for weather and climate services, where actors often work in segments (a few closely related nodes or product components) across multiple nodes in the chain (Perrels *et al.* 2020).

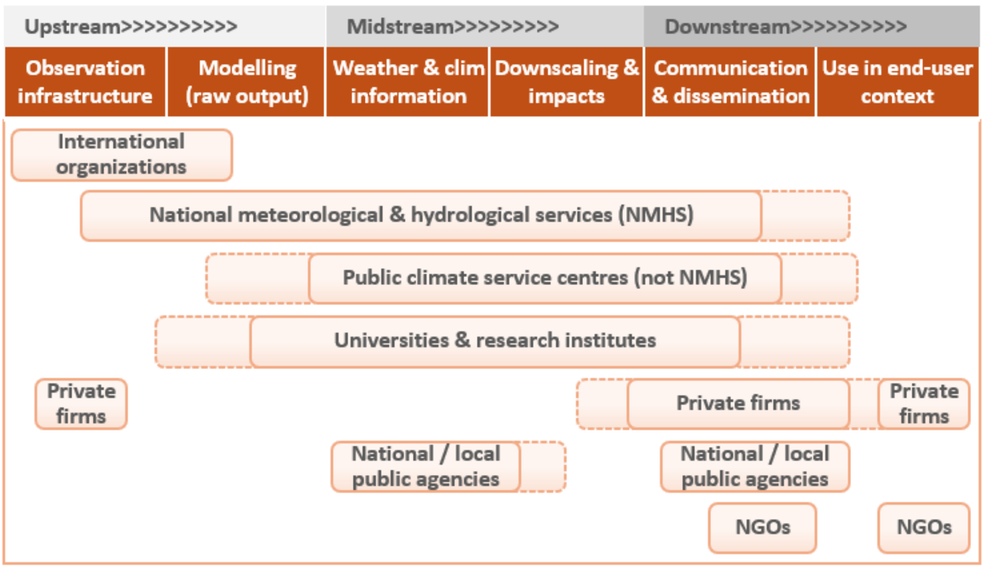


Figure 2.4. Value chain segments in weather and climate service provision and typical positions of actors providing the services.

Source: Adapted from Perrels *et al.* (2020)

Representing the value chain as a sequence simplifies the often complicated flows of information and resources between actors and nodes. It is possible to quickly understand the main elements of how information is gathered, transformed, and utilized to generate value, and the dependencies between different stages of the value chain.

A sequential value chain is a useful foundational framework for analysis. It is possible to analyze each node for its information generation, quality, and value addition and pinpoint areas for improvement. The Value Of Information Characterization and Evaluation (VOICE) framework (Lazo and Mills 2021) can be used to describe the actors and information flows in a weather information value chain, including each actor's objectives, resources, and constraints, and the value added at each node and at the end (see Chapter 4 for details).

When multiple services depend on common "upstream" information (for example, weather forecasts supporting warnings for both flood and wind impacts), then a value tree may be useful (Annex 1). In scenarios with multiple information value chains, such as a comparative study to inform best practice, a linear representation allows easy comparison to recognize disparities and understand relative strengths and weaknesses.

A limitation of the sequential or linear value chain is that it often implies a top-down or unidirectional flow of information when the reality is more complex. Nevertheless, it is still a useful approach for building understanding of the value chain components in a specific early warning service.

Cycle - Visualizing the service or value chain as a cycle is especially useful when aiming to represent a service that is adaptable, user-centric, and continuously improving. Figure 2.5 depicts the people-centred Multi-Hazard Early Warning System (MHEWS) as a value cycle. In this case the emphasis is on the "last mile", that is the community of people who must engage and act upon the information provided. The community may also be the "first mile" if they are brought into the process of designing, operating and communicating the warnings (Kelman and Glantz 2014; see also Chapter 5). This goes beyond the concept of the community as merely a receiver of information to one where they can also be a producer and facilitator of information (Global Disaster Preparedness Center, 2022).

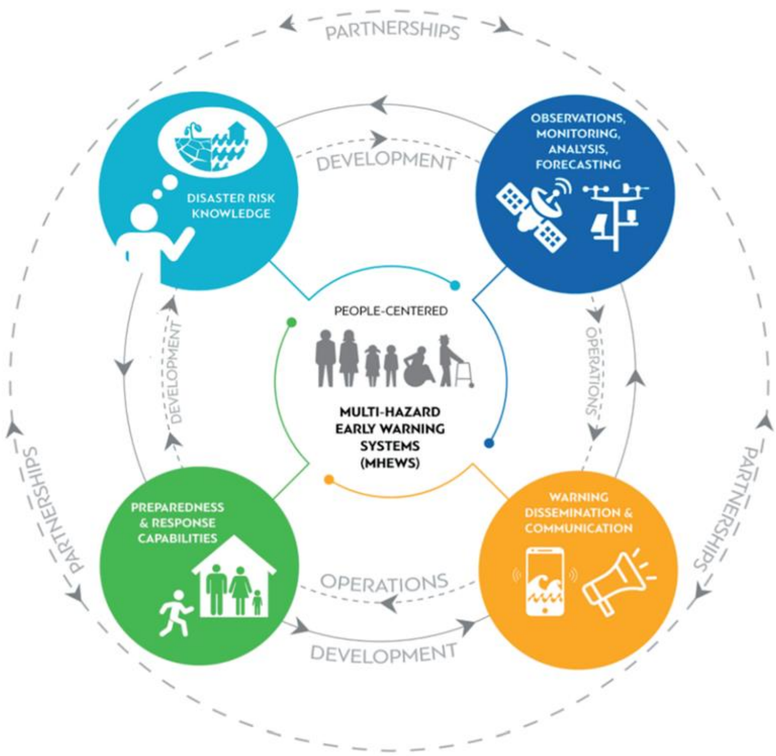


Figure 2.5. Value cycle for a multi-hazard early warning system

Source: WMO (2022a)

This holistic view emphasizes the interconnectedness of various stages within the value chain. It encourages cross-functional collaboration, where different actors can contribute their expertise and feedback to enhance the overall service. It can represent real-time service adjustments and improvements based on new data sources, user experiences, and rapidly changing requirements (Fearnley and Kelman 2021).

As the service is refined through each improvement cycle, it opens doors to new ideas and can better align with emerging technologies, trends, and user expectations. Insights gained from previous cycles can lead to the development of more sophisticated algorithms, improved response strategies, and the identification of new ways to enhance the value provided by the service (Figure 2.6). Building upon the successes and learnings of the previous cycle, the service gradually becomes more effective, valuable, and sustainable.

Implementing iterative service improvements through a cycle allows changes to be managed in a more controlled manner. Smaller, incremental changes are often easier to implement and adapt to than large, disruptive overhauls, and potential risks can be identified and mitigated early in the process, minimizing negative impacts on service quality.

Existing warning value cycle diagrams such as those shown in Figures 2.5 and 2.6 often do not depict the value achieved by the early warning system. This could be remedied by more explicitly including the community benefit in the centre of the cycle, linked to the response node (and perhaps to other nodes that directly generate value for the community).

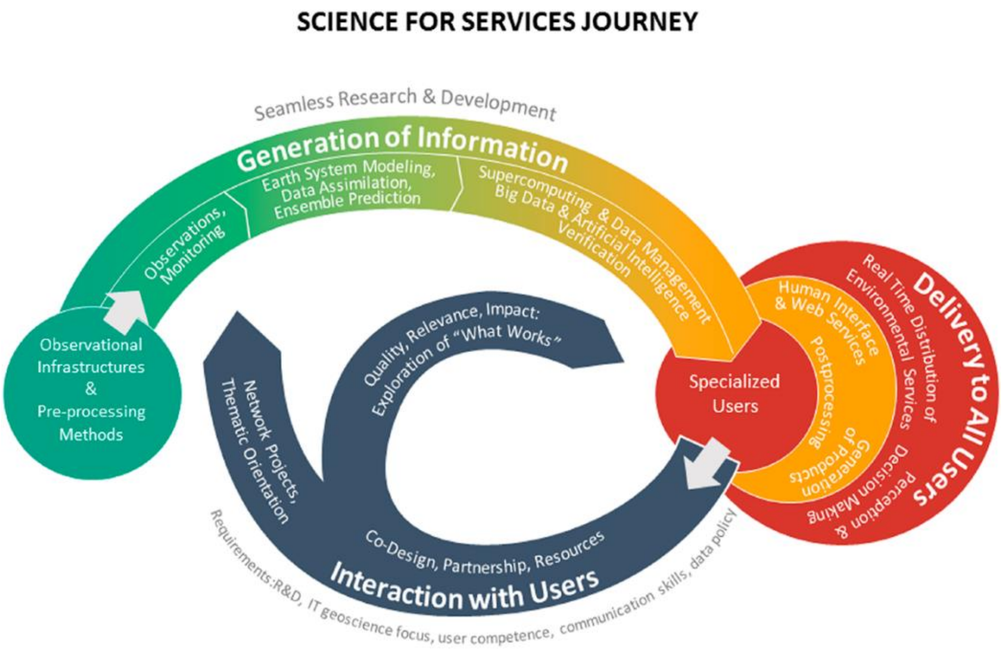


Figure 2.6. "Science for services" value cycle emphasizing the role of research and development in service improvement

Source: Ruti *et al.* (2020)

Network / ecosystem – Value chains for early warning services are typically complex, involving many data sources and types, processing steps, interactions, and feedbacks. Network diagrams and ecosystem maps such as those shown in Figures 2.7 and 2.8 acknowledge this complexity and provide a visual aid to manage and optimize the system.

By using a "systems thinking" perspective to show the connections between different nodes, actors, and data sources and flows, actors can recognize how their actions and contributions interact with different parts of the ecosystem and influence the overall outcomes and value. This transparency can enhance trust and accountability and inform proactive risk management and mitigation strategies. Identifying key nodes, bottlenecks, feedbacks and opportunities within the ecosystem aids in making informed decisions about resource allocation and improvements.

Ecosystems are dynamic and adaptable to changes. This view of the value chain emphasizes the need for flexibility and responsiveness. Ecosystems also often have redundancy and backup mechanisms, with alternate data sources, processes, and communication channels that ensure service continuity even in the face of disruptions.

As with value cycle visualisation, the value to the end user may not be represented explicitly in network and ecosystem diagrams. In principle this would be fairly easy to add in order to complete the value chain.

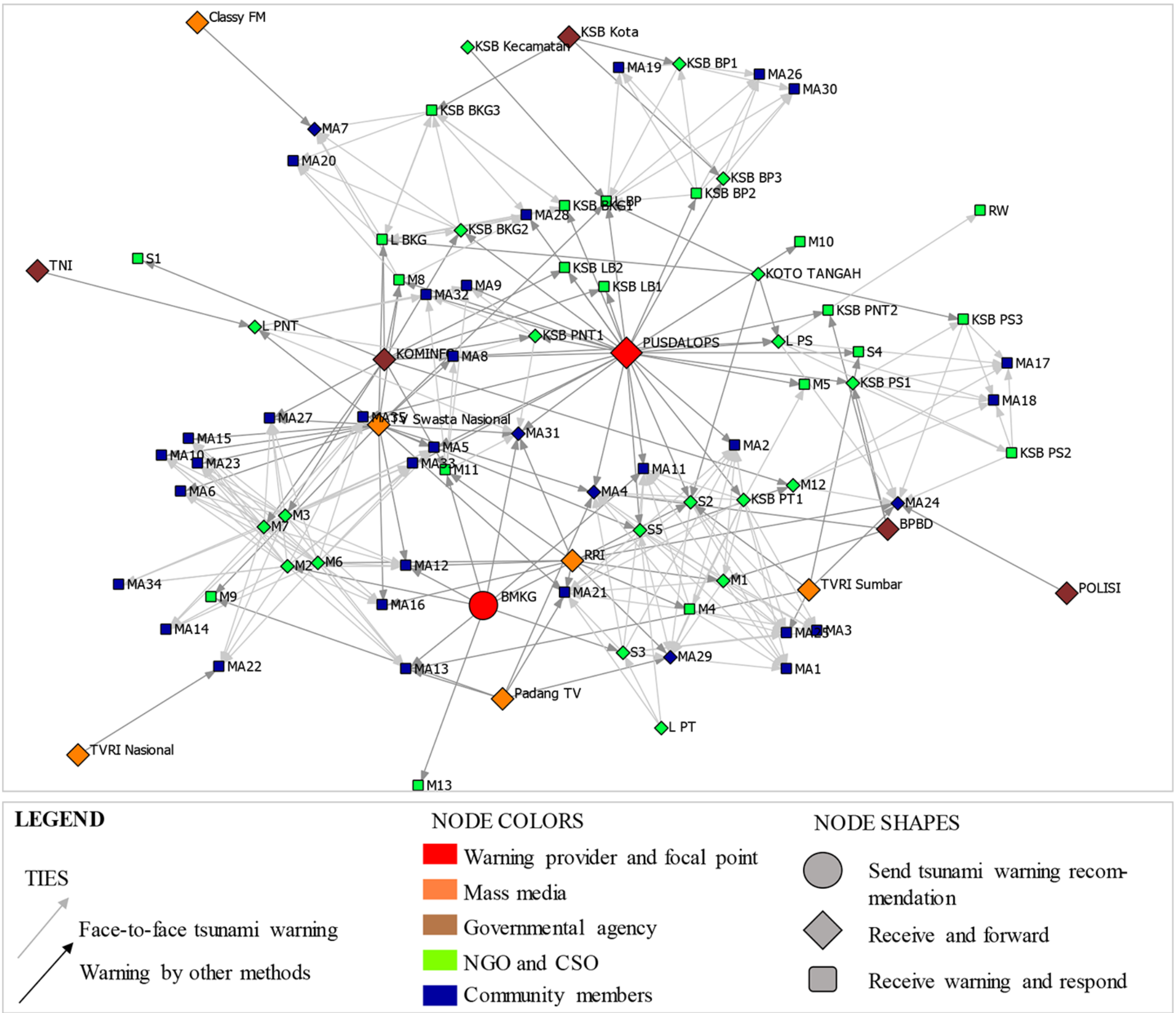


Figure 2.7. Network diagram for a tsunami early warning system in Indonesia showing the linkages between different nodes in the complex value chain

Source: Rahayu *et al.* (2020)

2.2 Collecting information and characterizing the value chain

To effectively assess a warning system, it is crucial to build a comprehensive understanding of service objectives, actors, nodes, capabilities, data/information flows and relationships. Methods for gathering this information are described in Box 2.1. They differ in their required investments, with some well-suited for smaller-scale initiatives and others demanding more substantial resources. For example, reviewing existing operational protocols and guidance documents in small groups or as individuals may provide a preliminary overview that is sufficient for many purposes. Describing a value chain could involve a small team mapping out the service value chain, utilizing interactive tools like whiteboards and group discussions. Conducting interviews and focus groups requires substantial planning and effort but can provide more and richer data for analysis.

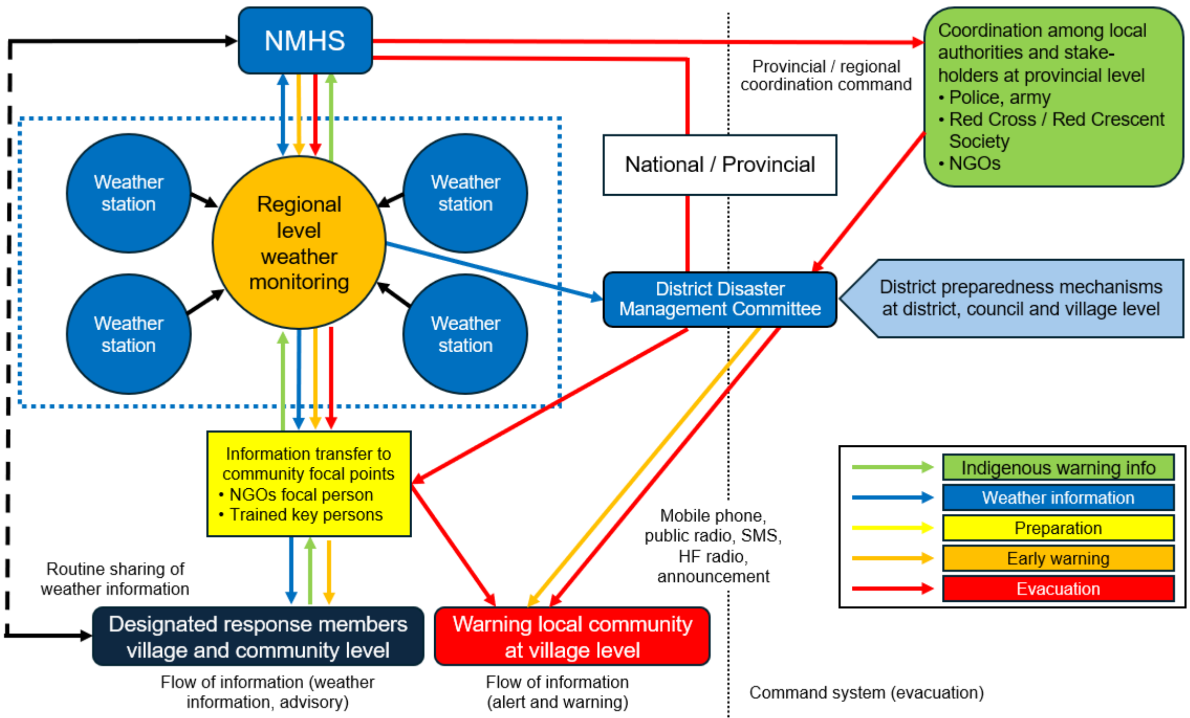


Figure 2.8. Example of information flows at province and district/community level for an early warning system

Source: Adapted from Mohanty *et al.* (2019)

While it is possible for a value chain study to be conducted by a single individual, involving a greater number and variety of stakeholders in the activity enhances the learning and enables a better understanding of the entire process. From the NMHS perspective, this means engaging not only internal staff (representing research and development, observation systems, computing and data management, operational forecasting, and service functions) but also external groups such as emergency response and management, media, health services, transportation, electricity/power, water management, non-government organizations, and segments of the public, depending on the specific service and risk being addressed.

Establishing consensus on the fundamental building blocks of the value chain is essential. Workshops in particular are an excellent way to gather information and gain insights on warning value chains. Individuals with diverse roles and perspectives can contribute and learn from one another, moving toward a collective understanding of the value chain. Participants from across the value chain can collectively describe the service including the relevant threats, the roles and objectives of service providers, and their relations with other actors. They can document the information that is produced, provided and used, and note the information exchange processes.

Box 2.1. Methods for gathering information

The most common methods of data collection are summarized in Table 2.1 below, along with their relative effort or cost. Applying multiple methods as a complementary approach can produce more complete information and address potential biases and other weaknesses associated with individual methods. If those conducting the study are themselves a part of the value chain they aim to describe and analyze, they must acknowledge their own assumptions and beliefs and reflect critically about how this affects their findings. Steps will often need to be taken to protect the rights of information providers.

Table 2.1. Methods for gathering information

Primary methods (original information collected for the purpose of the study)	
Brainstorming	Generates ideas by gathering people (often internally) to collate a list or solve problems. This collaborative approach elicits diverse perspectives but does not screen ideas, with the result that some information may not be high quality. *Effort/cost: Small*
Stakeholder workshops	Explores a topic in depth with key stakeholders who may have different backgrounds but share a common interest. They can foster trust, ownership, and empowerment among stakeholders, and facilitate learning and innovation. Challenges include managing diverse and conflicting interests (which can be extremely valuable to characterizing a value chain), ensuring ethical and inclusive participation, and balancing participants' time and resources. *Effort/cost: Medium*
Questionnaires and surveys	Yields a broad perspective from large groups of people by asking them predefined questions. Designing effective survey questions requires careful consideration of question wording, response options, and question order. Incorporating classificatory variables (for example, urban vs. rural), may prove useful for analysis. However, one-way communication and close-ended questions do not allow the capture of a full range of expression from the respondents. *Effort/cost: Medium*
Tabletop exercises	Facilitator-led sessions with participants meeting in an informal setting to discuss their roles and responses during a hypothetical emergency situation. Exercises allow identification of strengths and weaknesses in emergency preparedness plans, policies, and procedures. However, responses may differ between hypothetical and real scenarios. *Effort/cost: Medium*
Expert elicitation	Gathers knowledge and opinions from experts on specific topics, often where empirical data might be sparse, uncertain, or unavailable. It can be a cost-effective way to obtain necessary information relatively quickly. Different experts may differ in their opinions; it may be useful to synthesize information from multiple experts. *Effort/cost: Medium*
Interviews and focus groups	Engages directly with individuals or small groups to collect rich data, explore their opinions, motivations, beliefs, and experiences; the findings may be used to inform a survey to sample a wider population. Groupthink (conforming to dominant opinions) is a risk; participants may feel more comfortable expressing their opinions and experiences in a private interview setting. Analysis can be time-consuming, subjective, with the potential for bias. *Effort/cost: Medium-Large*
Direct observation	Collects data about behaviour and events by observing how individuals interact with their natural setting. This approach is well-suited for exploratory research and hypothesis generation. It frequently does not require technical skills. However, only some things are observed, and subjective data can be prone to interpretation bias. *Effort/cost: Medium-Large*

Social media monitoring	Queries specific online platforms using a data analytics tool. It can be a cost-effective method for exploiting vast amounts of user-generated content for analysis. Unverified sources make it difficult to confirm the accuracy of the information. Social media data may be biased if certain groups communicate more frequently. Information should be obtained ethically and legally. *Effort/cost: Medium-Large*
Case studies	Provides detailed, contextually rich data to explore complex situations in depth. The holistic perspective highlights the interplay of multiple variables and factors within a real-world context. Conducting case studies can be time-consuming, depending on their depth. They are susceptible to researcher bias, including 'global north' perspectives (a focus on events that most researchers are more familiar with). Findings may not be generalizable to other contexts. *Effort/cost: Medium-Large*
External consultants	External consultants often possess specialized knowledge and expertise in research methodologies, data collection techniques, and analysis tools. Their experience can enable them to work efficiently and effectively. However, the cost may be high. External consultants can be at a disadvantage because they are less familiar with the organization and its partnerships, but they are also likely to be able to give strong and independent opinions from outside the local system and to draw parallels with other locations or systems. *Effort/cost: Large*
Secondary methods (interpretation of pre-existing information)	
Journal articles and books	Journal articles and books contain published information about a topic. Authored by experts in the field, providing authoritative and well-researched information, peer-review ensures this information is more reliable. Often data is already analyzed and put into context. This should be a precursor to primary data collection. There may be access barriers to this information if it is behind a paywall. *Effort/cost: Small-Medium*
Documentation review	Documentation review gathers information and data by examining existing data and information from reports, records, written policies and procedures, etc., much of which can be accessed online. While relatively inexpensive, it is time-consuming to collect, review, and analyze many documents. Grey literature may not undergo the same level of peer review and quality control as traditional academic sources. *Effort/cost: Small-Medium*

Further reading: Sheppard, V., 2020: *Research Methods for the Social Sciences: An Introduction*.

The outcomes of these sessions can suggest how to structure the value chain effectively and identify areas for improvement that can be assessed in greater detail (see Chapter 3 for more on improving a warning service). An inductive and organic approach encourages participants not to assume a predefined structure but rather let the value chain emerge naturally during discussions. In workshops where discussions lack structure or facilitation is required, introducing one or more predefined value chain structures can guide the conversation, particularly when focussing on an already established warning service. Some agencies may have already mapped portions or the entirety of the relevant value chain structure, including both formal and informal partnerships.

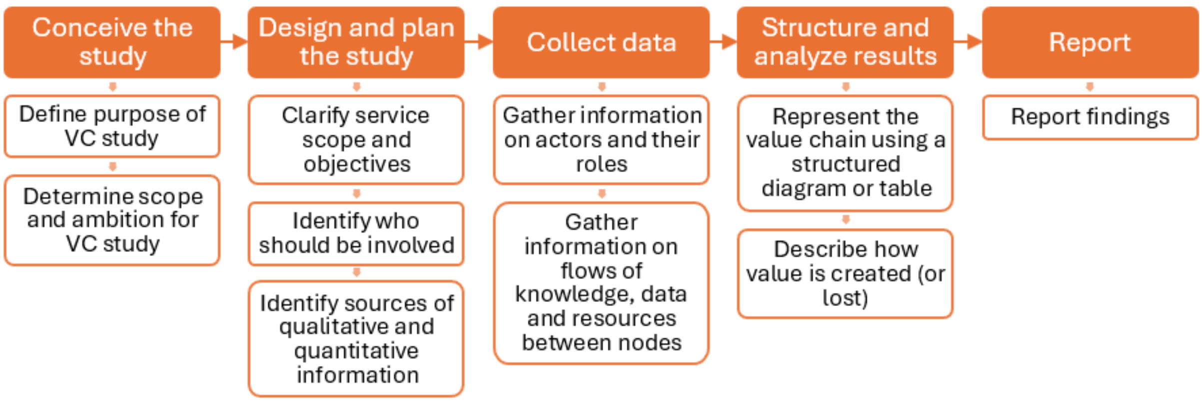
2.3 Steps for using a value chain to describe a service

The general steps for describing an existing warning service using a value chain are summarized in the diagram below. While this seems like a simple process, the complexity of the actual value ecosystem with its many nodes, actors, and flows, and the different time and space scales that it operates in, makes it challenging to capture fully. It may be useful to iterate on describing the value chain in order to resolve uncertainties and fill in missing details. The tools below offer a structured way to characterize the warning value chain in greater detail than shown by the diagrams in this chapter.

Activity: Value chain description and analysis - Participants describe a value chain for a warning service they are familiar with and analyse how information moves through the value chain to support decisions. **Annex 1**

Tool: Value Of Information Characterization and Evaluation (VOICE) framework - This organizing framework enables better understanding of how actors in an information value chain create, translate, communicate, and use weather-related information to produce value. **Chapter 4**

When describing a value chain for an early warning system it may be necessary to restrict the scope of the study to certain time and space scales, decision makers, etc., to make it more tractable. Moreover, most services evolve over time with emerging new technologies, partnerships, and data. Describing the value chain can be an iterative process involving re-evaluation and continuous improvement.



2.4 Further reading

Hoffmann, D., Ebert, E. E., Mooney, C., Golding, B., & Potter, S. (2023). Value chain approaches to evaluate the end-to-end warning chain. *Advances in Science and Research*, 20, 73–79.

Risk-informed Early Action Partnership (REAP) (2024). The Early Warning Early Action value chain. A compendium of visualisations.

3. Assess the effectiveness of a service and identify improvements

Chapter 2 showed how to use value chain approaches to describe an early warning service. This chapter shows how the value chain can be used to help understand a service, its effectiveness and where and how it might be improved.

Consideration of the effectiveness of a current service may be prompted by a service failure or a significant event, where deficiencies become apparent. Post-event analysis is common and the value chain can be a useful approach to apply in this type of analysis. In addition, there is increasing recognition of the need for continuous improvement, and this relies on evaluation of the current service to understand how it meets the needs of users. NMHSs are continuously investing in ways to detect and predict hazardous events. Making sure that these investments lead to improvement in early warning service value requires detailed analysis of the warning system. A value chain analysis can support these considerations and decisions about investments to improve value.

When considering improvements it is essential to understand the current service (that is, the baseline) and the relative potential impact of changes to it. The baseline service can be described qualitatively using approaches such as those seen in Chapter 2; economic methods for evaluating and valuing a service are considered in Chapter 4.

This chapter discusses ways to think about the societal value of an early warning service, non-economic approaches to describing its value, use of the value chain approaches to identify options for improvement, and the need for robust decision-making processes. The effort required to do this analysis will depend on the quality of information needed to decide on the improvement option(s), and may be proportional to the size of the change (and its cost). The more that is at stake, the more worthwhile it is to conduct a detailed analysis of the options.

3.1 Baselining the service

To begin to understand the benefit of a change, an organisation needs to understand the current service, how effective it is and whether it is creating the kinds of value identified in Chapter 1.

A service baseline is the level of service against which a change can be compared. This can include “no service”, a pre-existing service or the current service level. To establish the baseline some kind of evaluation will need to be undertaken. The steps required to do this are summarized in Table 3.1. The different service levels and their effectiveness can be analyzed qualitatively and quantitatively. Establishing a baseline and developing and adopting a consistent evaluation framework before, during and after a change will help to demonstrate the overall value of the service and the impacts of any change.

Data to baseline a service

The scope of the evaluation will influence the data required to baseline the service. Clearly defining the service under consideration will assist in clarifying the requirement. This can range from a particular product, such as a warning, through to a portfolio of weather services (observations, forecasting, provision of data and decision support to emergency responders) which support the early warning service. The value chain is an excellent framework for organizing the relevant data to describe the service(s).

A challenging aspect of evaluation is having the right data on which to base the assessment. If the aim is to evaluate the effectiveness of a warning in a specific case, then data relevant to that event is required. A more systemic evaluation of a portfolio of weather services for example, will require more complex data on which to base the assessment. A service baseline can be measured quantitatively or qualitatively and it can be based on both primary or secondary data sources.

Table 3.1. Steps to baseline a service

Step	***Questions***
Define the objectives of the study	What is the current situation? What needs does the service address? What are the shortcomings in the current service?
Define the scope	What is the current service (including “no service”)? Who are the current users of the service? Who needs to be involved? Who has a stake in the service?
Develop the data collection approach	Decide whether to use secondary data sources, document analysis, surveys, interviews, focus groups, observations or a combination. Undertake ethics review/seek approval. Prepare information sheets and/or interview consent forms, as required.
Check that the data collection approach is valid	Pilot test surveys and interviews, and/or do a practice run of focus group question/scenario.
Collect the data	Put in place data collection and storage systems (noting privacy requirements). Systematically record the data.
Analyze the data	Quantitative data can be statistically analysed. Qualitative data can be analysed using content or thematic analysis.
Interpret the findings	Interpret the findings in the context of the objectives of the study and the questions aiming to be answered.
Report and communicate	Prepare a report to communicate the findings with the target audience. Use appropriate language, style, graphics, and presentation.

Usually a combination of primary and secondary data will be needed to baseline a service. Primary data collection typically involves elicitation of observations, beliefs, and opinions among key informants, actors, experts, and segments of the general public. Some methods for primary data collection were discussed in Section 2.2 and these same approaches will be useful for collecting data for a baseline study. The *Warning Value Chain Questionnaire* in Annex 1 is one example of an instrument that NMHSs could utilize. By posing targeted questions, the questionnaire provides a concise yet comprehensive understanding of the warning system's performance, identifying strengths, weaknesses, and areas for improvement. This strategic tool helps reconstruct event dynamics, offering valuable insights to enhance future warning and response efforts.

Attention and careful consideration should be given to the need to collect primary data, including the potential impact on people providing information and the ways their privacy will be protected. Ethical approval may be required, and an ethical process must be followed which includes informing people why data is being collected and how it will be used and stored. NMHSs may not have the expertise internally to collect primary data using best practice methodologies - in this case getting external input is advisable.

In many cases secondary data will be very useful and is often underutilized. Secondary data sources may be used to gather facts to describe a warning system or hazard event and establish a timeline of important decisions, actions, responses; impacts, warning bulletins, hazard levels, and so on. These may include

- traditional print, audio or video media reports
- government records, databases, meeting minutes, reports, legislation, policies
- private sector records, communications (for example, press releases)
- non-government records, reports and accounts (for example, from emergency responders)
- social media accounts of events
- peer-reviewed academic literature

Some sources immediately lend themselves to quantitative analysis (for example, hospital injury records, insured loss claim data) while others require significant processing/pruning (for example, social media comments, photos, video, sound) and/or the application of other techniques (for example, content analysis) to make them suitable for such treatment.

3.2 Conceptualising value using a value chain approach

In the context of an early warning service, value is created when information/knowledge is considered and applied in decisions and actions to change outcomes that affect, are important to, and provide utility to the actor/user. Users along the value chain will value different aspects (Leviäkangas 2009). For the general public, clear actionable messaging may be of most value, while for an emergency responder a location specific forecast of a hazard may be more important.

It is important to consider the production of the warning by the NMHS and its partners and the use of that information in decision-making leading to protective action. However, the creation of value, along with any problems or issues, is very much rooted in the web of nodes and actors and the flows of information and resources that connect them. Explicitly defining, analyzing, and reflecting upon these elements are the core tasks involved in applying a value chain approach. Some nodes, actors and linkages will constrain or even degrade value, others will be essential enablers or amplifiers of benefit, and some will be neutral.

The ability of actors/users to maximize beneficial use of warning information will depend on a variety of situational and context-specific variables. However, they fall into two general categories, namely the attributes of the information, and the users’ ability to take suitable action to mitigate weather-related risks.

Attributes of warning information

The attributes of the information that contribute to its value are likely to be influenced directly by NMHSs and include:

- **Relevance** of content to recipients’ decision-making context and understandability (intended vs. actual meaning, consistency across hazards, language)
- **Accessibility** and reach of the warning
- **Precision** (social, spatial and temporal)

- **Timeliness** of initial advisory information and subsequent updates before, during and following an event
- **Accuracy** (level of error in deterministic and probabilistic guidance measured at different scales of precision, lead time, and risk levels)
- **Suitability** of content format (graphical, video, textual, audio) and delivery (for example, web, e-mail, push to phone-based apps and social media, personal communication, automated vs. tailored dynamic support)
- **Reliability** (consistency in acceptable levels of the above attributes; strength of relationship and trust among actors)
- **Validity** (the information measures what it is supposed to)

These attributes can be measured and used to assess the value of [changes in] warning systems (more on this in Chapter 4).

There is often a significant focus on the lead time, which refers to the time between the issuance of a warning and the onset of a hazard. A longer lead time can increase the range of mitigating actions that can be put in place to avoid damage. However, the trade-off of longer lead time is usually lower certainty, which may make the warning less valuable for some users.

The quality of the information is shaped, limited, or improved by the different stages of warning communication, translation, production, and use, all of which impact the overall value of the information delivered by an early warning system.

Communication of information along the warning chain can be affected by a whole range of actors and factors. The way traditional media firms—or increasingly social media channels—interpret, repackage, and share warning and related actionable information with their audiences is important. This can increase value by extending the reach of information or decrease its value by degrading its quality, relevance or actionability.

Technological advances including smartphones and other digital channels have greatly enhanced the penetration, accessibility, and productive use of weather warning services. The use of smartphone alerting and direct messaging can increase the reach and personalisation of a message. The durability of these channels in extreme weather conditions needs to be considered and backup methods for message delivery should always be in place..

Other actors and intermediaries along the warning value chain may add value to the information provided by NHMSs. For example, a response agency may provide information about relevant actions to the weather warning that will increase the relevance of information to the user by providing advice about what they should (or must) do in response to the hazard. Word of mouth is a key source of information for many people. Ensuring that information is suitable in language and content can influence message translation and dissemination and ultimately useability by a range of informal actors across the value chain.

Capacity to take mitigating action

The users' ability to take suitable actions to mitigate weather-related risks is tied to the range, type, scope, and effectiveness of actions available to them. This is influenced by the weather warning information and having effective preparedness measures in place. However, response ability also depends on the inherent vulnerability of people, places, and assets to the impacts of hazards, which are determined by their physical, social, economic and environmental circumstances. Fundamental problems of poverty, poor health status, or the lack of basic resources has an enormous impact on communities' capacity to prepare and respond to weather warnings. Personal response level is also affected by social norms or practices and many other factors.

Other elements along the warning value chain (beyond information generation) are important to the realisation of value. Physical structural options such as levees and shelters, and policy, legal, and operating procedures/protocols can enhance or detract from value. For example, advanced planning by local authorities and emergency responders will mean that resources are available to mitigate the impact of the weather hazard. On the other hand, policies that restrict or slow access to data (for example) can be bottlenecks limiting the accrual of value.

This section described how weather information can create value by being used to inform decisions and actions that mitigate the impact of a hazard. The importance of actors and information flows along the whole warning chain was touched upon. The next section proposes two approaches for analysing why the value anticipated from an early warning system is not being realised.

3.3 Assessing gaps in an early warning system

The baseline study provides important information to understand the strengths and weaknesses of the early warning system and diagnose the reasons why its full value is not being realised. It will also provide a foundation on which to consider options to improve or enhance a system regardless of any identified deficiencies.

Outcomes and indicators for an effective warning *system* differ from indicators to measure warning *performance* using a value chain. The former considers the collective elements of the warning value chain, and the social and political environment in which they operate, which together will determine the effectiveness of the early warning system. The latter assesses how the warnings performed (for example, how many warnings were issued, their timeliness, whether they reached their intended recipients, and so on) and the degree of success in reducing the losses associated with hazard events. Both approaches are valuable.

Tool: Indicators for measuring improvements - A non-exhaustive list of indicators that may be useful for measuring the effects of a change in different parts of the warning value chain.

Annex 1

Gap analysis using a warning system approach

Some excellent resources exist for assessing whether a warning system is likely to meet requirements.

- *Multi-hazard Early Warning Systems: A Checklist* (WMO 2018) presents a comprehensive checklist listing 89 key components and actions corresponding to the four elements of a people-centred multi-hazard early warning system. Case Study 3 shows how the Bureau of Meteorology in Australia used this checklist to do a thorough audit of its warning services.
- *Multi-Hazard Early Warning System Custom Indicators & Methodologies for Computation* (UNDRR 2022) to assist national agencies that are legally mandated in the multi-hazard early warning system value cycle to monitor and evaluate their early warning system and identify areas where further progress can be made. The indicators span the four areas in Figure 1.3 as well as governance, which is essential to smooth warning system operation.
- Country Hydromet Diagnostics (Alliance for Hydromet Development 2021) provide a peer-reviewed, structured way to assess a country's hydrometeorological services, spanning four

categories of enablers (governance, partnerships), observation and data processing system, service and product development and dissemination, and user and stakeholder interaction. The Hydromet Gap Reports (Alliance for Hydromet Development 2021, 2024) shows how these analyses can shed light on which areas require urgent attention.

Case Study 3: Evaluating operational warning services against the WMO Checklist

In 2019 the Australian Bureau of Meteorology undertook an audit of 57 warning products and 11 warning services to compare them against the best practice attributes of an impact forecast and warning service. The *Multi-hazard Early Warning Systems: A Checklist* (WMO 2018) guided the questions developed for the audit. The audit was undertaken by product and service owners, people from regional forecasting offices and in community outreach. Together they have a deep understanding of the services and could provide a qualitative assessment of the presence or absence of elements of the end-to-end warning system requirements described in the WMO Checklist. The resulting "heatmaps" provided a clear indication from a systems perspective of where the strengths and weaknesses of the warning services lay.

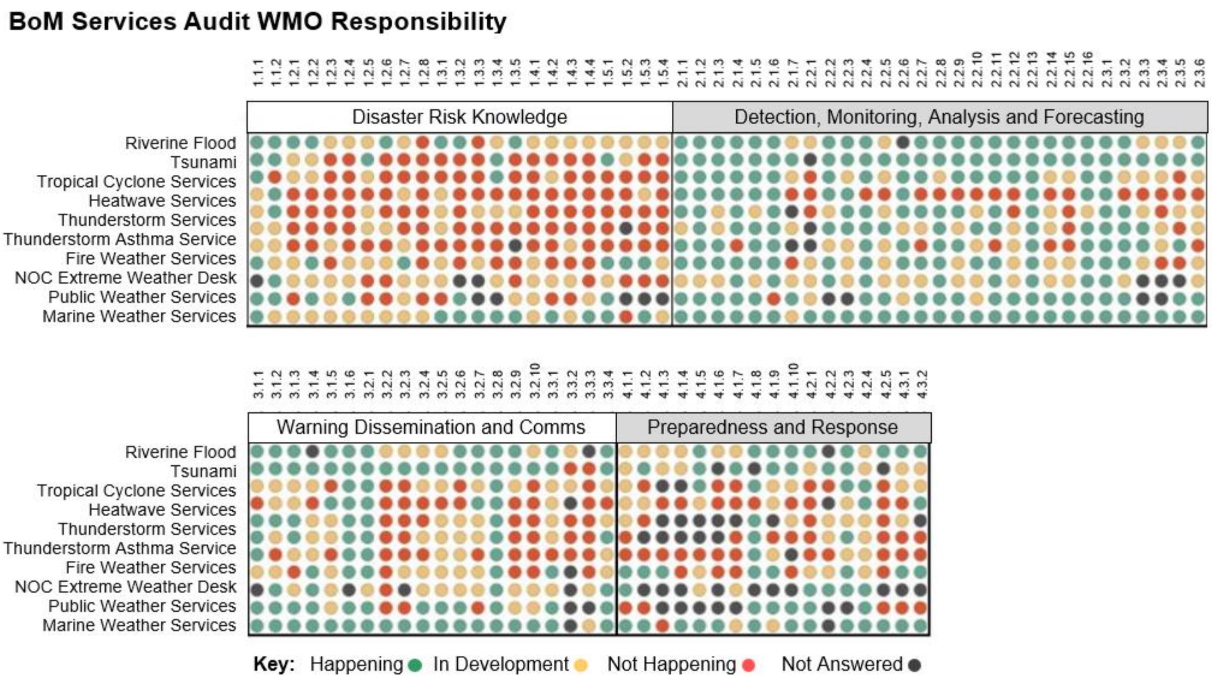


Figure 3.1. Heatmap showing strengths and weaknesses of different warning services.

Source: Bureau of Meteorology

Moraes (2023) offers an approach to assess the four pillars of an early warning system using numerical indicators based on responses of "yes", "no" or "partial" to a set of closed questions about the institutional structures, processes and working methods within each of the pillars. This objective approach enables early warning systems to be monitored and compared. Figure 3.2 illustrates many of the frequently identified gaps in multi-hazard early warning systems.

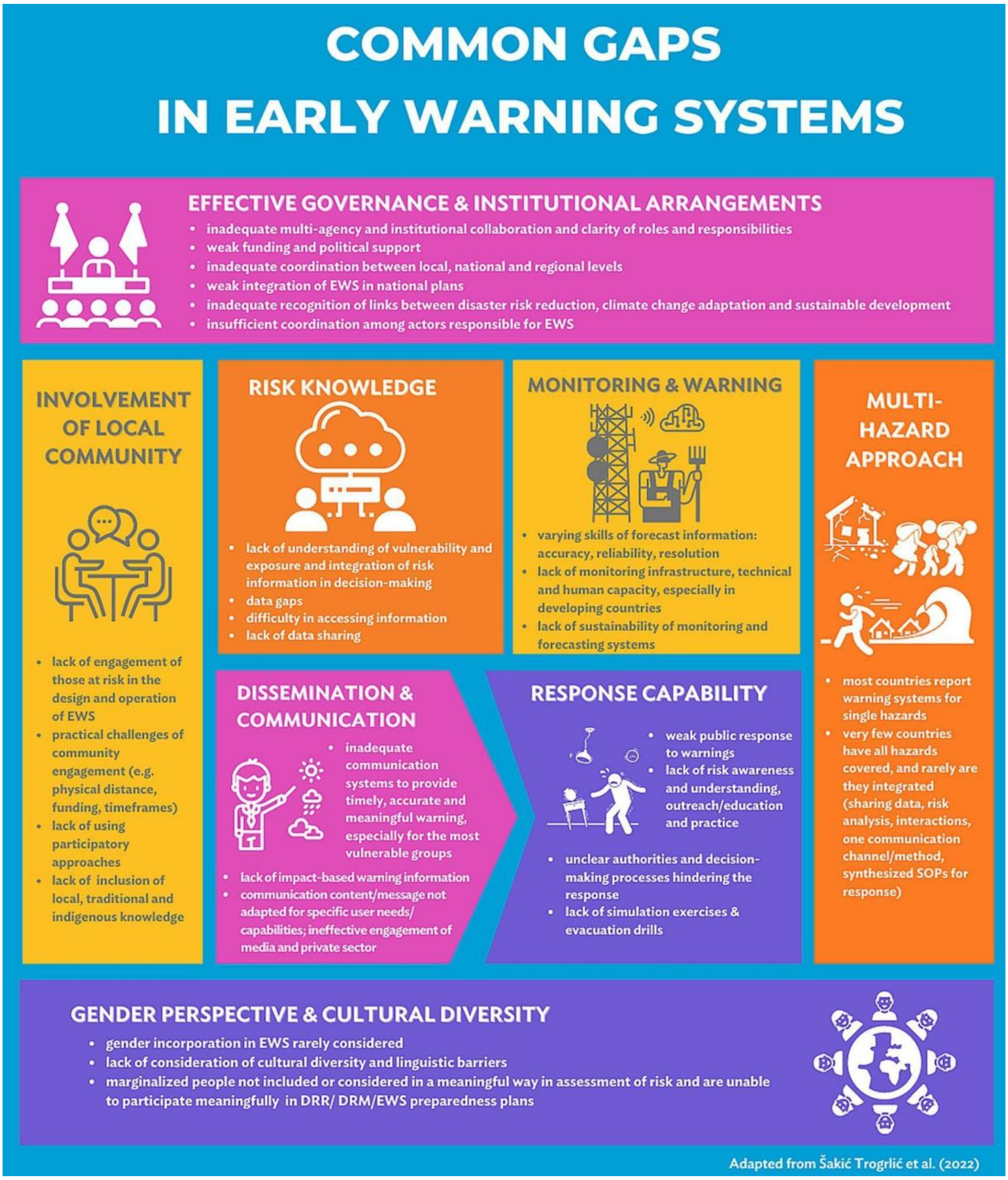


Figure 3.2. Common gaps in early warning systems

Source: Courtesy Asian Development Bank

Gap analysis using a value chain approach

The warning system approach to gap analysis described above focuses on the extent to which a warning system has all of the necessary elements to succeed. In contrast, a value chain approach to gap analysis examines the many interactions and information flows between system components, and how these work in practice to deliver benefits for users.

> **Tool: *Warning Value Chain Questionnaire*** - This comprehensive case study questionnaire supports the recording and analysis of information on the end-to-end production and flow of information and decision-making along the warning value chain during a natural hazard event.
>
> Annex 1

Issues of warning service failure or inadequacy typically appear during and immediately following acute risk events that lead to unsatisfactory social, economic or environmental outcomes. Retrospective studies are relatively common and involve looking at the past after outcomes have been realized. NMHSs and their partners often conduct post-event reviews following a major hazard event, sometimes in response to a government inquiry. These studies typically draw on secondary data sources or can be reconstructed through recall, opinion and inference. Such studies are often very descriptive in nature, with varying degrees of detail. Depending on which partner is responsible, the analysis may only cover part of the value chain and can be biased toward that partner's perspective.

Warning Value Chain Questionnaire

Forensic investigation of the warning chain for a past hazard event, or of a warning service more generally, is a useful way to understand what went wrong (or could go wrong) and identify what needs to be improved. The WWRP Value Chain Project developed a comprehensive warning value chain questionnaire for recording and analyzing information on the end-to-end production and flow of information and decision-making along the warning value chain during a natural hazard event (Hoffmann *et al.* 2023, Ebert *et al.* 2024). An accompanying guide provides detailed descriptions of the information requested in the questionnaire for high impact natural hazard events.

Figure 3.3 shows the structure of the *Warning Value Chain Questionnaire*. The essential information section collects brief facts about the event, providing an overview and enabling easy comparison with other events that also used the questionnaire. The second section collects more detailed information to help understand what was unique about the warning chain for the event. This includes examples of observations, forecasts, and forecast performance for weather, hazards, and impacts; what warning information was communicated, and to whom; warning response and its effectiveness. Importantly, the questionnaire assists the user to analyze the production, flow, and use of different kinds of information in the warning value chain, enabling successes and gaps to be characterized. A final subjective evaluation section allows the team or individual completing the questionnaire to assign an effectiveness rating to each node in the warning value chain, and its overall effectiveness. This assessment should not be used for quantitative analysis due to potential biases of the assessors, but rather in a *relative* sense to identify which nodes in a particular warning value chain performed better and worse.

A compact *Rapid Assessment Template* is also available for collecting and displaying data for warning value chain case studies. This slide template can help with early post-event analysis where there is not time to complete a full questionnaire, and for storing perishable and/or key information until a time comes to complete a full questionnaire.

The *Warning Value Chain Questionnaire*, guide, and *Rapid Assessment Template* can be freely downloaded from https://zenodo.org/records/10457434. The WWRP Value Chain project is creating an online database of warning case studies that will be freely available to researchers and practitioners. An extract from a completed questionnaire is shown in Figure 3.4 (Neal and Titley 2024). Neal (2024) provides an example of a rapid assessment for a surface water flooding event in the UK in 2022.

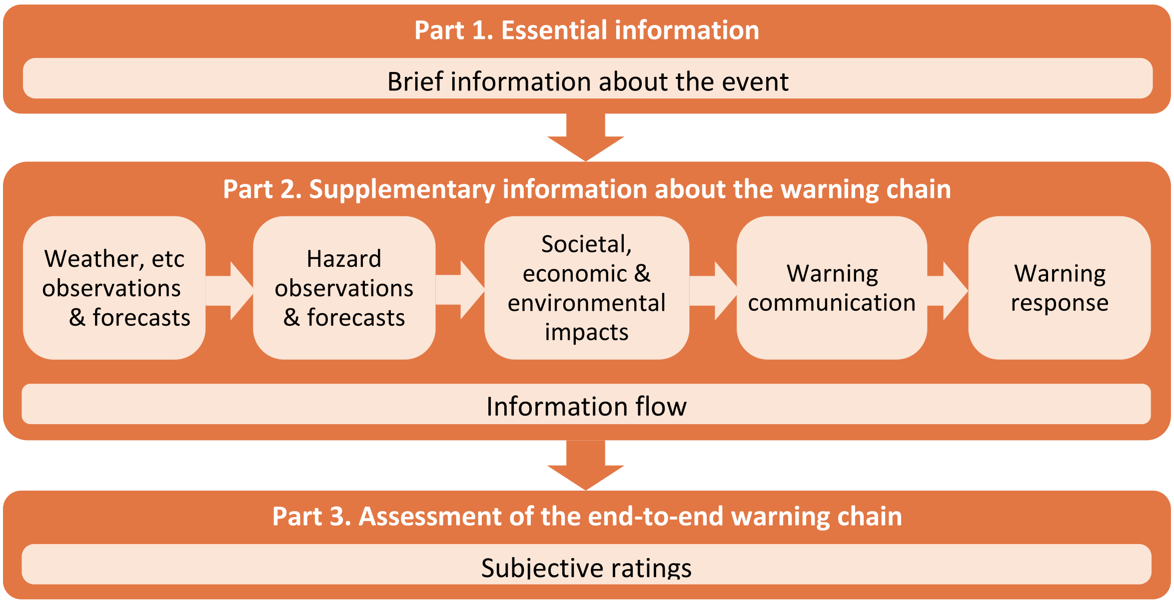


Figure 3.3. Information collected in the Warning Value Chain Questionnaire

Studies also may be comparative across different hazard, socio-cultural, institutional, spatial and temporal contexts, as done in Case Study 4. Annex 3 lists several studies that apply value chain approaches to analyze warnings for natural hazard events.

Case Study 4: Comparison of warning value chains for extreme events

Comparative studies can help with identifying problems and their sources. Golding *et al.* (2023) used the *Warning Value Chain Questionnaire* (Annex 1) to investigate and compare the warning value chains and their outcomes for eight extreme events that occurred in 2021. Common themes that emerged included

- inadequate forewarning of the magnitude of the event,
- lack of preparedness for the extremity of the event,
- communication failures,
- lack of recognition of impact on vulnerable groups, leading to loss of life.

By analysing the set of events they were able to recommend a number of improvements, starting at the community side of the warning chain, to enhance warning effectiveness:

- Help communities understand their vulnerability to extremes beyond those experienced.
- Plan for the reasonable worst case but have a backup plan for the unreasonable case.
- Involve communities in designing the warning system so that they understand and trust the advice.
- Use the best available forecasts to provide reliable information.
- Forecast potential impacts early, to inform early actions, even when the probability is very low.
- Communicate possible impacts and responses early, while being open about uncertainty.
- Monitor responses to early warnings and reinforce messaging when needed.
- Strengthen partnerships to facilitate effective early actions.

Use of a common approach to evaluate the warning value chains for different hazard events made it easier to draw conclusions about common problems and better practices.

Figure 36. A screen shot from the BBC One 6 O'clock national news, which had the headline running with the story about the recent issuance of the first red weather warning. Here the new presenter is showing the weather warning map. Source: BBC/YouTube (https://www.youtube.com/watch?v=fwu8PmdGCS8).

Comment on the use of uncertainty information in the warning i

Forecast uncertainty is given by the position of the weather warning within the weather impact matrix. The first warning (issued at a 4-day lead time) described the warning as a 'low likelihood of high impacts'. The likelihood level associated with subsequent warnings gradually increased, with the first amber warning issued at a 2-day lead time being described as having a 'medium likelihood of high impacts'. The final red warnings were then described as having a 'high likelihood of high impacts' and were positioned in the top-right hand corner of the matrix. The likelihood and impact levels are subjectively derived by the Met Office chief meteorologists on shift at the time following detailed analysis of the NWP output and specialised forecasting tools shown in this questionnaire. Chief meteorologists will also discuss optimal warning levels (with regards to likelihood and impacts) with Met Office regional civil contingency advisors as previously discussed in this questionnaire.

To what extent were communication systems in place and operating effectively? i

No issues were reported, and the cascade of information worked smoothly using well established channels. Various teams around the Met Office immediately swung into action to inform stakeholders and keep them updated with the latest information and data. The stakeholders are wide ranging and include UK Government, as well as the Governments in Scotland, Wales and Northern Ireland, the Environment Agency, Scottish Environment Protection Agency, local authorities and emergency services across the country, energy providers, road and rail operators, the Civil Aviation Authority, National Air Traffic Service, and airports including Heathrow. Not least of these were the Met Office civil contingency advisors whose efforts helped to mitigate the impacts of the storm in their various regions.

Figure 3.4. Extract from the completed Warning Value Chain Questionnaire for Storm Eunice (2022)

Source: Neal and Titley (2024)

Multi-Hazard Early Warning System Value Chain Vulnerability Matrix

Applying a value chain vulnerability assessment across multiple hazards within a national or regional warning responsibility can highlight the areas in greatest need of attention. This matrix approach supports a high-level assessment of the vulnerabilities of a multi-hazard early warning system. Table 3.2 draws from the experiences of doing such an assessment for a small island developing state (A. Tupper, 2024, personal communication).

The concept is to get a strategic view of multi-hazard system vulnerabilities (places where the system may fail) on a single page, using analysis drawn from case studies (including formal value chain assessments) and example scenarios for reasonable worst cases for the rarer (but high impact) hazards. Including these reasonable worst cases is a way of addressing “hazard bias” towards building warning systems for recent impactful events, rather than what may be just around the corner.

The process starts by evaluating the natural hazards of most concern (possibly using agreed reasonable worst case scenarios) and listing them in priority order. Then the current state of each major capability (the “mountains” of the value chain in Figure 2.3) in the early warning systems are examined for each hazard. Colour shadings are assigned based on the degree of concern. A “red” assessment would indicate a major risk of warning system element failure in the scenario described, and a consequent risk to the effectiveness of early warnings. This approach can then be combined with value-tree analysis or other techniques to consider the impact of different interventions and whether they would be sufficient to lower the level of concern (and for what hazards - seismic observations, for example, are necessary for volcanic monitoring and earthquakes but not useful for hydrometeorology).

Table 3.2. Multi-hazard early warning system value chain vulnerability matrix for a small island developing state

Hazard	Observations	Weather / Phenomenon Forecast	Hazard Forecast	Impact Forecast	Warning	Decision
Cyclone (Extreme risk)	Limited observations (obs) exchange and limited marine obs. No upper air obs. No weather radar.	Global weather models available but not receiving obs. No convection-resolving modelling for fine detail.	Specific wind, rainfall, storm surge info could be improved through better modelling and observations, allowing more specific warnings.	Vulnerable communities largely known and extensive preparation work. Impact forecasting ready to implement.	XXX site is subject to storm surge. Strong social media presence. Limited App Support. No Common Alerting Protocol, limited text messages. Warning dissemination systems unreliable.	Public aware and engaged. Cyclone warnings can be complex with multiple simultaneous hazards.
Volcanic eruption (Extreme risk)	Seismic network partially effective but needs finer resolution. No deployable volcanic monitoring gear.	Little local capacity or expertise on met department staff for volcanic process modelling and knowledge.	Little local capacity to predict and provide information on hazards.	Vulnerabilities largely understood but location of next eruption not known. No impact forecasting	Potential for panic in the face of uncertainty and traditional knowledge from previous eruptions.	There is no current information flow from met department on volcanic information in the region, meaning a large ‘spin-up’ when activity commences.

Tsunami **(Extreme risk)**	Staffing at critical levels. Limited monitoring network. Limited access to official network. Volcanic tsunami – poor information flow for siren activation decision. Potential for over-warning.	No local modelling – focus is on quick assessment and response. Regional and distant tsunami can use advice from Pacific Tsunami Warning Centre.	Broad brush advisory products from Pacific Tsunami Warning Center, likely unavailable until after major event due proximity of trench.	Vulnerable communities largely known and prepared. Regular tsunami exercises. Siren network still developing. No impact forecasting.	Extremely rapid warning required for local events. Ability to trigger sirens for south coast (most at risk). Challenging deadlines for issuance of warnings before site evacuation.	Public aware and engaged following YYYY event and community training. Short warning time means public response will always be challenging, particularly for most vulnerable.
Flood **(High risk)**	Good gauge and rainfall network, especially for xxx basin. Could be expanded to other catchments but sustainability of maintenance is an issue. Limited analysis tools. No radar. Obs not available to public.	Models do not resolve rainfall well. 3 km WRF model used for predictions, but not an 'operational' class model. Flash floods not part of system.	Fast response catchments require simple approach to flood warning. More accurate rainfall predictions will help develop scenarios ahead of events.	Vulnerable communities largely known and extensive preparation work. Impact forecasting ready to implement.	Joint agency SOPs appear unclear. No flash flood warnings. Fire & Emergency Services have expressed a need for greater real-time communication for general situational awareness.	Sirens have been tested, but community standards and procedures need to be put in place around siren activation and flooding response.
Earthquake **(High risk)**	Staffing at critical levels. Limited seismic network. Limited real-time access to data from other countries.	Real-time forecasts not possible at moment (monitor 'shake alert' progress).	Real-time hazard forecasts not possible – key is preparation, building codes, community education.	General impact information could be included in earthquake alerts.	Real-time information communication is limited, which may increase community concern.	Community is aware of earthquake risks and actions to take during an event, with community education initiatives.
Landslide **(High risk)**	Reasonable rainfall network, particularly in Upolu.	Rainfall forecasts limited in skill	Landslide risk areas broadly known	Real-time landslide forecasting not feasible without more specific info.	No real-time communication, but landslide risk mentioned in rainfall and tropical cyclone bulletins	Community are aware of landslide risks. Limited procedures around precautionary actions.
Forest Fire **(High risk)**	Limited real-time intelligence. Forest fires could be observed by satellite hotspot – capability not yet implemented.	Forecast of fire spread is feasible but not currently implemented.	No real-time operational procedures around fire management.	Forecast of fire impacts is feasible.	Fire & Emergency Services have expressed a need for greater real-time communication for general situational awareness	Limited community fire response procedures.

While the emphasis in this stage is on diagnosing the problem, retrospective studies may also be employed to explain relationships among variables and outcomes in qualitative or quantitative methods (for example, correlational, quasi-experimental studies such as Case Study 5 which relates impacts of hazardous winter weather to warnings). Doing this sometimes results in new and interesting characterizations of problems not apparent in purely descriptive accounts. However, for rare events (such as an extreme solar storm, tsunamis, or volcanic eruptions), retrospective studies will be unlikely to capture the worst reasonable scenarios. To address this, representative scenarios using, for example, downward counterfactual analysis (Woo 2019) can be developed to explore potential weaknesses in the warning system, and can also be tested through warning simulations.

In some instances, concern may relate to a real or perceived unwarranted amount of response effort and expense if the risk event has not occurred as expected (unnecessary evacuation order, school/business closures, etc.). On the other hand, successes typically go unseen and receive much less attention unless exceptional avoidance of loss has been achieved, or when contrasted by failures in neighbouring regions. This is unfortunate as these situations offer an equal and underutilized learning opportunity and therefore should not be overlooked when identifying "problem" cases to investigate and apply value chain concepts (Podloski and Kelman 2023).

3.4 Developing the improvement options

The gap analysis of the early warning system using systems and value chain approaches described above will have identified where and how the service is not meeting the needs of users. The next step is to identify and describe a set of improvement options before deciding which, among the possibilities identified, to invest in.

Typically, improvements tend to focus on particular nodes of the service chain, for example, the observing systems or the forecast models. While improvements in certain capabilities or nodes may lead to improved warning outcomes, often the full benefit is not realized due to weaknesses in other parts of the chain. For example, if information is not being exchanged in a timely or effective manner, then more accurate forecasts may be less beneficial than improving the infrastructure, knowledge and partnerships that would enhance the flow of information. Considering the whole value chain is essential when deciding on system changes or other interventions.

Activity: Information exchange - This group activity uses paired discussions between actors across the value chain to explore the effectiveness of their information exchanges.

Annex 1

A **theory of change** describes how and why an intervention of some kind is expected to lead to an outcome. In developing improvement options it is important to interrogate underlying assumptions about how a change will flow through a system and lead to increased value. For example, a fundamental assumption often made about early warning systems is that the issue of warnings about a hazard will lead to people/communities/organisations taking action to mitigate the potential impact. However, as discussed earlier, if a person has little or no capacity to act in response to a warning the information has limited or no value to them. A theory of change helps build a systematic understanding of the relationships between different elements in the warning system and the underlying assumptions about what leads to its effectiveness.

Case Study 5: Weather-related injury risk analysis

Winter storms present challenges to the mobility of Canadians and the transportation systems upon which they depend for safe, orderly, and reliable travel. The public and private sector invest significant amounts to minimize these hazards, maintain safety, and limit disruptions.

Mills *et al.* (2019, 2020) conducted longitudinal analyses of the relative risk[1] of motor vehicle collisions (2002-16) and fall-related injuries (2009-2017) for a mid-sized city region (~620,000) in Ontario, Canada. Radar imagery and complementary surface station data were used to define 196 winter storm events and corresponding control periods that were free of hazardous weather and matched to the same hour and weekday, either one week earlier or one week later than the storm event. Injury counts for the event-control pairs were tabulated using regional road collision data derived from police reports and hospital emergency department visitation data. Event-control pairs were statistically analyzed to estimate relative risk, assess temporal trends, and examine the influence of storm attributes and government-issued weather warnings.

The two studies found that winter storms were associated with significant increases in the relative risk of motor vehicle collisions and fall-related injuries, with higher relative risk for storms involving freezing rain. Absolute injury risks from falls were over 60 percent greater than observed for motor vehicle collisions. Much higher relative risk occurred during the shoulder months at the beginning and end of the winter season. The relative risk decreased over the study period. Interestingly, no statistically significant differences were found in relative risk between warned and unwarned events; however, over half of all impactful (where relative risk > 1) events went unwarned.

When viewed through the lens of the information value chain, the findings suggest that it is important to consider a wide range of possible risk outcomes (for example, the significance of falls in overall weather-related mobility risks). They hint at complex interactions between weather warnings, vulnerability, exposure, and response behaviour operating at different temporal scales. To further understand these relationships and accurately attribute the effects of warning information, alternative qualitative and quantitative research designs would be needed.

[1] A relative risk value greater than 1 indicates that more injuries occurred during events than controls. For example, a relative risk of 1.61 means that 61 percent more injuries occurred across all of the winter storm events than corresponding controls.

One fundamental aspect of the theory of change methodology involves documenting the actors involved in the warning system and understanding the processes through which the service is expected to affect outcomes. The value chain concept is highly relevant to this type of analysis. For existing early warning systems it is useful to undertake stakeholder analysis and consider whether all relevant actors are involved in the process of design, review and delivery. The range of actors from meteorologists through to neighbours who communicate messages by word of mouth will have different roles across the value chain. Stakeholder consultations, workshops, and iterative feedback loops can be used to develop and refine the theory of change (see Chapter 2).

Global Evaluation Initiative (2022) offers useful advice and tools for using theory of change methodologies. For example, a logic model can be a useful tool to help visualise the inputs, activities, outputs, outcomes, and impacts of a planned intervention. By referring to the value chain, it is possible to see the downstream influences of a change and identify any issues (for example, through simulation). Case Study 6 demonstrates a complex analysis using cognitive mapping linking warning effectiveness to improvements which underpin a theory of change for increasing warning effectiveness.

Tool: Logic model - A concise visual representation that outlines the inputs (resources), activities (what is done), outputs (immediate results), outcomes (short and long-term changes), and impacts (broader societal changes) of a program or planned intervention.

Annex 1

3.5 Selecting an improvement option

If many parts of the early warning system need improvement, it may not be possible to tackle them all. Deciding between various options requires a systematic and strategic approach, ideally involving the main actors in the value chain, to choose options that will deliver the most beneficial impacts.

Making a decision on the best option(s) for improving an early warning system entails considering several criteria. The first and most important is whether a proposed change would meet the needs of the users to achieve the goal of early warnings. The value chain concept helps to broaden thinking to include both technical solutions such as increasing monitoring or enhancing numerical modelling, to administrative or communication options. Service providers can directly target those parts of the warning value chain within their influence, applying the value-relevant criteria of relevance, accessibility, precision, timeliness, accuracy, suitability, reliability and validity (see Section 3.2).

Other important criteria to evaluate when deciding on improvements include feasibility, cost, robustness, scalability, sustainability, and availability of human resources. These are considered in greater detail in the next two chapters.

The effort (and resource) to make the decision should reflect the size or expense of the intervention. For making an incremental change, one might use a decision matrix (possibly weighting the criteria) or benchmark against other similar services to identify the likely optimal change. For major changes involving substantial investment (and often greater complexity and risk), more comprehensive decision analysis approaches such as cost-benefit analysis and multi-criteria analysis should be used. These evaluation approaches are described in Chapter 4 on valuing service improvements. Decision analysis tools and value chain approaches have much in common since they both systematically evaluate complex processes and support informed decision-making. Both quantitative and qualitative approaches (mixed methods) may be needed. Pilot projects and prototypes may also be helpful.

Case Study 6: Dynamic modelling of an early warning system

Researchers at CEMADEN (National Early Warning and Monitoring Centre of Natural Disasters) in Brazil used a systems dynamics approach to investigate factors that may increase the effectiveness of early warning systems (da Silva *et al.* 2020). Based on interviews with experts, they identified 95 concepts related to warning production, warning system improvements, and value generation and produced a cognitive map linking the concepts to the ultimate outcome of increasing warning effectiveness (Figure 3.5).

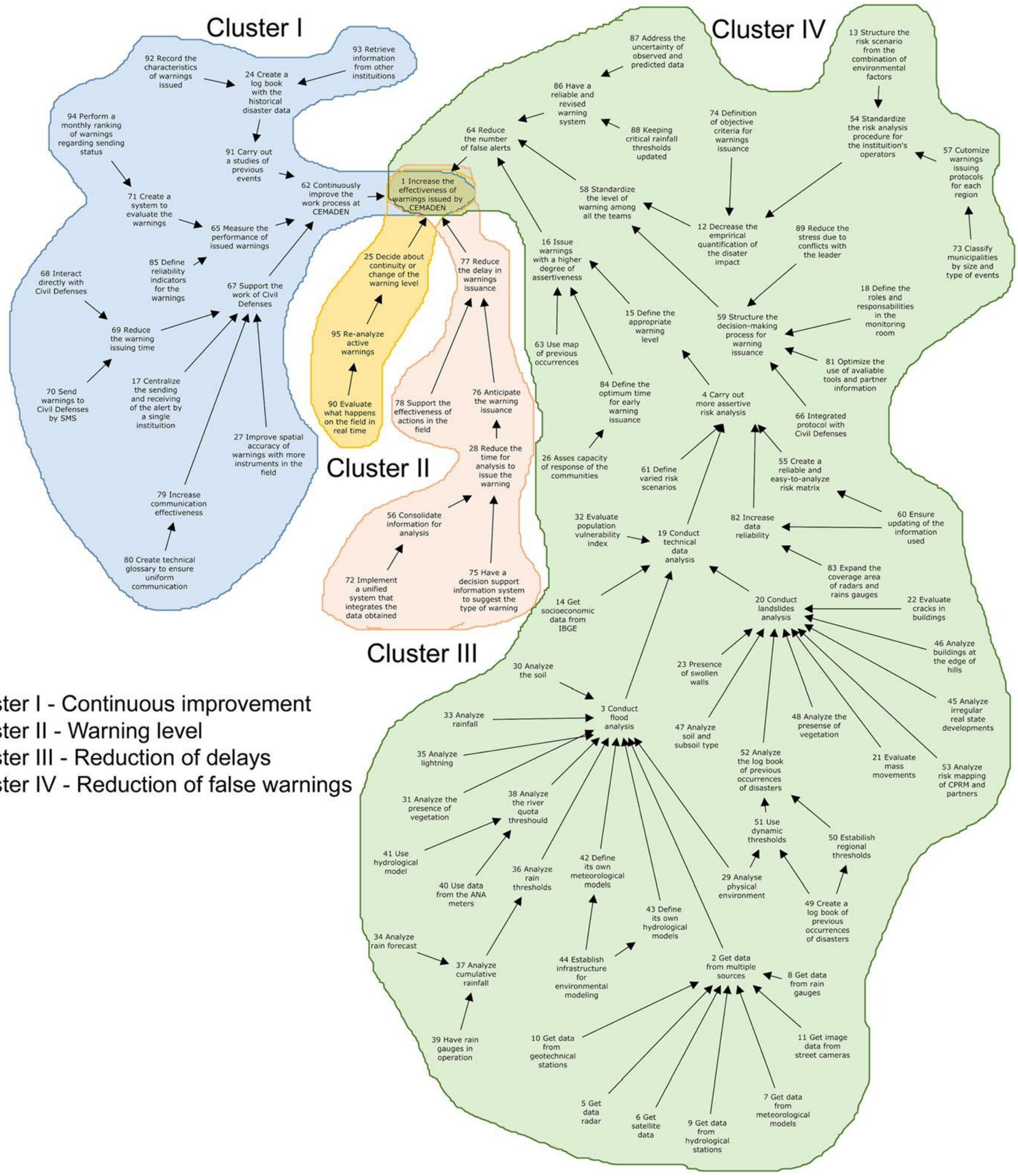


Figure 3.5. Cognitive map linking concepts for improving the effectiveness of CEMADEN's warnings

Using graph analysis, the overall problem structure from the cognitive map was used to develop a qualitative system dynamics model in the form of a causal loop diagram (Figure 3.6) to explore the effects of proposed improvements on other parts of the value chain and ultimately the warning effectiveness.

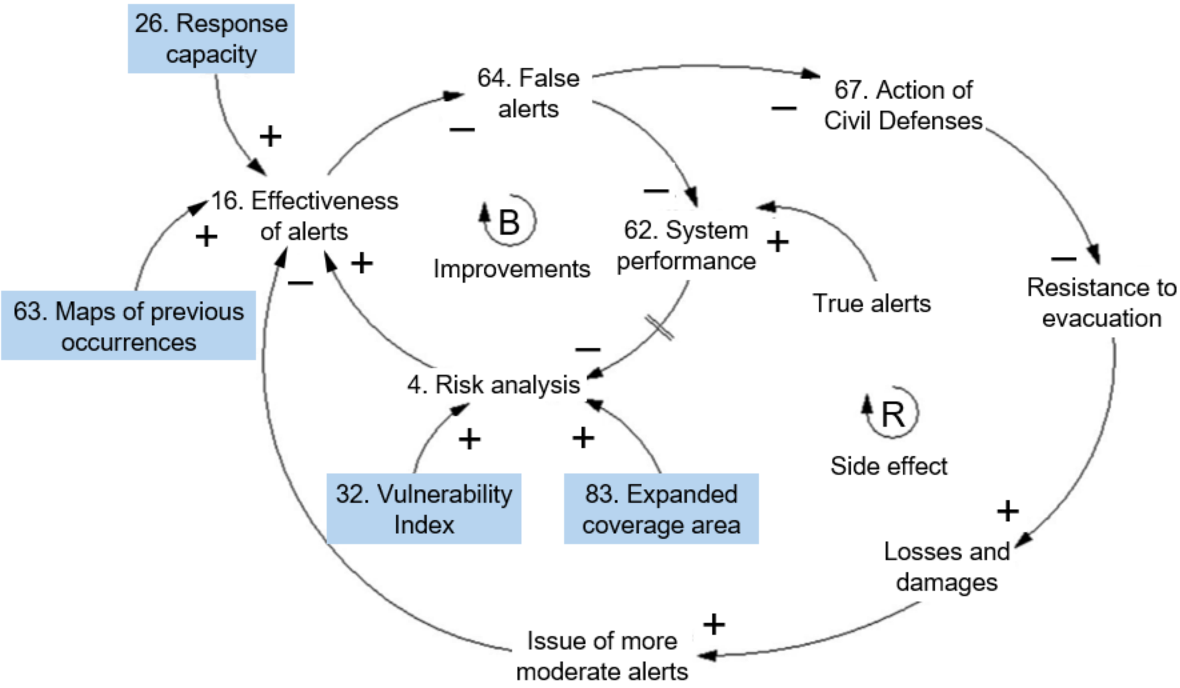


Figure 3.6. System dynamics model showing how proposed improvements (blue boxes) could improve the warning system effectiveness, taking into account feedback loops related to false alerts

The analysis revealed that implementing strategies to improve the warning system and strengthen the risk analysis would ultimately reduce the number of false alerts (warnings that did not eventuate in hazards). This balance loop "B" works to overcome the reinforcement loop "R" connecting an increase in false alerts with decreased confidence of the population and greater resistance to evacuation, resulting in more damage and deaths and a greater propensity to issue alerts. Because the improvements take time to implement, their beneficial effect is delayed.

Evaluating in advance the likely benefits of a proposed improvement (to support making the right choice) requires having some idea of the relative magnitudes of the benefits and how they should be measured. In practice, this is an iterative process where the first round of decisions is often based on rather crude information. For incremental improvements, this may be all that is required. For larger investment decisions, as the options are filtered and refined it becomes necessary to weigh up more carefully the economic, social and environmental implications of the proposed improvement options in order to make a well-informed choice. The effort involved in doing that more detailed assessment can go a long way toward establishing an evaluation framework for assessing the actual benefit of the change.

A theory of change is also useful for defining the results framework (that is, the monitoring and evaluation) of activities and investments necessary to effect the change. This is true whether it be a small, localized initiative or a large, complex program. An example of the latter is the theory of change that was developed to support the EW4All initiative (Figure 3.7; WMO 2023). Its progress is tracked on the Early Warnings for All Dashboard (https://earlywarningsforall.org/site/early-warnings-all/early-warnings-all-dashboard), helping to inform decision-making and measure success.

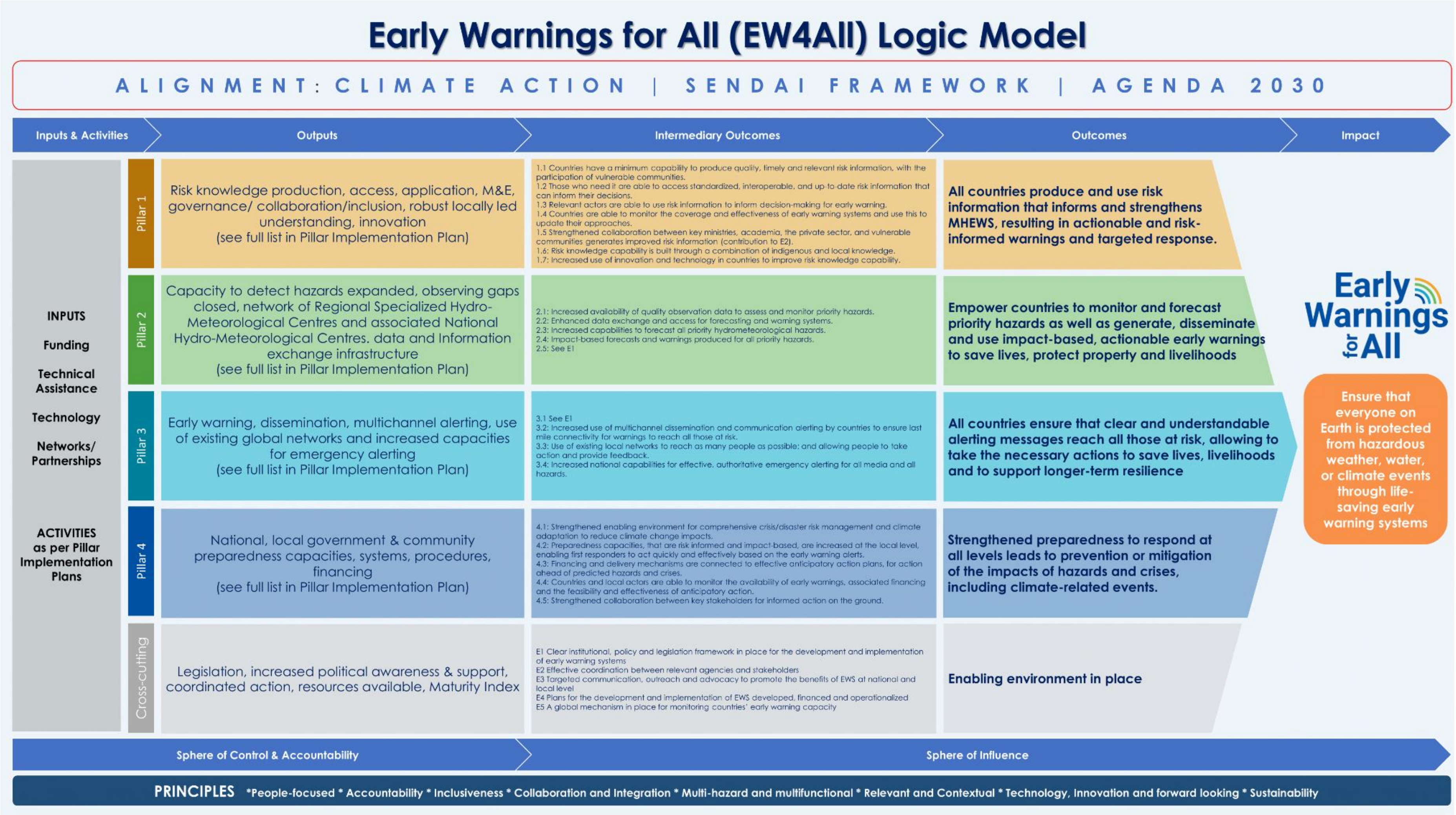


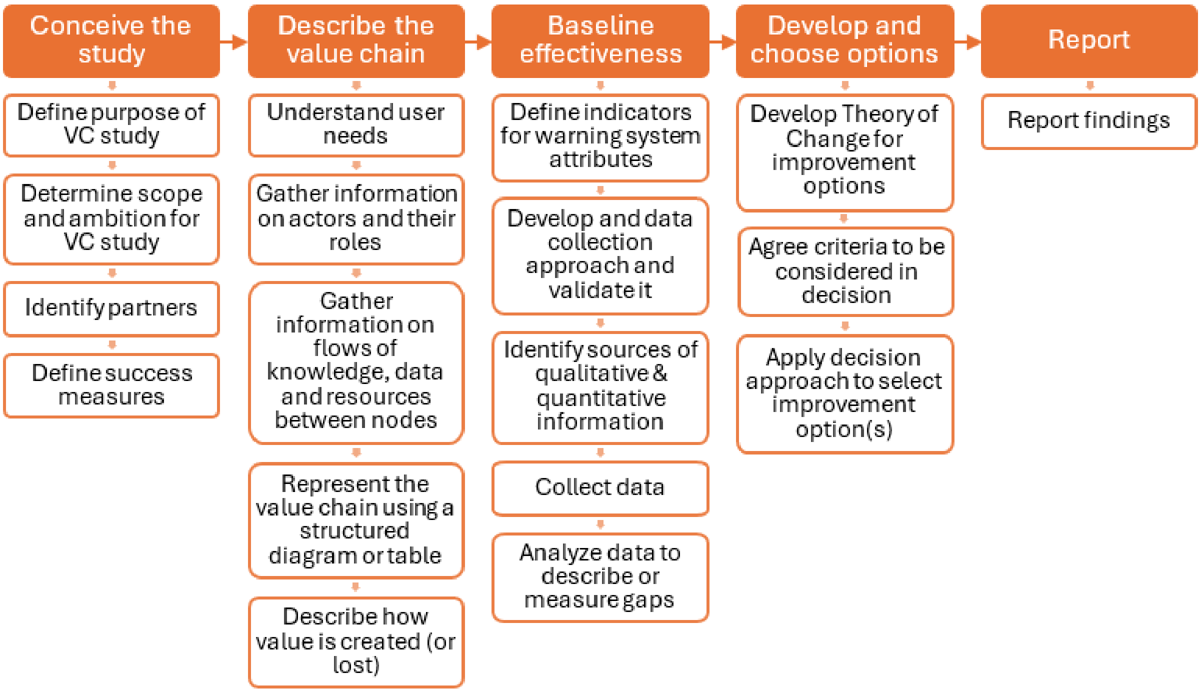
Figure 3.7. Theory of change for the Early Warnings for All initiative

Source: WMO (2023)

3.6 Steps for using a value chain to improve a service

The steps for improving an existing early warning service begin with describing the service and baselining its performance. While measuring the inputs and outputs of a warning system is important, it is also crucial to measure the outcomes and benefits to understand how effective the warning system is in providing value to users. The focus then becomes identifying gaps that reduce the value of the warning and what changes could be considered to improve the warning system effectiveness.

When the whole warning value chain is considered, there are usually multiple options for interventions and improvements that could enhance the value of the warning system. To make the best choice(s) requires systematically considering the options, their feasibility and likely effectiveness, and then applying an appropriate decision approach.



3.7 Further reading

Garcia, C., & Fearnley, C. J. (2012). Evaluating critical links in early warning systems for natural hazards. *Environmental Hazards*, 11, 123–137.

Rogers, D.P., Tsirkunov, V.V., Kootval, H., Soares, A., Kull, D.W., Bogdanova, A.-M. & Suwa, M. (2019). *Weathering the change: How to improve hydrometeorological services in developing countries?* Washington, DC: World Bank.

Šakić Trogrlić, R., van den Homberg, M., Budimir, M., McQuistan, C., Sneddon, A. and Golding, B. (2022). Early warning systems and their role in disaster risk reduction. In *Towards the "Perfect"*

Weather Warning: Bridging Disciplinary Gaps through Partnership and Communication (pp. 11-46). Cham: Springer International Publishing.

4. Valuation of improvements in a service

Chapter 3 discussed the baselining of a service to assess its effectiveness, and the identification and selection of options for making improvements. When significant investments or extra operational costs are involved, or the components of the value chain are significantly modified, it is worthwhile to assess the net socioeconomic benefits of the planned or achieved improvements. This chapter introduces evaluation approaches and valuation methods for quantifying the value of warning service improvements based on information about the reductions in losses and damages. It also describes two evaluation approaches specifically designed for value chain analysis, namely the Value of Information Characterization and Evaluation (VOICE; Lazo and Mills 2021) and Weather Service Chain Analysis (WSCA; Perrels *et al.* 2012).

The methodologies described here apply both to estimating the value of considered or planned changes beforehand (*ex ante*), often as part of a decision process considering various improvement options, and assessing the value of implemented changes (*ex post*). While "valuation" often connotes economic value, it can also encompass social and environmental value as discussed in earlier chapters. A more complete description of socioeconomic evaluation approaches and valuation methods can be found – among others – in the book, *Valuing Weather and Climate: Economic Assessment of Meteorological and Hydrological Services* (WMO *et al.* 2015)[1].

The purpose of the valuation guides the selection of the appropriate methodology. The valuation team and/or experts must answer questions like:

- Do we wish to assess the value of the warning service as a whole, or does it suffice to focus on certain segments?
- Do we wish to measure the contribution of a *particular* investment or improvement within a specific segment of the value chain to an increase in the overall benefit?
- Do we seek to understand how an investment or enhancement in a specific segment of the value chain propagates value throughout the chain, achieving desired outcomes further downstream?

Depending on the methods used and the level of detail in outcome data (such as reported damages and the number of people responding to warning information), the analysis underpinning the valuation can show how different factors contribute to the realized value. For example, forecast accuracy is essential for creating value from warnings. However, once forecast accuracy reaches a high level, other factors like information accessibility and comprehensibility become more critical for further enhancing the benefits. This does not imply that efforts to improve forecast accuracy should be neglected, but rather that a greater portion of the R&D budget should be allocated to improving these other factors to maximize the return on investment in warning system improvements.

By measuring how interventions (changes) in one or more parts of the value chain affect the quality and flow of information elsewhere in the value chain, and the warning outcomes, the propagation of the value through the system can be evaluated. Since value chains are imperfect representations of complex systems, understanding the sources and magnitude of uncertainty in the valuation results is a crucial aspect of interpreting the results.

[1] This book is freely available online at https://sdgs.un.org/publications/valuing-weather-and-climate-economic-assessment-meteorological-and-hydrological.

Socioeconomic evaluation of existing or proposed weather services aids decision-making within NMHSs and their partner organizations, as well as key external stakeholders such as ministries and development banks that provide funding or regulatory oversight. In the early planning phases, a superficial scan may suffice and can be conducted with limited external professional support. However, in more advanced planning phases, it is essential to ensure adequate socioeconomic evaluation expertise. Regardless of the degree of outsourcing for the evaluation, this chapter offers insights on what to expect from such evaluations, depending on the scope and type of evaluation.

4.1 Socioeconomic valuation

To be able to assess the value of a new or improved service the outcomes must be compared with the outcomes in the baseline or counterfactual situation. The warning outcomes are preferably not only expressed in terms of warning output (number of warnings, timeliness, false alarm rate, and so on), but also in terms of their intended outcomes, such as avoided damage and avoided casualties, if these can be estimated (see Table A1 in Annex 1 for a more comprehensive list of indicators for early warning systems).

The differential between outcomes of the baseline and of the new service is the basis for the value creation. The baseline can be dynamic, that is, there may be changes in exposure (population), vulnerability, resilience levels, as well as the evolving nature of hazards due to climate change, and these needs to be accounted for in the analysis.

Socioeconomic valuation, as a concept, comprises two levels: the overall evaluation approach and the specific methods applied within that approach. Specifically,

> **Evaluation approach** - the overall framework or approach chosen to infer the value (monetized or otherwise appraised). Its structure and logic are based on a concept of how value should be rated, aggregated and prioritised. Different evaluation approaches answer different questions about the value.
>
> **Valuation method** - an analytical protocol for estimating the value of a product, service, assets, or outcome. Valuation methods are tools used to infer the value emanating from particular value propagation mechanisms, often regardless of the evaluation approach. Different valuation methods are applicable to different market/ non-market conditions and different types and availability of data.

In short, evaluation approaches (frameworks) provide the structure for a socioeconomic valuation study; valuation methods are applied within the evaluation approach. More detail on these is provided later in this section.

To make it easier to compare different improvement options with each other and with the baseline, it is desirable to “synthesise” the value, that is, to express the various impacts and benefits in a unified form, often represented in monetary terms or other commonly understood units such as quality-adjusted life years. This can be particularly important when the resourcing of the development and implementation of a new or improved service is competing with other propositions for the same resources. It is also relevant when comparing service performance between regions or countries. Public health and safety indicators also allow monetization (for example, statistical value of a life). However, ethical concerns and uncertainties must be considered when aiming to monetize any potential outcomes.

While quantification is valuable for analysis, it may overlook some of the nuanced, non-tradeable intrinsic values associated with the service. Other factors like societal impact and well-being, safety enhancement, and reductions in morbidity and mortality rates may be adequate for capturing and representing the actual value of service improvements, aligning with the service's mandate and broader social goals (Hallegatte *et al.* 2017).

The role of equity emerges as a crucial factor in determining what warning services to provide and how broadly they should be offered. This consideration of vulnerable groups ties into the discussion of service co-design in Chapter 5. Early warning services are generally treated as public goods, meaning they are free and accessible to all citizens, companies, and organizations within a country. However, with the rapid growth of innovations in observation and communication technologies, there may be an increasing number of additional services that are not fully public.

The target audience, and the available time and resources, influence the scope and level of ambition for the study. Evaluating the benefit of warning system improvements in terms of reduction of human losses and material damage may suffice for formal decision-making regarding its implementation, especially if these improvements do not require significant amounts of (extra) resources and/or notable changes in the make-up of the value chain. For instance, measuring improvements in tropical cyclone warnings could merit using a more detailed approach like cost-benefit analysis since these events have a big impact on society, the economy and the environment. The availability of suitable data also plays a role in what evaluation approaches can be used.

Evaluation approaches

Many evaluation approaches exist for conducting valuation studies. It is important to align the approach with the purpose of the study, that is, the decision to be made based on the study's results. Some commonly used evaluation approaches are described and compared in Table 4.1. Annex 1 suggests some resources for learning more about two of the most widely used approaches, namely cost-benefit analysis and multi-criteria analysis. WMO *et al.* (2015) describes how to conduct cost-benefit analysis and describes case studies of economic assessment of weather and climate services from around the globe.

Table 4.1. Evaluation approaches and key questions they aim to answer

Cost-Benefit Analysis (CBA)	Cost-Effectiveness Analysis (CEA)	Economic Impact / Benefit Potential Study	Market Uptake Study	Multi-Criteria Analysis
• What are the total expected costs and benefits? • Do the benefits outweigh the costs? • To whom or to what different groupings accrue the costs and benefits	• What is the most cost-effective way to achieve a specific outcome? • How do different alternatives compare in terms of cost per unit of effectiveness (cost per life saved)?	• What are the potential broader economic effects on a region or community? • How would the service contribute to the local, regional or national economy?	• What is the potential demand for a new service? • What are the incentives to take up the service? • What are the barriers to uptake and how can they be overcome?	• How do different options compare based on multiple criteria which may have different weights? • How to balance trade-offs between conflicting objectives?

Cost-benefit analysis (CBA) (also called Benefit-Cost Analysis) is a method for assessing the financial and economic implications of making a change. It involves quantifying and comparing the costs associated with implementing improvements to the system with the benefits it is expected to generate over its lifetime. In the case of development and deployment of a new or improved warning service, its "lifetime" extends until a new service is developed and deployed. When using CBA to decide between options, the option with the greatest difference between the *present value* of the benefits and the cost is generally considered the most economically viable and cost-effective choice. A CBA tends to be more demanding than other approaches. To do CBA properly requires economic expertise and relevant data on different types of costs for each option and how benefits can be monetized.

Tool: Cost-benefit analysis – Online advice and a tool that aids in social cost-benefit analysis by helping to monetize impacts and compare different options using a consistent and rigorous approach.

Annex 1

Cost-effectiveness analysis (CEA) is a special case of a CBA, in which the objectives are given (for example, a specified service level) and the analysis assesses how these can be achieved against lowest cost. In that case benefits don't need to be assessed, making the evaluation easier to conduct (as costs are often easier to infer than benefits).

An **economic impact study** or **benefit potential study** focuses on analysing how and to what extent an investment or measure (often featuring innovation) affects one or more economic sectors or region(s). In the case of improved warning services such studies illustrate how, for typical levels of avoided costs and casualties, benefits propagate in and across sectors in the regions of interest. A benefit potential (or economic impact) study aims to map the different client groups, their likely ways of using a particular warning, and the (type of) benefits they expect from using the warning information. It does not necessarily indicate the expected share of potential users actually using the warning, nor does it precisely quantify how large the benefits typically are for various types of users.

A **market uptake study** assesses to what extent a new (service) product will be taken into use by current users of comparable products and by new users, depending on user characteristics, obstacles to take-up (for example, related to access and skill requirement), and performance features of the service product. A market uptake study focuses on possible barriers against uptake and factors that promote uptake and may include indications of the growth in users when barriers are reduced and/or positive factors reinforced.

Multi-Criteria Analysis (MCA) can be used when multiple criteria such as cost, effectiveness, reliability, partner contributions, and other factors are important criteria for choosing a development or improvement option. A comprehensive approach for (semi-) quantitative assessment of options, MCA can incorporate more complex relationships between criteria and options, allowing decision-makers to explore the impact of improving one criterion at the expense of another. Multi-criteria analysis differs essentially from the other evaluation approaches as it is not specifically meant to provide economic (monetized) values, but rather to assist managerial or political decision-making in ranking the alternatives. Therefore, MCA can also be used in cases where effects, deemed non-monetizable, play a notable role.

Tool: Multi-criteria analysis – A decision-making tool for evaluating and comparing multiple options or alternatives based on various qualitative and quantitative criteria.

Annex 1

Comprehensive versions of MCA can also include CBA or CEA, for example if the selection of alternatives on the basis of complex performance rating should be guided by affordability or budget guidelines.

Different evaluation approaches (CBA, CEA, market uptake, economic impact) will often be interested in the same information, even though the judgement (evaluation) of the outcomes differs. Studies of market uptake and economic impact may also function as an intermediate step towards CBA.

When choosing between options for improving early warning services, both CBA and MCA provide a consistent way to value and compare the options, enabling a transparent ranking and selection process. Without using CBA or MCA, the evaluation may produce disjunct sets of service attribute appraisals, making it difficult to rank and select between options. Annex 1.4 offers some resources for using these two evaluation frameworks.

Valuation methods

Table 4.2 provides an overview of economic valuation methods that are applicable to early warning services, with relevant methods for data collection to support the valuation. Further details for several of the valuation methods are given in Annex 2 on economic valuation methods.

Valuation methods are the analytical protocols for inferring the economic effects (that is, the costs, benefits, and their distribution over user types, economic sectors, and areas) of different types of service improvements. The methods can refer to the benefits for a specific sector or to the valuation of the overall socioeconomic benefits for society, including so-called induced benefits (for example, resulting from better risk management in various sectors). When the benefits and costs of a particular existing warning service are measurable (for example, for certain industries), then transaction-based valuation methods such as contingent valuation can be used. However, for other user groups the benefits and costs are in terms of non-traded welfare or well-being effects, necessitating survey or interview-based techniques or methods that consider indirect value effects, such as hedonic pricing.

Benefit transfer methods are widely used when conducting an original valuation study is not feasible. These methods are divided into two main types: value transfers and function transfers. Function transfers may involve adjusting parameter values from one region to make the model applicable to another. Since original social data is often expensive and time-consuming to collect, valuation studies for early warning systems will likely rely on benefit transfer methods frequently. For more detailed information on benefit transfer, see Johnston et al. (2015, 2021).

Table 4.2. Overview of economic valuation methods.
Asterisks indicate methods that are described further in Annex 2.

Valuation method	*Description*
Market valuation – transaction based	Cost and benefits are inferred from observed changes (*ex-post*) in volume and/or price of transactions directly caused by the project or service improvement. Indirect effects (resulting from the direct changes) can be treated by sector and macro-economic modelling (see under economic models).
Non-market valuation – stated preference	
Contingent valuation*	Survey-based elicitation of individuals' preferences and values, for example willingness to pay (WTP).
Conjoint analysis*	Similar to contingent valuation, except respondents are surveyed about a set of choices instead of a single WTP question.
Behavioural laboratory	Instead of conducting surveys, people are subjected separately or jointly to various consecutive sets of choice experiments, games or storylines in a laboratory, with the aim to obtain a more differentiated understanding of their responsiveness, critical thresholds, and the underlying factors. The number of participants is usually smaller than in surveys, however also virtual (online) behavioural labs do exist.
Non-market valuation – revealed preference	
Avoidance behaviour*	Surveys or observational studies that determine values based on expenditures that would have been made to reduce impacts of weather or climate events but were avoided because of improved information about the hazard risk.
Travel cost	Avoided damage to a site can be represented by the amount of (estimated) retained travel to that site for a certain period after the hazard. The value of early warning can also use travel data also to assess benefits for travel overall, if data on changes in travel behaviour for pre-warned and unwarned cases are available. This data can assist transport service providers to have the right capacity available in the right place and time.
Hedonic price*	Uses observed attributes of property, tourism or labour market to infer value changes for these economic factors owing to changes in information that affects the appreciation of those attributes.
Ecosystem service*	Uses ready models/estimates, possibly in combination with dedicated case modelling, to infer the economic value of affected ecosystem services, e.g. by looking at man-made substitutes for the lost nature products (like building materials), substitute areas elsewhere, and restoration costs.
Natural experiments*	Studies where response observations to a change (such as a new warning service) are available for the old and the new situation and the context has not changed much in other respects (or are well observed and separable). Difference-in-differences (DiD) is the most common quantitative method applied in this case. DiD can be inserted into analysis of the above-mentioned revealed preference methods.
Benefit transfer*	Applies results of existing valuation studies and transfers them to another context (for example, a different geographic area or policy context).
Economic modelling	
Decision models	Analyzes decisions and resulting values when people have access and choose to use services and when they do not; often paired with business or production models. These models are distinct from the MCA oriented decision models. Economic decision models typically use only economic inputs, such as (expected) prices, (expected) capacity, etc. Uncertainty can be accounted for, but behavioural and institutional features only to a limited extent.

Sector/market models	Sector models, such as for agriculture and transport, represent how lowered damage risk can affect production decisions (volume, quality, location, logistics). Market models refer to reactions of competing firms and clients in a sector regarding changed risks and associated price effects. This can be important for economically significant crops, electricity production, and logistics. The outcomes can be important regarding distributional effects (small vs. large firms) and leakage of benefits outside the sector or region (international food companies vs. local farmers).
Macro-models	If warning services are expected to generate significant benefits for many sectors, the overall economic impact, including the induced effects on the entire national or regional economy, can be assessed with macroeconomic models. The results can convince central governments that (tax based) public resourcing of the warning service does pay itself back - both to the taxpayers and the government.
Group decision methods in multi-criteria analysis	There are several methods for consistently aggregating preference, weights and choices in a valuation based on multi-criteria analysis of expert and/or stakeholder inputs. The total scores used to rank alternatives do not straightaway represent costs or (net) benefits as in economic methods, but are an expert based interpretation of the performance of considered alternatives.
Expert elicitation	A systematic process used to gather knowledge, judgments, or informed opinions from experts on a specific subject, typically in situations where empirical data is incomplete, uncertain, or unavailable.

Doing the valuation study

The steps outlined in Box 4.1 provide an idea of the significant work involved in conducting a thorough socioeconomic evaluation. These are described in much greater detail in WMO *et al.* (2015). A carefully conducted valuation study that describes and evaluates the elements across the whole value chain can be very useful in supporting broader benefit transfer studies in other system improvement contexts (Lazo and Mills 2021). As noted earlier, conducting a socioeconomic valuation should ideally be done by (or with) an economist or other expert in valuation methodologies.

Investing effort in the effective communication of the evaluation results (targeting communication to the appropriate audiences and engaging through relevant channels) will help ensure that those results are understood and used to influence decisions.

Box 4.1. Overview of steps in a valuation study

1. Define the amount of resources and ambition level for the valuation (this may have been decided in a preceding phase of problem definition as part of the value chain characterization).
2. To enable an analytically adequate valuation, specify the baseline (a pre-existing service or a situation without a service), and the new service (a service which recently became operational or is an envisaged new service):
    a. Give a general characterization of the baseline and the new service to support a common understanding among the valuation experts; the value chain characterization (Chapters 2 and 3) which preceded the valuation is a good basis for this.

   b. Describe the coverage of the baseline and new service in terms of area, addressed, user groups, etc.

   c. Define the outcomes to be considered and compared; these can include both intermediate and final outcomes, involving both natural science and social science related data.

   d. Check data availability and quality, and options for proxy data.

3. Choose an evaluation approach (CBA, MCA, economic impact study, etc.) and define by what measures (monetary and/or otherwise) and through which criteria the valuation will be conducted:

   a. Define the periods of use to be included (last year, last X years, next Y years, etc.)

   b. Check the need for contextual data to enable identification of possibly interfering factors (for example, exceptional conditions in infrastructure at the time of events) and standardisation of outcomes (for example, accounting for population growth in the involved areas)

   c. Revise preceding steps if incompatibilities arise regarding selected outcomes, data availability or expected data processing challenges, project budget, etc.

4. Collect data on outcomes and context for the agreed period; quality control and standardise collected data. These data will usually include observed weather/hazards and warning service data as well as data on recorded impacts, economic and health statistics, survey based data collected for the study (existing studies can be used to rate responsiveness, if deemed fit for benefit transfer). In a light-touch type of valuation, only readily available information is used, possibly supplemented by interviews.

5. Conduct data analyses for consecutive steps in the value chain. Assess possible threshold effects (for example, regarding number of warnings and responsiveness), conditional effects (such as local or personal conditions affecting ability to react), non-linearities (for example, prices can escalate if emergency induced scarcity worsens), information decay effects (see Weather Service Chain Analysis below), learning effects (new services will get more effective over time if warned event outcomes are analysed to support further (small) improvements), contextual effects (for example, effects of recent local hazard history), and significance of uncertainties.

   a. Assess to what extent different outcomes have to do with differences in technical quality levels of the compared services, with different responsiveness, and/or with different organisation of the value chain.

   b. Assess to what extent different outcomes have to do with differences in actions (since most value is realised at the “end” of the value chain).

6. Combine and analyze the data from the previous step to obtain an overall appreciation of the service’s value generation and importance of different influencing factors. Combine market and non-market effects by either assigning monetary values or using multi-criteria analysis (MCA), and compare the baseline service with the new service, including a sensitivity analysis to assess how changes in key assumptions might affect the results.

4.2 Value Of Information Characterization and Evaluation (VOICE)

A useful way to fully describe and quantify the relevant information flows and their attributes, the actors involved in the flows, and value added along the information value chain is the Value Of Information Characterization and Evaluation (VOICE) framework introduced by Lazo and Mills (2021).

VOICE applies “economic thinking” to identify at each node what the objective of the actor is, what their constraints are, and what resources they have. This may help to better identify how they intake, transform, and pass on the information or use it in decision-making. Understanding actors’ objectives helps appreciate why they do what they do with the information, and understanding their constraints may facilitate improving that information (Demuth *et al.* 2012). For instance, if understanding that a media outlet’s ultimate (perhaps implicit if not explicit) objective is to maximize market share, which means limiting broadcast time to 30 seconds per broadcast, it is easier to understand that their audience is going to be the broadest audience they can reach with brief information that is useful and understandable to the general public. This likely is different from a company providing precision forecasts for agriculture which will have very different objectives, resources, and constraints.

Socioeconomic value is only realized when the information has the potential to influence decisions by the end-user. It does not necessarily mean that there is a change in decisions; simply reducing uncertainty or increasing confidence in decisions may have value to the end user. Value may be added at any node if there is a change in the information that can lead to improved decisions. This may be in the form of better observations, better modelling, better communication (for example, more timely or geographically relevant), or improving the user’s ability to access existing information. Information value may also be lost or degraded at some node, perhaps if there is a delay in transmission of that information or if it is inappropriately altered or “translated.”

The value potential of a service can also change as a result of changes in users’ processes and context. For example, in logistics the minimisation of stocks increases the importance of efficiently coping with disruptions, hence the value of weather information increases in that case, even without innovation within the weather service. Conversely, if logistic companies innovate their disruption risk management with artificial intelligence and/or with new insurance products, the value of weather information could decrease, unless the weather services are tailored to the new disruption risk management logic. The latter proviso underscores the importance of recurrent improvement and innovation of weather service products in dialogue with user groups.

The VOICE template frames the value chain as information flows between actors. The version shown in Table 4.3 characterises a national hazard warning service, with relevant actors including international, national and local agencies, media, infrastructure, industry, and the community. Users of the VOICE tool can modify the template to suit their circumstances by inserting the actors (column headings) and data (grey entries) that are relevant to their value chain of interest. The more tightly the problem is defined (a specific hazard, outcome, and/or decision maker), the more straightforward it will be to characterize and evaluate the value chain.

Using the VOICE framework to characterize a value chain is a useful exercise in its own right for developing a deeper understanding of who is involved, what information is generated and flows through the chain, and the ways in which value is created and lost at each step - essentially, a more in-depth analysis than outlined in Chapter 2.

When a quantitative analysis of the propagation and evolution of value through the value chain is desired, VOICE facilitates the framing of the evaluation. After specifying the actors and relevant data, the applicable methods for collecting data on the flows, attributions, actors, and outcomes of use of the weather service information can be chosen. The data collection methods are closely associated with valuation methods. Once the baseline and final outcomes to be analysed and compared are defined, one can start to look for available indicators needed to compare changes in outcomes and to attribute change in outcomes to differences in inputs and contextual conditions. Table A1 in Annex 1 offers a far-reaching list of input, output/outcome, and quality indicators aligned to the warning value chain.

Table 4.3. Value Of Information Characterization and Evaluation (VOICE) framework

Actors	**Global space & meteorological agencies** *WMO* *Space agencies* *ECMWF and other global providers*	**National met-hydro and hazard agencies** *National weather services* *Geological hazard agencies* *Environment agencies*	**Civil protection agencies** *Emergency managers* *Fire & rescue* *Police*	**Media** *National broadcasters* *Print media* *Social media*	**Support agencies** *Red Cross/Red Crescent* *UNDRR* *NGOs* *Health sector*	**Infrastructure and industry** *Public utilities (energy, water, transport)* *Industries* *Finance/insurance*	**Community** *Municipalities and local governments* *Neighbourhoods* *Individuals* *Local businesses* *Volunteer groups*	**Socio-economic value - outcomes** Change in outcome resulting from the warning(s)
Objectives	*Coordinate data sharing* *Remotely observe weather and hazards* *Generate and share global NWP model output*	*Observe local/ national weather and hazards* *Run weather and hazard models* *Create and issue forecasts and warnings*	*Enhance preparedness* *Anticipate impacts* *Respond to impacts from hazardous events*	*Warn about the hazards and potential impacts* *Report events*	*Coordinate forecast-based finance* *Enhance long-term preparedness* *Provide relief*	*Prevent disruption* *Make a profit* *Encourage preparedness*	*Stay safe* *Protect assets* *Protect livelihoods*	
Resources	*Satellites* *High performance computing* *Numerical weather & hazard models*	*Observing network* *Radars* *Numerical weather & hazard models* *Nowcasting & post-processing systems* *Scientific experts*	*Emergency vehicles and equipment* *Integrated data and alerting platforms* *First responders*	*TV, radio* *Newspapers* *Websites, apps* *Journalists*	*International aid funds* *"On the ground" knowledge* *Shelters* *Staff*	*Resilient infrastructure* *Risk management* *Standard operating procedures (SOPs)*	*Homes, shelters, community centres* *Local knowledge* *Social capital*	
Constraints	*Scope and lifetime of satellite missions* *Computing resources* *Model resolution and accuracy*	*Sparse observing networks* *Model resolution and accuracy* *Time to issue forecasts*	*Insufficient knowledge of vulnerability* *Inadequate impact data* *Rigid SOPs* *Staffing pressures*	*Reach & reliability of communication infrastructure* *Ability to tailor messages* *Trust* *Broadcast duration & timing*	*Insufficient funds* *Competing priorities for assistance* *Supply chains*	*Resilience to extremes* *Financial constraints* *Logistics* *Regulations*	*Structural inequalities* *Disabilities and special needs* *Access to digital technology* *Inexperience*	

Flow – Information character-istics	*Weather/hazard elements* *Probability* *Intensity* *Location/extent* *Temporal evolution* *Data volume, frequency, medium, format*	*Weather hazard elements* *Probability* *Intensity* *Location/ extent* *Temporal evolution* *Data volume, frequency, medium, format* *(see also media elements)*	*Vulnerability* *Exposure* *Triggers* *Actions* *Socioeconomic & environmental impacts* *Authority* *Data medium, format* *(see also media elements)*	*What hazard(s)* *When & where* *Possible impacts* *How likely* *What to do* *Update timing* *Medium, format* *Language* *Channels* *Source of information*	*Triggers* *Actions* *Costs* *Resources* *Linkages*	*Risk tolerance* *Confidence* *Actions* *Likely effectiveness* *Service disruption* *Timing* *Laws & regulations* *Liability* *Accountability* *Responsibility*	*Local weather/ hazard/impacts observations* *Risk tolerance* *Prior experience* *Confidence* *Actions* *Cultural context* *Communication networks*	***Outcomes / changes in outcomes*** *People affected* *Deaths* *Damages* *Costs & losses* *Environmental impacts* *Immediate/lagged* *Acute/chronic*
Flow – Information quality attributes	*Consistency* *Precision* *Accuracy* *Timeliness* *Reliability* *Accessibility*	*Precision* *Accuracy* *Timeliness* *Reliability* *Accessibility*	*Precision* *Accuracy* *Timeliness* *Reliability* *Accessibility* *User-specificity*	*Timeliness* *Reliability* *Understand-ability* *Accessibility* *Reach* *User-specificity*	*Risk awareness* *Preparedness* *Knowledge of actions* *Timeliness* *Reach*	*Risk awareness* *Preparedness* *Compliance* *Knowledge of actions* *Response rate*	*Risk awareness* *Preparedness* *Engagement* *Inclusiveness* *Compliance* *Knowledge of actions* *Response rate*	***Warning effectiveness*** *Information utility*
Flow – Information enhance-ment	*Awareness of weather/hazard situation* *Global/regional context* *Input for modelling* *Heads up to enable early action*	*More precise knowledge of weather/hazard* *Climatological context* *Lead time to enable action*	*Knowledge of who and what is at risk* *Trust and authority* *Actionable advice* *Lessons learnt from previous events*	*Immediacy & frequency* *Broad reach of communication*	*Capacity building* *Shared knowledge and resources* *Coordination in disaster situation*	*Relevance of hazard for sector* *Magnitude and timing of service disruption*	*Local context and knowledge* *Direct communication* *Trust in messenger* *Articulation of user needs*	***Valuation*** *Reduction in and/or avoidance of negative impacts of hazards*

Source: Adapted from Lazo and Mills (2021)

4.3 Weather Service Chain Analysis

Weather Service Chain Analysis (WSCA) explores the propagation of informational value (Perrels *et al.* 2012, 2013). Specifically, it explores how weather information value tends to degrade as the information is filtered through consecutive stages of weather and warning information provision due to associated attributes of imperfect accuracy, deficiencies in customer orientation, physical or socioeconomic obstacles to access, limitations to comprehension and to ability to respond, and response effectiveness (Figure 4.1). Importantly, the value chain analysis in WSCA is concerned with one particular service product or at most with a few very closely related service products, aimed at the same user groups. It does not attempt to represent *new* information (value) added by actors in the chain.

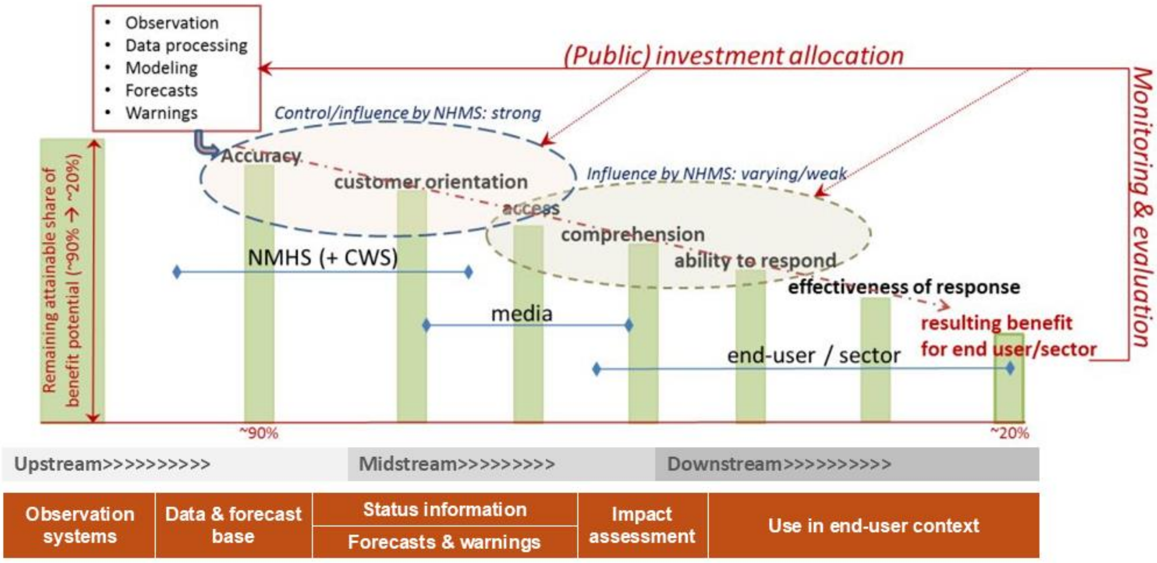


Figure 4.1. Weather Service Chain Analysis showing how the potential benefit is progressively reduced through sub-optimal attributes (accuracy, etc.) associated with consecutive stages (nodes) in the weather information value chain. The vertical bars represent the remaining fraction of the maximum potential.

Source: Perrels *et al.* (2013)

The key point is to understand which nodes in the value chain of a warning service affect which attributes in the information decay chain as used in WSCA. In that case, a significant contribution to decay in a certain attribute can be linked to specific activities in one or two stages of the value chain. It pairs well with the theory of change (Chapter 3) by formalizing the assumptions and drawing on empirical data, analysis and expert evidence to trace the diminishing benefit attributable strictly to the service improvement/project /intervention.

In its form presented here, WSCA doesn't specifically address potential information loss during the creation of forecast information (shown in the upper left of Figure 4.1). However, the method is flexible: attributes can be divided further if useful and supported by the necessary data. It is also important that estimates for each attribute are not treated as black boxes – identifying the underlying factors at different stages of the value chain and their (approximate) contributions is key. In this way, WSCA allows for a quick assessment of possible improvements to the warning service.

Tool: Weather Service Chain Analysis – WSCA explores how weather information progressively loses value due to the compounding effects of imperfect accuracy, customer orientation, access, comprehension, ability to respond, and response effectiveness.

Annex 1

WSCA can be used quantitatively to estimate the efficacy of each attribute, that is, the percentage of the maximum attainable performance of that attribute. Multiplying all of the efficacy values together gives the overall efficacy, or share of the potential value of the weather information which is realized, which may be substantially less than 100%. An example of an *ex-post* (after the changes) evaluation of an existing service is shown in Case Study 7.

Case Study 7: Weather Service Chain Analysis for Finnish traffic accidents

Poor weather conditions cause an estimated 10% of wintertime traffic accidents in Finland, with associated costs in the hundreds of million Euros. Road weather forecasts therefore have the potential to provide enormous savings and protection of life. Perrels *et al.* (2012) applied WSCA to analyse the effectiveness and value of road weather forecasts in preventing road accidents in winter. Using data gathered from a literature review and interviews, they described the current state of six stages that translate weather information to user benefit and estimated the degree to which each stage was not performing optimally (Table 4.3). Multiplying the efficacies, they estimated that 14% of the potential benefit of winter road weather forecasts were realized (Figure 4.2).

Based on accident and health care statistics the average annual cost of road traffic accidents was estimated at 226 million euros for the study period, 2000-2009. Given the 14% estimate of WSCA, 226 million represents 86% of a theoretical maximum damage in a no warning context. From this can be inferred that the road traffic oriented weather warnings generated approximately 36 million euros per year in avoided traffic accidents in Finland. The attributable costs for the entire value chain, including supply and use of media, were estimated at 2.5 million euros.

Table 4.3. Assessment per stage

	Filtering stage (attribute)	Recommendations for provider	Current state	Efficacy (%)
1	*Weather forecast accuracy*	Up-to-date and well maintained weather observation and forecasting system; adequate and 24x7 staffing; monitoring and evaluation of forecast accuracy.	Accuracy levels good; 19 out of 21 adverse weather days were predicted.	92%
2	*Customer orientation of the information*	Provision of technical forecast information in textual and pictorial formats meeting information needs of targeted user groups; well-tended and lasting customer relations.	Majority of drivers understand what is meant by “normal” “poor” or “very poor weather”.	90%

3	*Access to weather information*	Weather / hazard information distributed through diverse media channels to maximise reach to different users; emergency back-up; technical and socioeconomic access to media channels.	High availability, but user rates it at ~62% only; messages needed about current road weather conditions including in-car systems, road signs.	62%
4	*Comprehension of the information*	Easy to grasp representation of information using standard terms; trust (including possibilities and limits of forecasts); further education via schools, media and customer relations	Weather information makes the judgement about current conditions more accurate.	85%
5	*Ability to respond effectively in a timely manner*	Timely availability of weather/hazard information (related to 24 x 7 staffing and agreement with media channels on access).	Warning frequency sufficient to enable timely response, but apparent threshold to change travel plan is high; people with weather info change more often, but still poor response overall.	40%
6	*Actual effectiveness of responses*	Largely outside the realm of influence of the weather service provider, but promotion of education on (use of) weather/hazard information will help.	Mostly correct responses	80%
	Percent of potential value that is realized (product sum of the scores per attribute)			14%

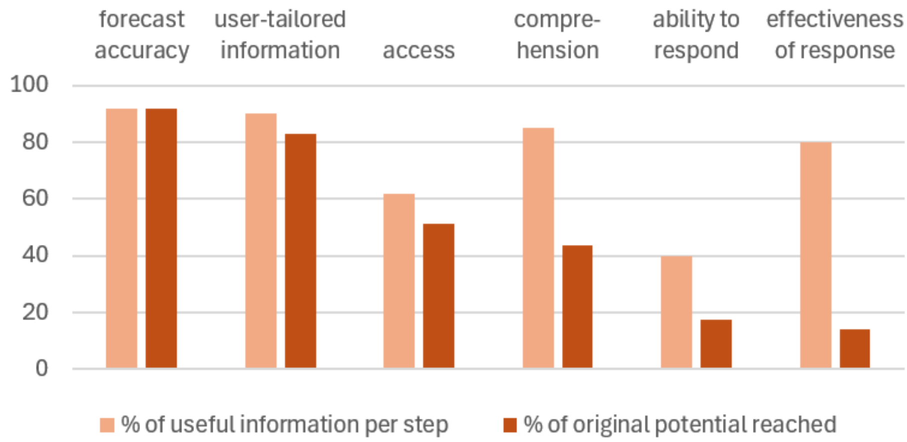


Figure 4.2. Responsiveness to weather information by factor

Source: Abridged and adapted from Perrels et al. (2012)

WSCA can also be used semi-quantitatively, when only tentative indications of performance of attributes can be given. That version suits multi-criteria analysis and can result in an ordered scoring of the benefit potential for the various attributes. WSCA can be used qualitatively to show the “weak links” in the value chain that may merit more investment to increase the overall benefit. WMO *et al.* (2015) includes a case study of improving hydrometeorological services in Bhutan in which an *ex-ante* (before the changes) assessment employed WSCA in a semi-quantitative fashion.

Because WSCA represents a causal path from the original weather information to the benefit, it is also possible to estimate how improvements in one or more of the stages in the value chain flow through to improved benefits for the user (assuming no unexpected changes in behaviour). As with all value chain methods, WSCA can be applied to subsets of the overall value chain, for example, considering emergency responders as intermediate users. A WSCA tool is included in Annex 1.4.

4.4 Accounting for uncertainty in valuation

The results of valuations of (improvements in) early warning services are shrouded in uncertainty. Documenting the assumptions and providing an estimate of uncertainty in the valuation results are critical to enable the results to be interpreted with an appropriate level of confidence. This is especially important when making a case for investment or comparing alternatives for warning system improvement.

Although some valuation tools can produce formal uncertainty ranges, it is usually more informative to perform a sensitivity analysis, possibly in combination with a scenario analysis. These types of analyses indicate how robust the results are to assumptions (which includes models) and input uncertainties, and provide insights on the factors which are most critical to influence the outcomes.

The overall uncertainty regarding the effectiveness (and hence the value generation potential) of the warning service encompasses much more than weather observation and modelling uncertainties. A certain percent improvement in forecast accuracy does not automatically translate into the same percent reduction in losses from severe weather. There is almost always large uncertainty about the assets and people at risk (property, communities, etc.), the responsiveness and capacity of the responders to act, and the effectiveness of the actions. In many studies the NMHS is forced to make "heroic assumptions" about the preparedness and capacities of disaster managers and communities to react to warnings, which may be unrealistic. As well, actions that initially seem effective in reducing immediate risks to life and property may inadvertently create new risks, such as sanitation or food security problems for evacuated populations. This suggests that, rather than just comparing expected levels of immediate costs and losses, it may be more helpful to periodically run adaptive scenarios to explore potential chains of consequences and how they may play out over time.

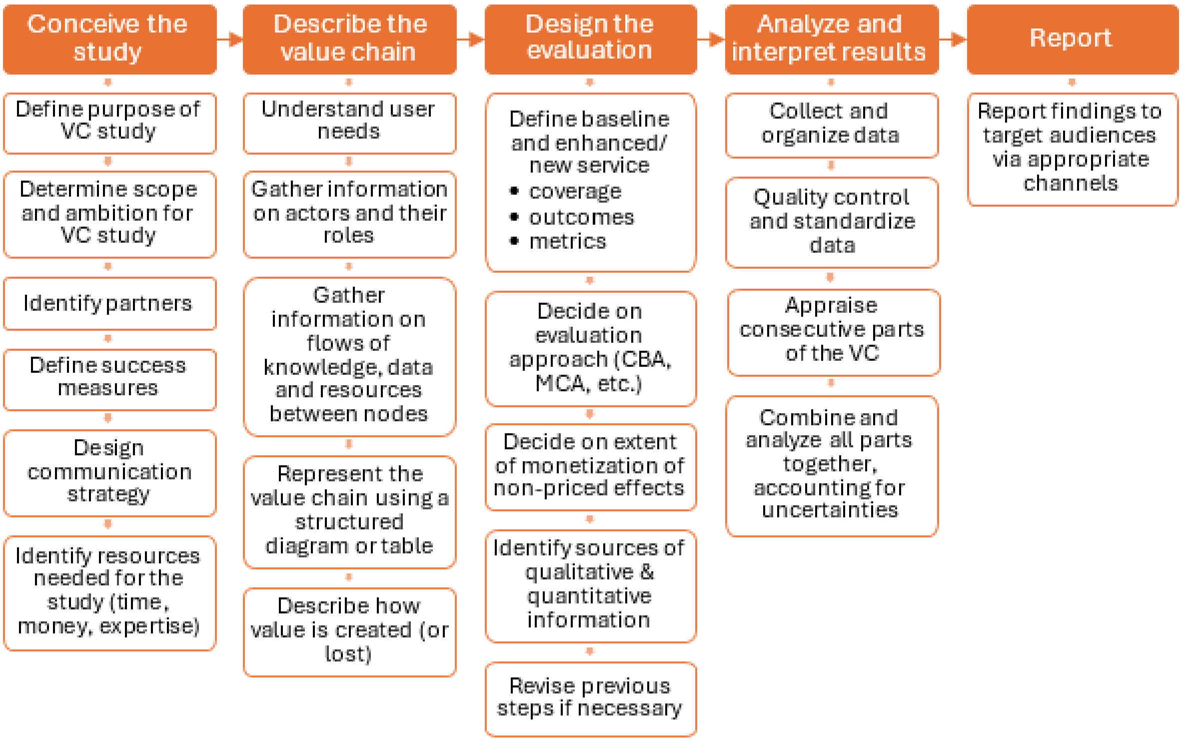
The simplest method of simulating uncertainty is forward analysis, that is, propagating prior assumptions about sources of uncertainty (Box 4.2) through the value chain. In a study of the monetary benefit of early flood warnings in Europe, Pappenberger *et al.* (2015) estimated a range of 20-year cost benefit ratio of 1:4 to 1:409, based on a sensitivity analysis. Where processes can be modelled, then mathematical, statistical and stochastic (Monte Carlo, for example) methods can be used to propagate uncertainty from inputs to outputs. In some instances, uncertainty can be reduced or constrained by verifying observations (which may be assimilated into the modelling), statistical modelling or calibration, and by the experience and expertise of actors in the value chain. Chapter 5 addresses the verification of warnings to establish their accuracy.

At each step in implementing a VOICE or WSCA it is useful (and potentially important) to identify the source and extent of uncertainty, and then to evaluate how (or even if) it can be reduced. It is also worth understanding how uncertainty is communicated at each step from actor to actor.

The compounding of information and response uncertainties can lead to a wide distribution of valuation outputs, in some cases too wide to be of use. In the face of such uncertainty it may be advisable to interpret the values (for example, the benefit-cost ratios) obtained from a valuation study as general indicators or rough estimates. They can help determine whether the net societal value is robust, less robust, or even probably insufficient to justify the cost.

4.5 Steps for using a value chain to value improvements in a service

The steps for valuing service improvements using a value chain approach such as the VOICE framework or Weather Service Chain Analysis can be summarized as:



Box 4.2. Sources of uncertainty in the warning value chain

Input data for hazard prediction rely on observations of physical variables, often from sparse networks or indirect measurements from remote sensing with limited spatial and temporal resolution and coverage. The limited quality of input data affects both the accuracy of the hazard predictions and the hazard model calibration.

Natural hazard models are vital for all phases of risk assessment and disaster management. However, incomplete knowledge of the complex physical processes and their representation in the models, and constraints in spatial and temporal resolution, lead to prediction uncertainties which augment or amplify existing uncertainties in the input data. In the case of hazard and hazard impact modelling, errors in weather (for example, precipitation) modelling can be amplified by errors in flood or wildfire models, with some types of “upstream” errors having a greater impact than others on “downstream” errors in the modelling chain (Golding 2009, Titley *et al.* 2024).

For numerical forecasts with routine updates, data assimilation can constrain model errors by integrating the most recent observations. Ensemble prediction using numerical models is widely used to account for uncertainties in both the initial conditions (related to input data) and the model’s representation of physical processes. Predicting extremes is especially challenging as assumptions about the tail of the distribution affect the likelihood of extreme values. Cascading/compound hazards and their impacts are also difficult to model and forecast.

Impact data often have severe limitations and biases. Vulnerability and exposure data are difficult to obtain and often not available at the desired scale for use in impact and risk modelling. Damage to infrastructure and systems are often modelled by semi-empirical fragility curves but may also have the characteristics of "catastrophes", that is, a sudden failure at some critical point or a domino effect in a system. Observation density for impacts is often insufficient, especially for evaluating at hazard scale, and may need to be aggregated to larger scale for evaluation. Socioeconomic loss and damage assessments from hazards are closely related to the type of reporter, their purpose and the level (for example, individual, organization, nation) (Wyatt *et al.* 2023) and temporal and spatial scale of impacts. Their estimated monetary value depends on the wealth of the society; for comparison purposes it may be possible to normalize.

The warnings must be interpreted and translated by providers and intermediaries (such as media), which in turn are received and interpreted by users; uncertainty can occur at each of these stages. Competing or confusing messages, misinformation, language, jargon, and lack of risk awareness are factors that exacerbate uncertainty among warning recipients (Doyle *et al.* 2019).

External influences such as cultural and societal factors, economic conditions, and government policies and regulations can change how people and institutions respond to warnings and therefore how effective warnings are in mitigating losses from hazards (Mileti and Sorenson 1990, Wisner *et al.* 2004). The same warnings may be effective for some communities and much less so for others. Although behavioural responses are difficult to track, indicators such as traffic monitoring, mobile phone data, and localized digital (retail) transactions offer insights into how at-risk populations move and, to some extent, how they prepare and care for others. Surveys and community consultations capture only a subset of the affected population.

4.6 Further reading

European Investment Bank (2023). *The Economic Appraisal of Investment Projects at the EIB - 2nd Edition*.

Khandker, S.R., Koolwal, G.B. & Samad, H.A. (2010). *Handbook on Impact Evaluation: Quantitative Methods and Practices*, World Bank.

Tassa, A., Willekens, S., Lahcen, A., Laurich, L., and Mathieu, C. (2022). On-going European Space Agency activities on measuring the benefits of Earth observations to society: Challenges, achievements and next steps. *Frontiers in Environmental Science*, 10, 788843.

WMO, WBG, GFDRR, and USAID (2015). *Valuing Weather and Climate: Economic Assessment of Meteorological and Hydrological Services*. WMO-No. 1153, 286 pp.,

5. Co-design a new service

Earlier chapters have demonstrated how the value chain can be used to characterize a warning system, identify gaps and choose among improvement options, and value improvements. This chapter consolidates these concepts and applies them to the challenging task of co-designing a new warning service. It highlights how value chain approaches can be useful in the phases of collaborative design, development, evaluation and ongoing monitoring of a new warning service. It particularly emphasizes the importance of working in partnership to design and deliver the benefits of early warnings.

The Early Warnings for All initiative has highlighted the need to develop new and effective warning systems for the estimated third of the world's population still not covered by early warning systems (UNDRR 2023). As of 2022, only half of the countries worldwide reported having adequate multi-hazard early warning systems (WMO 2022a). The development of new warning services and comprehensive renewal of existing warning services, built on the collaboration of service providers and users, is intended to ensure that those threatened by hazards are empowered to act appropriately in sufficient time.

A people-centred approach, where the community is involved in the design, delivery, and evaluation of the warnings, can be more effective than a top-down warning process in which "expert information goes from a centralized source to the inexpert masses", especially when the issuing authorities do not have the trust of the community or warning communication is ineffective (Fearnley and Kelman 2021). People-centred early warning systems recognize the importance of community empowerment, local knowledge, and participatory approaches in disaster risk reduction.

Co-designing a new service can be more demanding than improving an existing service, involving a sequence of iterations toward the final design. It requires taking the time to engage deeply and thoughtfully with the community about their knowledge, understanding and capabilities. Rather than rushing into solutions, it is an opportunity to consider a range of potential pathways to meeting the needs of the users. This may include reviewing successful early warning systems used elsewhere.

There are many excellent resources that describe good warning design and development (WMO 2015, 2018, 2022b; IFRC 2021, Fearnley and Kelman 2021). The Early Warnings for All initiative has inspired further excellent work in this area (World Bank 2023). Readers are encouraged to consult those resources for detailed advice on best practice in warning design.

5.1 Defining the problem

New warning services are usually created in response to unmet needs. Demand for new warning services may come from the public, partner agencies and sector stakeholders, often in response to changing hazard intensity or frequency, or increased vulnerability to a hazard. For example, in recent years recognition of heat health impacts and increasing heatwave intensity associated with urbanization and global warming have led to the development of many new heatwave warning services. The impetus may be driven by government policy, for example, to better address the special needs of diverse citizens. Post event reviews or inquiries following disasters or extreme events commonly identify areas where the service must be improved or redesigned.

In a people-centred approach, service design is driven by the needs of the users. Establishing the appropriate processes, arrangements and relations for co-design requires consideration and planning (Fleming et al. 2023). Figure 5.1 illustrates an inclusive co-production paradigm in which everyone is involved in the design, maintenance, operation, and use of the early warning system.

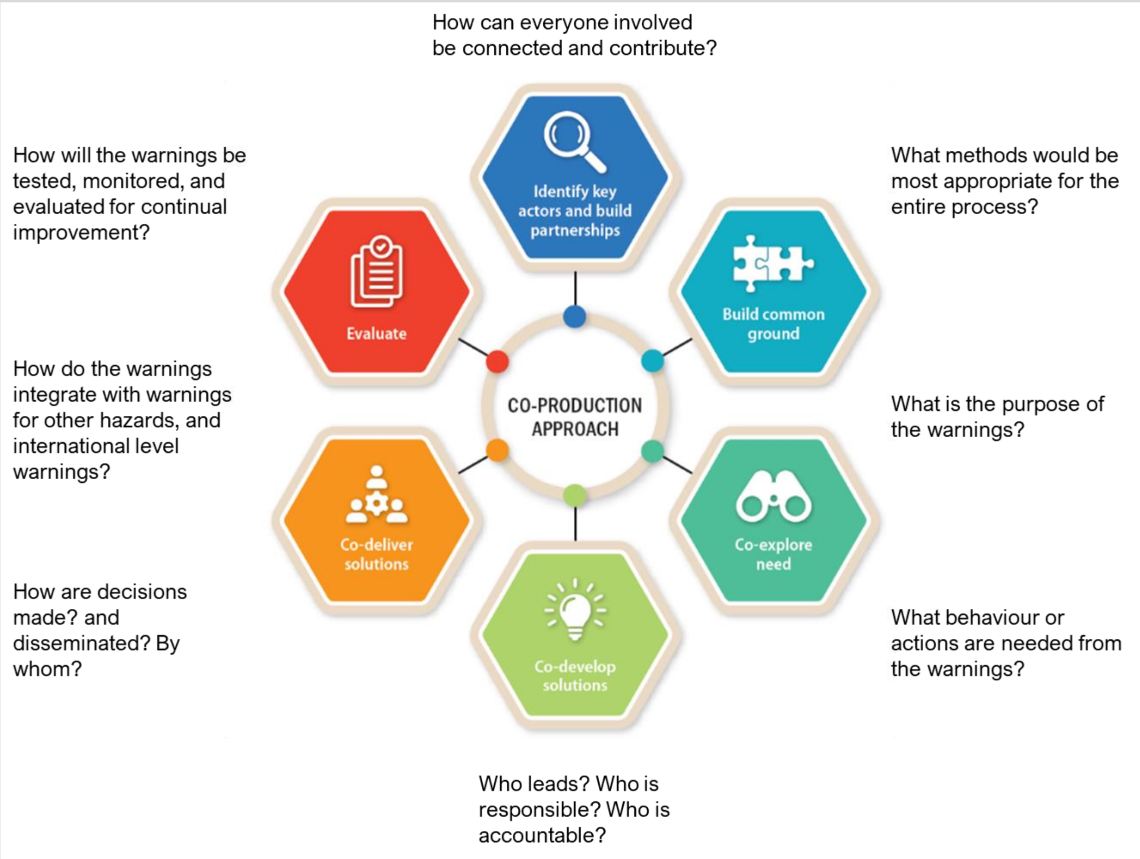


Figure 5.1. Co-design and co-production of early warnings

Source: Adapted from Carter et al. (2019) and Fearnley and Kelman (2021)

Identifying and engaging relevant stakeholders and partners is often done before or in parallel with the needs assessment (determination of what needs to be addressed to achieve the desired goals). Parties who may wish to invest in the success of the warnings include government agencies, non-governmental organizations (NGOs), community groups, academic institutions, and private sector entities. Stakeholder mapping can be a useful tool for developing a common understanding of who is involved and the nature of their engagement. Initiating partnerships early in the process can provide valuable insights and resources to support the needs assessment.

Tool: Stakeholder mapping – This diagram aims at clarifying roles, levels of engagement, and relationships between stakeholders. **Annex 1**

Undertaking needs assessment, and engaging with community representatives, stakeholders from various sectors and levels of government, and experts through workshops, surveys, and other means of communication, allows everyone to express their requirements, expectations, and priorities, as well as their ability to contribute to a new warning system.

Mapping out a conceptual value chain for the warnings (see Chapter 2) helps to identify who should be involved in operating and using the end-to-end warning system. It is a good idea for all parties to be included in the co-design process, as well as in ongoing collaboration and communication to refine the early warning system to meet evolving needs and challenges.

Once the users' needs and likely delivery partners have been identified, the scope and objectives of the warnings can be defined. This is essential for getting everyone aligned to the same goal. However, it is likely that some of the stakeholders will have very different views of the objective, may describe it in quite different language, and may not even recognise the problem. Value chain analysis can help tease out the specific needs, requirements, and preferences of all stakeholders in the early warning system. Partners in the warning service chain will have their own requirements for information to support their own decisions. This collective input informs the broad scope and objectives of the early warning system: what types of hazard(s) to address, the geographic area, and what outcomes it aims to achieve (reducing loss of life, minimizing damage, enhancing preparedness, etc.). Once the new warning system is in place, those same outcomes can be monitored and evaluated to assess its effectiveness.

Case Study 8 describes an example of a new warning system that was created following an unusual hazard event. Value chain approaches were useful in all stages of the service design, operation, and evaluation.

Case Study 8 - Thunderstorm asthma early warnings

Thunderstorm asthma is a rare hazard linked to airborne allergens and poses a risk to the population of southeastern Australia in springtime (October-December). In November 2016, an unprecedented epidemic thunderstorm asthma event in the state of Victoria resulted in many thousands of people developing breathing difficulties in a very short period of time. It caused ten deaths and created extreme demand across the Victorian health and emergency services. In response to this event, a new early warning system for epidemic thunderstorm asthma risk was rapidly developed and implemented in 2017, accompanied by a full range of community, health and emergency sector awareness raising and education activities (Bannister *et al.* 2021). The warnings are delivered through a partnership between the Victorian Department of Health, the Bureau of Meteorology, the University of Melbourne, and AirHealth Lab.

Value chain concepts were instrumental in the design of the warnings. Starting with the user needs, namely health sector preparedness and community safety, the partners worked backwards using a theory of change approach to determine the value chain of necessary capabilities (communication, risk assessment, hazard prediction, modelling, observations) and information flows that would be needed to provide a thunderstorm asthma early warning service. The value chain process helped define the partners' roles and responsibilities in delivering the warnings. It also highlighted gaps in knowledge of the hazard, and the need to develop capability to measure and predict grass pollen to support the thunderstorm asthma warnings. The warning system is reviewed annually by the partners to examine all aspects of its performance and identify areas for further improvement.

5.2 Ideation and conceptual design

Given the scope and objectives, the next step is to develop and work through ideas, concepts, and approaches for an effective new warning system. Table 5.1 summarises many factors that must be considered when designing early warning systems. Deeper information on the necessary components and activities can be found in the WMO (2018) checklist for multi-hazard early warning systems introduced in Chapter 3.

Table 5.1. Key considerations when designing early warning systems

Scope & Collaboration	Science & Technology	Response & Societal Factors	Governance & Sustainability
Clear objectives and scope: What types of hazards or risks will it monitor and address? What geographic area will it cover? **Stakeholder engagement:** Involve government agencies, emergency responders, user communities, and relevant experts. **Co-design approach:** Ensure diverse perspectives are integrated into the warning system design. **International cooperation:** If applicable, collaborate with neighbouring regions or countries, as many hazards can cross borders.	**Data collection and sources:** Weather data, sensor networks, social media & historical incident data. **Warning criteria and thresholds:** What conditions trigger warnings and at what severity levels? **Communication channels:** Multiple channels such as text messages, sirens, social media, mobile apps. **Technological infrastructure:** Hardware, software, and data storage capabilities. **Redundancy and reliability:** Ensure the system works in the event of hardware failures or other disruptions. **Continuous improvement:** Monitoring and evaluation of the system's performance including user feedback.	**Community engagement and education:** Raise awareness about the EWS, its purpose, and how to respond to warnings. **Accessibility and inclusivity:** Consider the needs of vulnerable populations who may require additional support. **Response protocols:** Specify how authorities and communities should respond to warnings, include evacuation plans, shelter locations, and communication procedures. **Testing and training:** Regular system testing and drills & training for emergency responders.	**Institutional arrangements and partnerships:** Collaborative frameworks and clear responsibilities in warning production and dissemination. **Legal and regulatory compliance:** Ensure the EWS complies with relevant laws, regulations, and standards. **Data privacy and security:** Take care when collecting and storing sensitive information related to individuals or organizations. **Funding and sustainability:** Secure adequate long-term and sustainable funding for the development, maintenance, and operation of the system.

Partnerships

Strong internal and external partnerships, including with the user community, are essential for the success of early warning systems. Establishing good governance processes with the partners for both the design and the operation of warning systems helps to ensure effective coordination, accountability, compliance, and sustainability, among other things. Challenges may arise when partners are new to each other; having clear objectives and integrated and cohesive joint planning is helpful in overcoming misunderstandings and working together toward a common goal. At times, the objectives of different actors may conflict, such as balancing the need for water supply security during droughts with maintaining sufficient dam capacity to mitigate floods, which can add complexity to warning systems. Stibbe and Prescott (2020) provide an excellent guide on building and sustaining multi-stakeholder partnerships.

It is crucial during the design process to agree on clear roles and relationships between the partners involved in producing and delivering the new warnings. Value chain analysis can identify opportunities for collaboration, sharing resources, and leveraging complementary strengths. During a hazard event, trusted relationships between partners enable them to make quick decisions under pressure, combining their expertise to assess a situation and act accordingly (Uccellini and Ten Hoeve 2019). Failure of a chain arises from its weakest link, while strength comes from its end-to-end integration.

When developing a new service it is likely that some form of warning system already exists, even if it is informal or basic in nature. Engaging with the community to understand existing approaches and actors provides a solid foundation for an effective co-design process which builds on local knowledge and empowers action. Case Study 9 describes how providers and users of environmental services in the polar regions are collaborating to enhance the design and co-production of a service value chain that will better meet the decision-making needs of a diverse set of users.

Traditional and customary knowledge continues to have an important place in many communities around the world. Pacific Island communities for instance have survived and prospered using weather and climate predictions based on the behaviour of plants and animals, temperature and rainfall, and astronomical indicators (Chambers *et al.* 2017). In some places there is concern that the loss of traditional knowledge, impacts of land use and climate change is leaving people with less effective early warning systems than in the past. Meteorological agencies can work with communities to understand existing early warning systems, to consider the potential contribution of forecast products and how they can be integrated with traditional methods. The Solomon Islands Meteorological Services (SIMS) for example, is working with Traditional Knowledge holders to bring together traditional ways of predicting weather and climate into SIMS forecast products (Solomon Islands Meteorological Services, 2023).

Case Study 9: Co-design of a polar weather service

The Polar Prediction Project (PPP) had a goal to enable a significant improvement in environmental prediction capabilities for the polar regions and beyond, by coordinating a period of intensive observing, modelling, prediction, verification, user-engagement and education activities.

People in polar regions use environmental information for planning and scheduling activities, making operational decisions, and managing risk and human safety. A mismatch between the services provided and the information needs of users was highlighted by the many challenges experienced accessing and using weather information. Useability challenges can be addressed through co-production, where users contribute to the design of products and services and providers incorporate an understanding of user needs and continuous feedback to tailor services (Figure 5.2). The societal value of polar environmental services is enhanced by better understanding the diversity of highly specific user contexts and tailoring services towards greater actionability (Lamers *et al.* 2024).

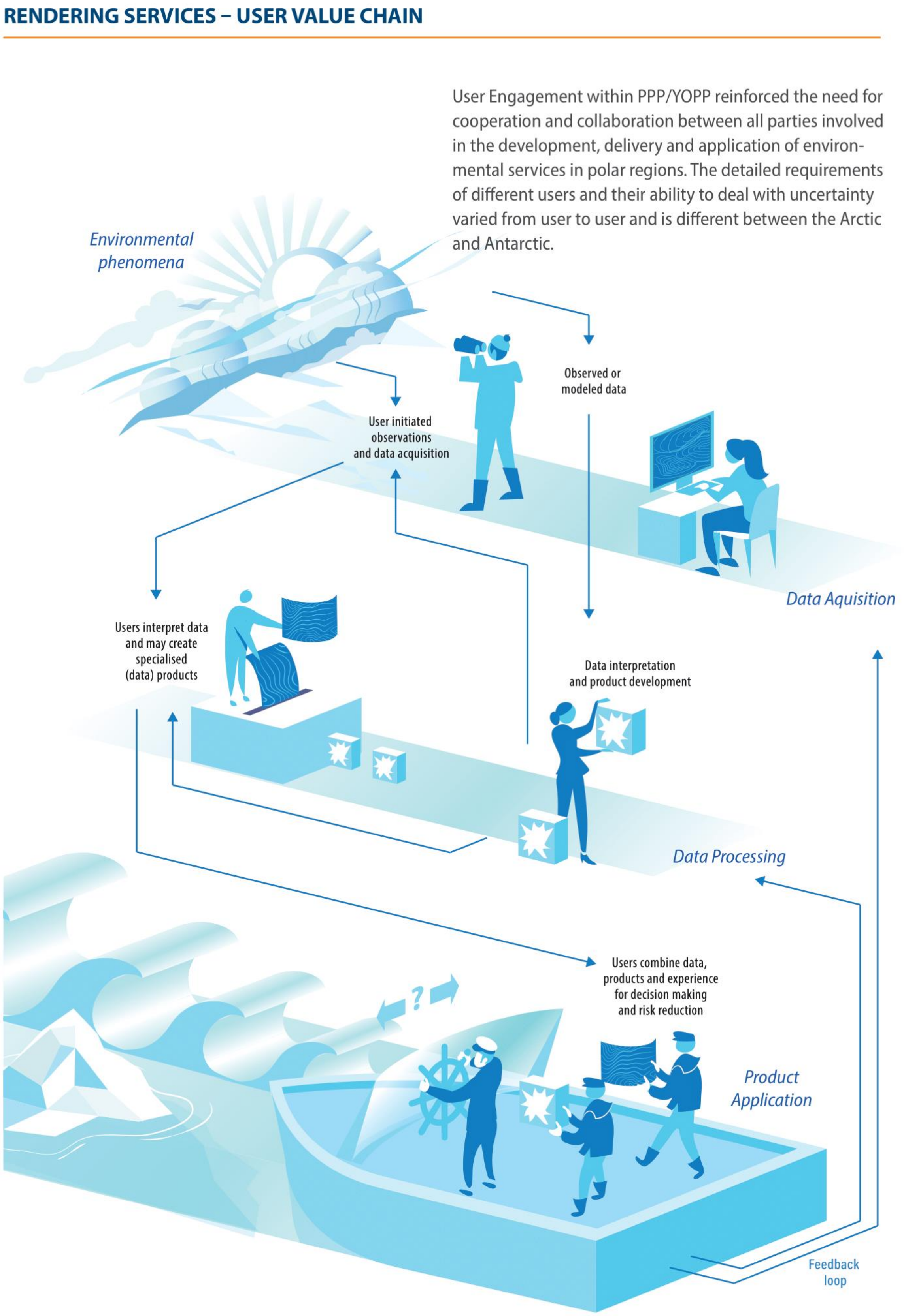


Figure 5.2. User value chain for environmental weather services in the polar regions

Source: Alfred Wegener Institute (2022)

Wider context

As well as the community's capacity to respond to hazardous weather, structural and institutional elements (for example, engineering solutions such as levees, governance and coordination mechanisms, legal and regulatory frameworks, institutional capacity and resources, etc.) also influence how well an early warning system can mitigate the impacts of a hazard. Appraising these elements together with all of the partners is important to understand the broader context in which the new warning value chain will operate and provides a basis for a realistic idea of what can be achieved. Since accurate hazard prediction is challenging, it is inevitable that some warnings will be false alarms and some events will be unwarned for. Understanding the impact on the community of false alarms and missed events must be factored in, especially when planning for the worst case (see Case Study 4).

Documenting the warning value chain and outcomes for the current situation can establish a baseline of comparison for the future service's structure and impact. The process of conducting a socioeconomic benefit analysis of a major investment helps inform project advocates, its actual and potential end users, and policy makers. As noted in earlier chapters, gathering and analyzing the relevant information to determine the baseline can take a lot of effort. Community experience and local knowledge of disasters can provide important and foundational information not only to help describe the baseline but also to be incorporated in warning co-design (the "first mile"). For example, local knowledge of historical flood heights can provide important insight; if they are marked on public structures they can be surveyed and inform aspects of the service. In the absence of an existing warning system, broad damage and loss data, and case studies of what happened in previous hazard events can also help build an understanding of the current situation.

Co-developing a theory of change (Chapter 3) for the new service can explain the linked processes by which the new warning system or major change will deliver benefits and identify which qualities of the new service are most relevant to influence outcomes. This perspective enables everyone to understand the many processes, actors and information flows that could support or hinder the realization of benefits (add or subtract value, in IVC terms). It helps avoid the pitfall of assuming that a major innovation in one part of the value chain will automatically lead to much better outcomes. The theory of change also supports monitoring and evaluation of the warning system development.

When assessing the available technologies and service designs, considering such factors as reliability, scalability, affordability, and accessibility, it is wise to research similar warning systems that exist elsewhere, particularly those that work well in a similar country or setting. For example, Speight et al. (2020) compare the pros, cons and operational challenges of surface water flood forecasting systems of increasing sophistication. Characterizing the value chain for warning system options helps the partners to do a fair comparison between a service that they may wish to emulate and what is possible in their unique environment. Differences in observing systems, the organization of the nodes and actors in the warning value chain, and the regulatory environment (among other things), could mean that major adjustments would need to be made to that service. For example, the FASTA smartphone app can automatically alert users in Kenya to any storms predicted to reach their location, based on nowcasts from geostationary satellite observations (FASTA 2023), adapting the concept of radar-based smartphone alerts that exists in other parts of the world.

Resources

Certain stakeholders can be particularly influential when they are associated with a source of funding which may pre-determine the solution to a perceived or actual issue. For instance, decision-makers may sometimes favour visible, tangible solutions, such as new radars. Considering the entire value chain helps people to think more broadly and systematically about what is actually needed to provide an early warning service that is fit for purpose and will meet user needs. It may disrupt preconceived ideas about what an effective service can be, as there are many potential pathways to improving warning effectiveness. Using a structured approach to choose between various options (Chapter 4) makes the design of a new service (or the redesign of an existing service) less haphazard and supports the prioritization of the various warning system components. The value chain for multiple pathways can be stress tested in hypothetical scenarios before investing heavily in feasibility or cost-benefit studies or making the wrong investment.

The key components of a successful warning system (Table 5.1) may be constrained in various ways - finance, access to adequate technology and infrastructure, data availability and quality, human resources, interagency coordination, and legal and regulatory factors. These will have a strong influence on what can be considered, particularly for establishing warning services in developing countries (Rogers *et al.* 2019). Analysing the warning value chain for the new system can help identify intermediate steps or phases on the way to providing a comprehensive early warning system.

Deciding whether to proceed

After identifying potential budget and other constraints in setting up a new early warning system, a crucial decision arises: whether to go ahead with the project. This decision involves carefully looking at the information that has been gathered and balancing the expected benefits with the effort and costs involved. What is the potential of the new warning system to mitigate risks, save lives, and reduce damage? Is it fit for purpose for the community? How will it enhance response capacity, improve coordination among stakeholders, and strengthen overall resilience to disasters? Is the proposed warning service financially or scientifically feasible or will expectations need to be scaled down? Will further research or additional resources be required to address the identified constraints and proceed effectively? What other factors could limit success? Are there any low cost changes that could be made to the proposed solution that would enhance the value?

The strategies described in Chapters 3 and 4 offer a systematic and robust approach to identifying what the service is expected to deliver, how value is generated, transferred and transformed through the chain, how costs and benefits will be measured and by what processes, thus guiding the decision-making process.

5.3 Developing and implementing the warning system

The detailed development and implementation of a new warning system is well-described in WMO guidelines (2015, 2021, 2022). Figure 5.3 depicts the necessary elements of an early warning system as an integrated value cycle of information subsystems.

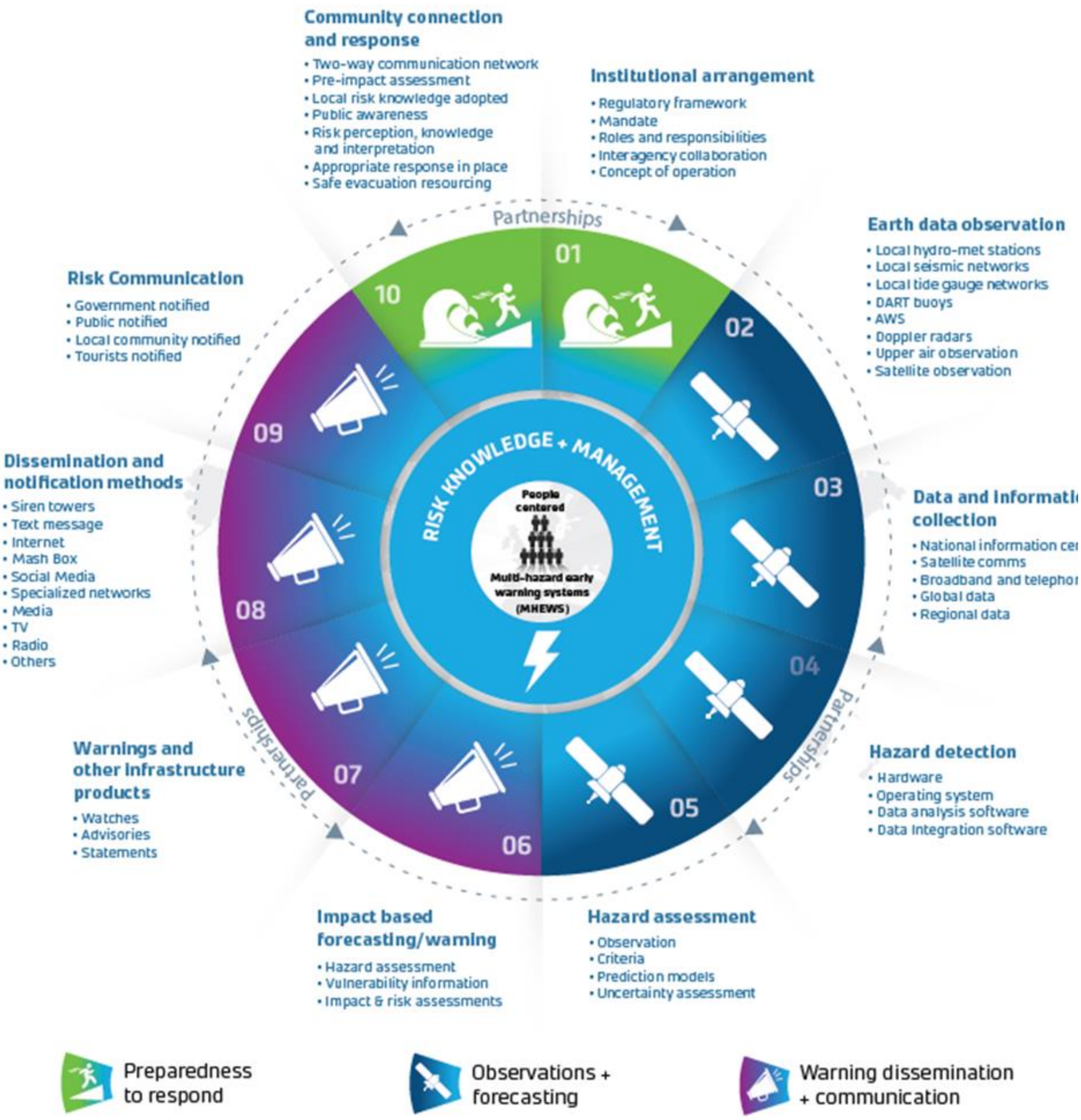


Figure 5.3. The end-to-end impact-based early warning system is a comprehensive integrated information system with aligned subsystems on monitoring and forecasting of diverse phenomena, impacts and risk assessment, communication, engagement and risk evaluation.

Source: Fakhruddin & Schick (2019), updated International Science Council (2023)

Since partnerships feature in virtually every part of the warning system, it is essential that the partners collaborate on its detailed design, development and implementation. Key aspects of the warning system must be collaboratively determined to provide users with actionable information while optimizing its relevance, accessibility, precision, timeliness, accuracy, suitability, and reliability. This naturally comes with trade-offs (for example, between timeliness and accuracy), which will need to be discussed and agreed. The strategies and tools introduced in Chapters 3 and 4 may be useful here.

As the technical and operational details emerge (Table 5.2), the specific roles and responsibilities of all partners in the implementation, delivery and verification of the warnings can be defined. Clear criteria, protocols, and channels for issuing warnings can be established. Communication/outreach strategies can be planned. Evaluation (Chapters 3 and 4) and verification strategies (described in the next section) can be created, and the outputs necessary for the evaluation can be designed into the system. Feasibility testing with the user community can help refine the system to optimize its value for their decision-making.

Table 5.2 Technical and operational features of warning systems

Technical features	Operational features
• Data and metadata management including acquisition, harmonization, interoperability and sharing strategies • Implementation of relevant technical tools (databases, models, information) • Dissemination platforms, protocols and formats such as XML/CAP, colour-coded graphics and GIS layers • Continuity of operations • Archiving	• Operational workflow between partners • Dissemination processes, communication and interaction with media • Backup means and contingency procedures • Real-time monitoring of impacts and feedback • Crisis management arrangements (escalation process, crisis communication) • Post-event assessment

Source: Adapted from WMO (2015)

It is expected that the partners bring much or most of the required knowledge and capability from their area of specialization. For example, NMHSs bring weather observations, numerical models, and weather knowledge, among other things. The community contributes local knowledge including vulnerable groups and areas, roads and shelters, and communication channels. Some new knowledge and capability may need to be developed if it does not exist - examples might include localized impact modelling and integration of climate change effects.

Triggers for issuing weather and hazard warnings may need to be determined from historic and climatological data and consultation with the community and emergency responders. Value of information approaches can guide the selection of thresholds for early warnings to balance the cost effectiveness or avoidance of losses against the costs of “acting in vain" (Lopez *et al.* 2020). Mitheu *et al.* (2023) showed how adjusting flood early warning thresholds according to crop calendars, in consultation with local stakeholders, could provide better information to support anticipatory action in Uganda. User-oriented thresholds can be developed by meteorologists, decision makers and communities drawing on local experience of a hazard and understandings of the impact of different levels of severity. For instance, the National Meteorological Service of Argentina collaborated with partners in emergency management and public organizations to redesign its weather warning service to be better oriented towards user's needs and decision-making (Scolobig *et al.* 2022).

Impact-based warning systems may need to develop impact knowledge (vulnerability, exposure, risk) as part of the project (WMO 2015, 2021). Value chain analysis may help in identifying some of the knowledge gaps. Some wealthy countries are experimenting with systems that transfer and translate information automatically through linked physical modelling and communication systems (Golding 2022); however, such systems are still immature.

For most hazards requiring early warning, shared professional insights are necessary as part of developing a warning strategy and ensuring consistency. This is particularly true in the case of compounding or multi-disciplinary hazards. For example, heavy rain might create flash flooding, landslide, or lahar (volcanic mudflow) risks, might feed riverine flooding, or might even trigger a volcanic eruption through lava dome erosion (Usman *et al.* 2023). It is far more effective if the warning system design allows collaborative professional input from a wide range of scientists who can give insights towards the warning strategy. Communication technology is a key enabler of this, or (if implemented poorly) can be a blocker in the value chain.

For a value chain to be effective and efficient, everybody within the chain must have access to the data that they need in an appropriate format considering the needs of the user for effective decision-making, and be able to trust that data (Harrison *et al.* 2022). That requires that data has clear ownership (for accountability), be quality managed to the degree possible, and be shared, including to community members where possible and appropriate. Shared data is part of developing a common ground between the affected community and the warning system actors. Data might include technical data (such as observations, including community observations such as shipping, pilot, and ground reports), and impact-related data. Tracking the flow of data and information through the value chain of the new warning system can indicate whether all partners are able to access the information they need. The information exchange exercise in Annex 1 may be useful for that purpose.

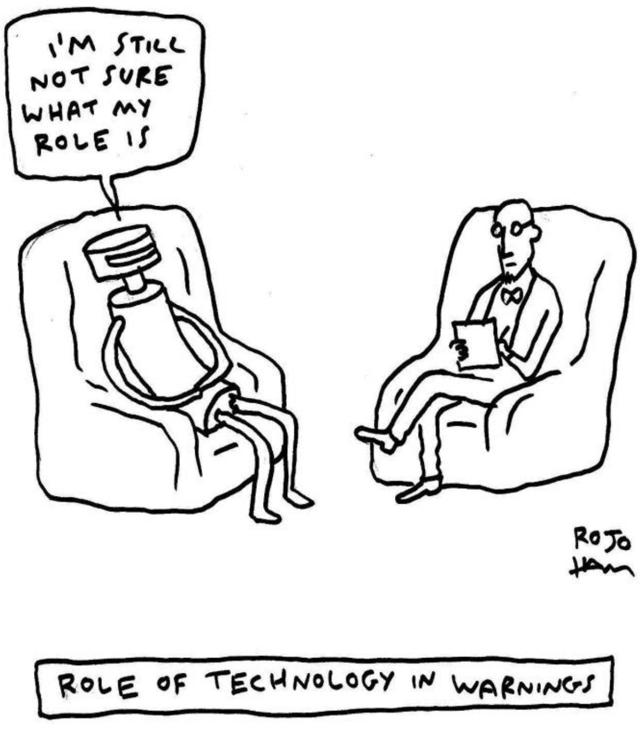


Figure 5.4. Discerning the best use of technology in the warning value chain is not always straightforward, particularly when it comes to what is appropriate and sustainable for a community.

Source: Courtesy Hameed Khan and Eugenia Rojo, from “Creating Effective Warnings for All” conference, UCL Warning Research Centre, September 2023

Technological choices in warning systems should reflect what is sustainable and scalable in the long-term and what provides a net benefit to the community (rather than, for example, create false expectations that a problem is solved, or prove to be a drain on maintenance resources). The impact of new technologies (individual or collective) can be conceptually tested in the value chain and evaluated for weaknesses. Going through that exercise can ensure that pilot projects are well designed and appropriate and not just a means of selling the latest gear. It may also help identify where processes could be optimized to improve efficiency.

Evaluation methods, including ongoing evaluation, should be built into the system's design from the start to ensure that its socioeconomic benefits can be measured; this is much more difficult when evaluation is left as an afterthought (Tall *et al.* 2018; see also Section 5.4). This includes access to relevant data sources, monitoring tools, and skilled evaluators. Including the evaluation in the early phases of the new warning system also allows adjustments to be made during development and facilitates iterative learning for the partners. Testbeds may also be useful for evaluating warning system prototypes. The experience of the user community and the value of the warning system to them is the ultimate measure of efficacy.

People will need to receive appropriate training and education on how to operate and use the new warning system. For service providers this may include training on data collection and analysis, warning dissemination procedures, emergency response protocols, and community engagement strategies. Organizations sharing training material with warning system partners can help build skills and understanding across the service chain. Involvement of the community in the design of the early warning system will inform the training and educational needs and relevant strategies and tools to raise awareness about the early warning system, its purpose, and how to respond to warnings. Community participants in the warning process may need to develop skills for aspects such as local system deployment and maintenance. Scientists and technicians supporting the warning system may also require targeted training.

It can be useful to pilot test the early warning system with a small segment of users to assess its effectiveness, usability, and acceptability. Feedback on areas for improvement can be collected from all stakeholders at this stage and later during routine operations, supporting a value cycle of progressive refinement.

Once the early warning system has been tested and refined, the next step is to scale it up to reach a wider audience and integrate into relevant disaster risk reduction and management frameworks. This may require further tuning of the warning value chain to integrate with broader aspects of governance and response. Case Study 10 gives an example of the integration of heatwave warning and decision support services delivered by an NMHS into national and state government, emergency service, and health agency procedures.

Case Study 10: Heatwave warning and decision support service for Australia

Effective response to heatwaves in Australia requires collaboration between national, state and local governments as well as health and emergency service agencies. Over a 3-year period, the National Heatwave Warning Group, comprising the Bureau of Meteorology (BOM, 2023) and state health and emergency services agencies, developed a Framework for a nationally consistent end-to-end warning service for heatwaves. The Framework establishes an agreed definition of heatwaves and sets out the roles and responsibilities of the different levels of government and state emergency service and health agencies across the end-to-end warning system (Figure 5.5).

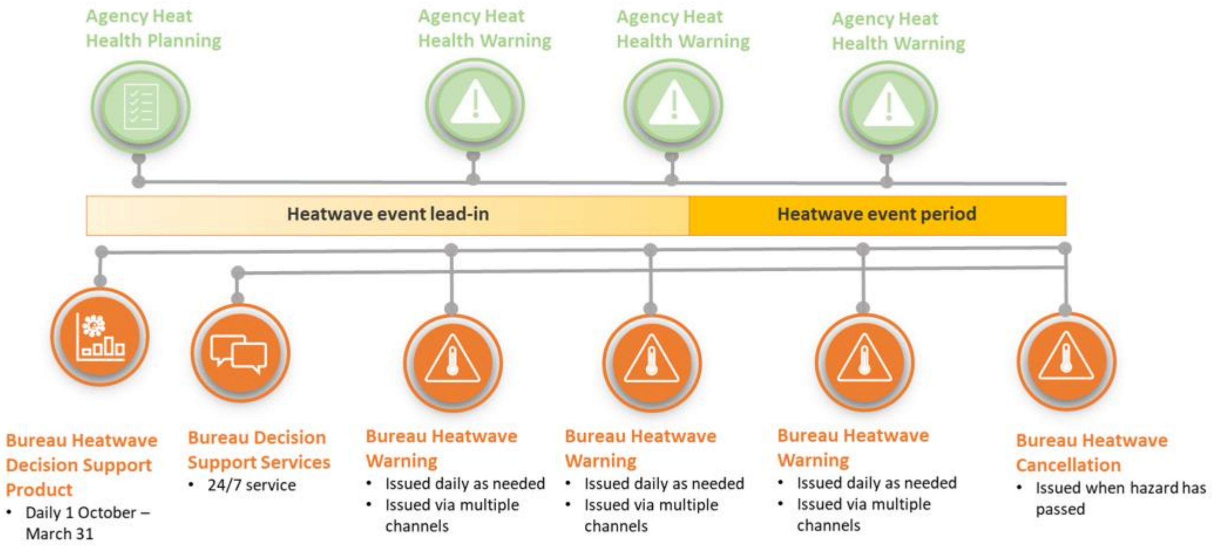


Figure 5.5. Interaction between BoM and state warnings in the National Heatwave Warning Framework

Source: Bureau of Meteorology (2023)

The agreed service includes early advice of an impending heatwave through a decision support product for emergency services and health agencies which is linked to jurisdictional heat health plans. These plans include various activities before, during and after heatwaves. They can trigger mitigation measures, including pre-positioning of resources, activation of local health networks and outreach to vulnerable groups (see, for example, SA Health Extreme Heat and Heatwave Strategy 2023).

As the heatwave approaches, the BOM issues public heatwave warnings, which include a description of the expected weather, its likely impact and general protective actions. In parallel, state emergency services issue heatwave warnings with nuanced and targeted messaging and advice.

Securing continuing funding, conducting ongoing community engagement to build local capacity, and cementing institutional partnerships for long-term operation and maintenance will all contribute to the warning system being sustainable in the long term. To obtain ongoing support, it is essential to provide clear evidence of the warning system's effectiveness in saving lives and reducing economic costs and losses (see Case Study 11).

Case Study 11: Early Warning System for Lake Victoria

Forecasters from the NMHS of Kenya, Tanzania, Rwanda and Uganda worked with leaders of fishing communities and other local, regional and international partners to co-develop a new regional early warning system for the Lake Victoria Basin (Roberts *et al.* 2022). This initiative, called the High Impact Weather Lake System (HIGHWAY) project, set the groundwork for a sustainable regional early warning system that utilizes weather data and marine forecasts to minimize loss of life and property damage, thus empowering fishermen, lake travellers, and lakeside communities to plan their daily activities effectively (Figure 5.6). The leadership of WMO in coordinating the work of the national weather services was instrumental in fostering trust and cooperation among the diverse stakeholders.

The HIGHWAY project invested in elements across the value chain from weather knowledge to community benefit. A year-long field campaign gathered data for studying the evolution of thunderstorms over the Lake Victoria Basin. Convection-permitting numerical weather prediction forecasts and novel nowcast products supported forecasters in creating new actionable and understandable marine forecasts and convective advice, co-designed with other project participants and leaders from fishing cooperatives.

Figure 5.6. Checking the latest forecast at a landing site in Uganda.

Source: Roberts et al. (2022). Photo by WMO.

Collaborative efforts in regional and national workshops led to sustained changes. Presently, three of the NMHSs coordinate daily via forecaster phone discussions to ensure aligned content and accurate severe weather forecasts for East Africa and harmonized twice daily marine forecasts for ten forecasting zones in Lake Victoria. Information is disseminated to a broad audience in local languages via radio, Beach Management Units, local intermediaries, and WhatsApp. Cooperative production and communication of the marine forecasts significantly increased trust in forecasts and weather warnings among fishermen, travellers, and lakeside communities, prompting them to take necessary precautions for safe travel and safeguarding their livelihoods. The resulting benefits included an estimated 30% drop in drowning fatalities and reduced weather-related losses.

5.4 Monitoring and evaluation

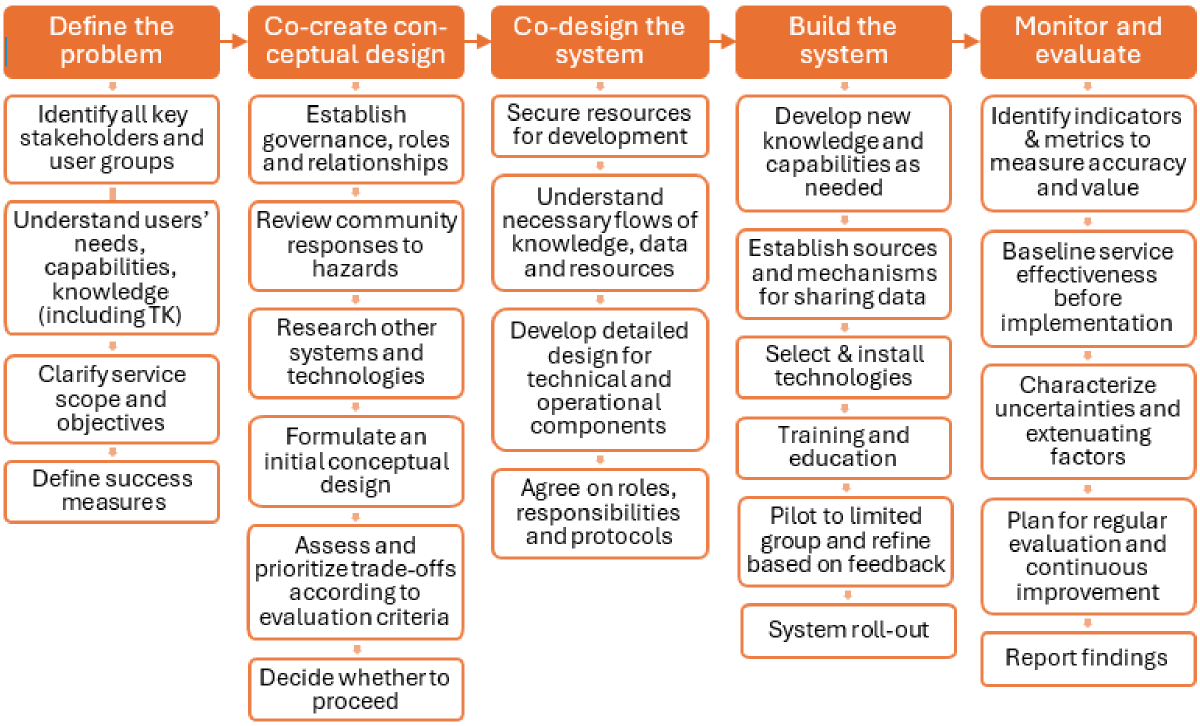
Establishing robust monitoring and evaluation mechanisms is essential to track the performance and value of the early warning system over time. This involves measuring key indicators such as warning lead times, accuracy, warning response rates, and the effectiveness of risk communication strategies. NMHSs often track gains in forecast accuracy but may overlook improvements in downstream elements of the service. Involving partners and user communities in evaluating the entire warning value chain requires a more systematic, collaborative and robust evaluation process than typically undertaken. Investing this extra effort into evaluating the whole value chain provides the clarity of thought to support an agile, dynamic service improvement cycle.

Once the warning system is in operational use, regular verification and evaluation of warnings is recommended (see Box 5.1). Tracking and describing near-misses and false alarms can help users understand the rationale for those warnings; this transparency enhances both credibility and engagement (Fearnley and Kelman 2021). Partners can play an important role as evaluators, providing performance data for monitoring and valuable feedback for improvement.

Measuring warning performance for many events (including missed events and false alarms) is needed to get a realistic assessment of the effectiveness of a warning system. It may be necessary to manage expectations, as many other factors beyond the warning system also act to influence the outcomes of hazard events. If a theory of change analysis was done as part of the service design, the assumptions that were made in that analysis can be tested through the evaluation process.

5.5 Steps for using a value chain to co-design a service

A summary of steps to co-design a new service is:



5.6 Further reading

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International Federation Red Cross/Red Crescent (IFRC) (2021). *The Future of Forecasts: Impact-Based Forecasting for Early Action*.

WMO (2022). Guidelines on Implementation of a Coastal Inundation Forecasting–Early Warning System.

World Bank (2023). *Designing Inclusive, Accessible Early Warning Systems - Good Practice and Entry Points*.

Box 5.1. Warning verification

Verification of warnings against observations is essential to monitor their quality as well as inform where improvements should be made. Verification helps inform users about how trustworthy the warnings are (for example, how often false alarms and surprises/missed events occur, and the magnitudes of any biases). Best practice is to verify all parts of the value chain, from measuring the accuracy of model output, hazard and impact forecasts to confirming whether warnings were received and acted on. Since an end-to-end verification is often not possible, warning verification tends to focus on those aspects for which observations are more easily obtained, namely, weather and hazard forecasts (Robbins and Titley 2018).

Estimating the accuracy of a warning system requires verifying many warning events to get robust statistics. It may take quite a long time to accumulate enough samples for such assessments, especially for rare events. Depending on the situation, the estimated accuracy for lower warning levels may be used to try to infer accuracy for rarer events. Estimating the statistical confidence in the verification results (for example, confidence intervals) is important when comparing different warning systems, or assessing whether a change in a warning system has led to improvements that are statistically significant.

Both objective and subjective verification are useful. The evaluation and verification approaches can be co-designed or agreed with hazard forecasters and warning users and include user-oriented metrics that reflect the use of the warnings by partner organizations and the broader community. Things to verify include the timing and location of hazards, their intensity (especially if standard operating procedures rely on thresholds to take action), severity of impacts, amount of lead time, and warning uptake.

Verifying impact forecasts is still an emerging field. The IFRC guide on *The Future of Forecasts: Impact-Based Forecasting for Early Action* (2021) provides excellent guidance on warning verification that goes beyond weather and hazard verification. It recommends comparing warnings against hazard and impact information from a myriad of sources such as government, civil protection agencies, disaster risk reduction agencies, media, social media, webcams and traffic cameras, and community groups and individuals. It introduces the Met Office Subjective Verification Process, a subjective assessment done by meteorologists soon after an event, which includes a scoring system that can be monitored over time and across different hazards.

Tool: Impact-based warning verification template – This template provides for a semi-quantitative verification of warning impact level, area, validity time, lead time, and wording.

Annex 1

Approaches and metrics for relating forecast value (utility in decision-making) to forecast accuracy are starting to be used more, especially as weather forecasts accompanied by quantitative uncertainty information (typically issued as probabilistic forecasts) increasingly drive decision-making in renewable energy, transport, agriculture and other sectors. Value-based metrics take into account the user's cost to take protective action, their avoidable losses when action was taken based on a warning, and the unavoidable losses that occur whether or not protective action was taken. Cost-loss models can be applied to categorical forecasts (de Elia *et al.* 2024), while the relative economic value metric, which measures forecast value for the full distribution of user cost-loss ratios, is often applied to probabilistic forecasts.

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Acronyms

CBA	Cost-benefit analysis
CEA	Cost effectiveness analysis
CWS	Commercial weather service
DRR	Disaster risk reduction
EM	Emergency management
EW4All	Early Warnings for All initiative
EWS	Early warning system
HIWeather	High Impact Weather (a WWRP project)
IVC	Information value chain
MCA	Multi-criteria analysis
MHEWS	Multi-hazard early warning system
NMHS	National meteorological and hydrological service
REAP	Risk-informed Early Action Partnership
TK	Traditional Knowledge
TOC	Theory of change
UN	United Nations
VC	Value chain
VOI	Value of information
VOICE	Value of Information Characterization and Evaluation
WMO	World Meteorological Organisation
WSCA	Weather Service Chain Analysis
WTP	Willingness to pay
WWRP	World Weather Research Program

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Annex 1. Value chain tools and activities

This annex provides tools and activities for using value chain approaches to describe, improve, value and co-design early warning systems. Some are specific to the early warning system context and were designed as part of the HIWeather Value Chain project. Others were created by value chain experts in the field of hydrometeorology and are described in greater detail in the relevant literature. Some generic tools that are widely used in the broader development and business communities are included.

Readers are encouraged to look online for additional resources (for example, BetterEvaluation.org has many excellent resources).

Contents

A1.1 Understanding value chain concepts

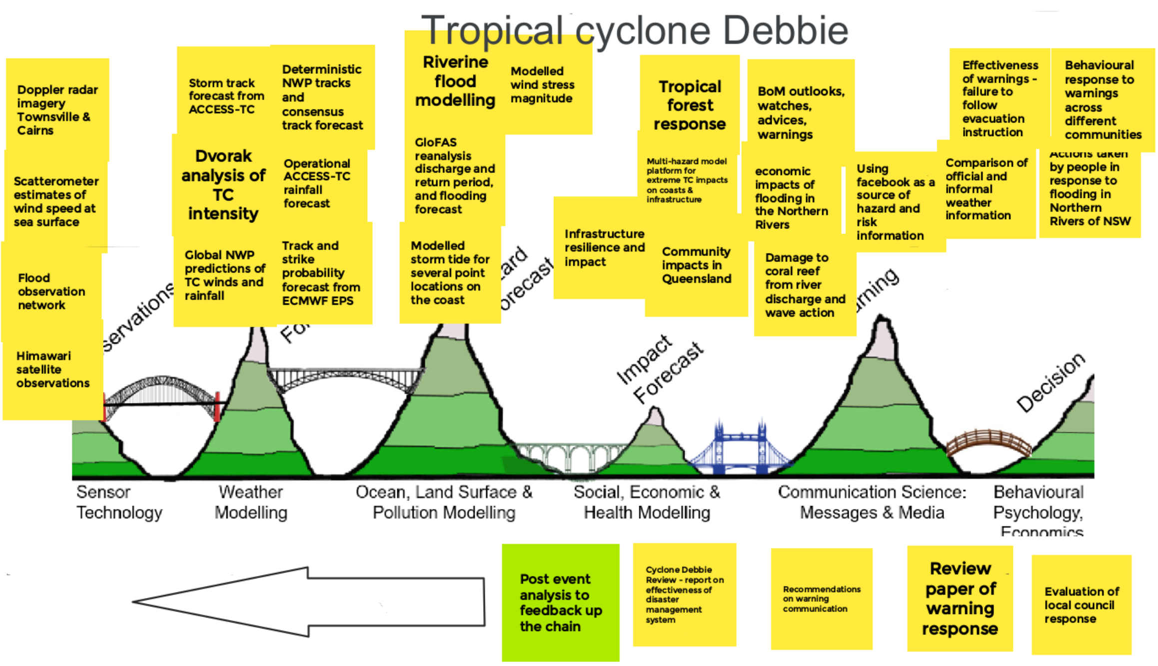
a. "What's in the value chain?" activity

Description: Participants use sticky notes (or electronic equivalent) to learn about the elements in a structured warning value chain. It is a good introductory activity for individuals and groups who may be learning about value chains for the first time, to think about who is involved in the value chain, what information they produce and use, and their decisions and actions. Allow 30-60 minutes for the activity and group discussion.

Preparation: At the top or centre of a flipchart, blank page or online collaboration board, place a picture of a conceptual value chain. On cards or sticky notes list 15-30 elements of a value chain for a particular type of service. For example, a value chain for flood warnings might include things like rainfall measurements, numerical modelling, weather forecasters, flood inundation maps, agency websites, emergency managers, etc.

Activity: Participants place the cards near the part of the value chain where they think they belong. Cards can be duplicated if necessary. Participants can also write new cards. An example is shown below. **Alternate activity:** Instead of providing pre-prepared cards, participants write their own cards to suggest what actors, actions, and information go with each part of the value chain. Allow more time for this version.

Discussion questions: What were some of the challenges you encountered? What influenced your decisions when placing the elements of the value chain? Did you notice any gaps or redundancies in the value chain?



A1.2 Describing a service

a. Value chain table

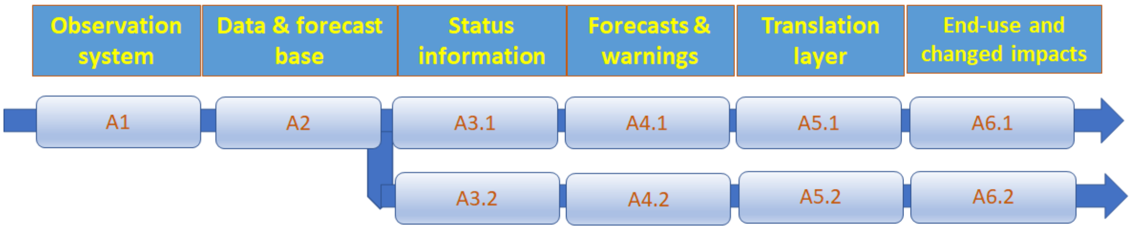
An easy way to start describing the value chain for a specific service is to list the nodes, actors, and flows in a table. The third column is offset to show the primary flows of information between nodes.

The example shown here is for a hypothetical flood early warning system in Germany.

Node	*Actors*	*Flows (information / data / relationships)*
Observations	• German Weather Service • Private weather services	• Open data • Geowebservices
Weather forecast	• German Weather Service	• Weather model output
Hazard forecast	• Federal warning centres • Hydrology department	• Web portal
Impact forecast	• (Federal warning centres)	• (Briefing)
Warning	• Federal Office of Civil Protection and Disaster Assistance • German Weather Service (rain) • Federal warning centres (flood) • TV/radio broadcasters	• Modular warning system • Warning apps (NINA, KATWARN) • Sirens/loudspeaker announcements • News
Decision-making	• Civil protection • Local governments / institutions	• Briefings • Press release
Response	• Governmental disaster aid • Civil protection • Community (i.e., households and businesses)	

b. Value tree

When multiple services depend on the same information produced upstream in the value chain it may be useful to depict the value chain as a *value tree*. This enables better understanding of economies of scale and scope and other synergies (production-wise) between closely related services. In this generic example there is a common data root that supports similar services (A). Subsequent value chain segments are consecutively numbered (1 – 6), while for different branches of the value tree a sub-type number is added by segment (n.1, n.2).



c. Value chain description and analysis activity

Description: Participants describe a value chain for a warning service that they have some familiarity with, either in a generic sense or for a specific local or national service, and analyse how information moves through the value chain to support decisions. This activity works best when participants have at least a rudimentary understanding of value chain concepts. Allow 60 minutes to a few hours, depending on the desired depth of analysis and whether it is done by individuals or groups. The result is often messy; however, the messier the drawing the more learning has been accomplished!

Preparation: Provide participants with paper and pens, flipcharts, different coloured sticky notes, etc. or else use an online collaboration board or mind-mapping software. Participants should also receive a copy of the analysis questions listed below.

Activity: Participants draw a rough value chain of a particular warning service using any structure that represents their understanding of how it works. They then work through the analysis questions below, adding new information to the value chain. At the end of the session participants discuss their value chains with the other participants.

Analysis questions

What is the purpose of the value chain?

- What values / decisions / outcomes are important to end-users / decision makers?
- How does weather impact that?
- How does weather information relate to that?
- How would changes in / improvements in weather information change those outcomes?

Who creates the information and why?

- Who are the information producers?
- What do they use to create the information?
- What are their institutional and functional objectives (goals and roles)?
- What are their resources and constraints?

Who uses the information and why?

- Who are the actors / decision makers?
- What are their information needs?
- What are their resources and constraints?

What information moves between the actors?

- How do different nodes and actors in the value chain add value to information (convert information input to information output)?
- What channels are used to “transfer” that information?
- What is the content and format of the information that is transferred?
- How is the information “quality” assessed, if at all?

Who/what are the endpoints of the value chain? Who benefits from the information?

- What weather-related information do they need to make their decisions?
- What other information goes into their decision-making?
- What are their objectives, resources, and constraints?
- What impact does an event / non-event have on them?
- How would the benefits of improving information to them be measured?

High impact scenario:

- What would be a low probability / high impact event (say, a “billion dollar day”)?
- What causes the impact?
- How does weather affect the impact?
- How does weather information affect the impact?
- How does uncertainty affect decisions?
- How does uncertainty information affect decisions?

A1.3 Improving a service

a. Indicators for measuring the warning value chain

When establishing a baseline or evaluating a theory of change, measuring a set of specific, observable, indicators shows the current state and the progress made toward achieving specific outputs and outcomes. The table below gives a non-exhaustive list of indicators that may be useful for baselining and measuring the effects of a change in different parts of the warning value chain.

Since collecting the data for an indicator can take a fair amount of effort it is important to first agree on an essential set of relevant indicators that will meet the identified information needs for evaluation.

Table A1. Indicators for measuring elements and outcomes of the warning value chain

Node	**Observations**	**Modelling & forecasting**	**Impact prediction**	**Communication**	**Dissemination**	**Preparedness & response**	**Decisions**	**Outcomes**
Input indicators	Instruments/ network Spatial density Reporting frequency Latency	Update frequency Time range Horizontal resolution Temporal resolution Ensemble size Output volume	Vulnerability Demographic info · granularity · currency · reliability	Trigger Lead time Message content Severity levels	Update frequency Coverage (population, area) Channels	Disaster preparedness measures Response plans Evacuation strategies	Perceived risk Cost/loss factors Prior experience Trust in authorities Knowledge of actions Capacity to act	- - -
Output/ outcome Indicators	Data collected Coverage Number of instruments	Hazard type Likelihood Magnitude Onset Duration Area affected (location, extent)	Impact types Area affected Severity of impacts Duration of disruption Numbers of people killed, injured, displaced Cost of damage Data outages Crops damaged, animals killed Air & water quality	Number of formats (graphical, text, video, audio) Actionable advice tailored to users Number of languages	Number of warnings issued Coverage (population, area) Number of communication channels used	Number of calls for evacuation Lessons analyzed and documented Number of drills and exercises	Number of users of the service Number/percent of people who were evacuated	Avoided damages Saved lives Reduced disruption Enhanced public safety Healthier environment
Quality indicators	Observation density Measurement accuracy Data latency Network reliability Data accessibility	Lead time provided Spatial/temporal precision Accuracy metrics (bias, RMSE, etc.) Value metrics (REV, etc.)	Lead time provided Spatial/temporal precision Accuracy metrics (bias, RMSE, etc.) Value metrics (REV, etc.)	Lead time provided Clarity of warning regarding risk and impact Level of trust in warning providers Message consistency	Number/percent of people who received the warning Number/percent of people who understood the warning	Level of community risk awareness Adherence to response plan	Number/percent of people who acted on the warning	Level of user satisfaction with warnings

b. Warning Value Chain Questionnaire

The *Warning Value Chain Questionnaire* is a purpose-built template for capturing and analyzing the details of the warning value chain for a high impact natural hazard event, helping to draw valuable lessons. This comprehensive case study questionnaire was developed by the WWRP Value Chain Project to support the recording and analysis of information on the end-to-end production and flow of information and decision-making along the warning value chain. Chapter 3 gives more details.

An example of a completed questionnaire for Storm Eunice, which affected the United Kingdom in 2022, can be viewed at https://zenodo.org/records/12697561 (Neal and Titley 2024). An example of a rapid assessment for a surface water flooding event in the UK in 2022 can be viewed at https://zenodo.org/records/12770101 (Neal 2024).

c. Multi-hazard early warning system value chain vulnerability matrix

Applying a value chain vulnerability assessment across multiple hazards within a national or regional warning responsibility can highlight the areas in greatest need of attention. A matrix approach supports a high-level assessment of the vulnerabilities of a multi-hazard early warning system by providing a strategic view of multi-hazard system vulnerabilities (places where the system may fail) on a single page.

The process starts by evaluating the natural hazards of most concern (possibly using agreed reasonable worst case scenarios) and listing them in priority order. Then the current state of each major capability in the early warning systems is examined for each hazard. Colour shadings are assigned based on the degree of concern. A “red” assessment would indicate a major risk of warning system element failure in the scenario described, and a consequent risk to the effectiveness of early warnings. This approach can then be combined with value-tree analysis or other techniques to consider the impact of different interventions and whether they would be sufficient to lower the level of concern.

See Chapter 3 for an example of this approach.

Hazard	Observations	Weather / Phenomenon Forecast	Hazard Forecast	Impact Forecast	Warning	Decision
Most important hazard (risk level= extreme/ high/ moderate/ low)	Short description of scenario; major warning system vulnerability	Short description of scenario; significant room for improvement	Short description of scenario; some improvement needed	(etc.)	(etc.)	(etc.)
Next most important hazard (risk level)	(etc.)	(etc.)	Short description of scenario; minor improvement needed	(etc.)	(etc.)	(etc.)
(etc.)	(etc.)	(etc.)	(etc.)	(etc.)	(etc.)	(etc.)

d. Information exchange activity

Description: This group activity uses paired discussions between actors across the value chain to explore the effectiveness of their information exchanges. As information users, actors describe what information they need from the other actors as providers (for example, flood forecasters need rainfall information from meteorologists). As information providers, actors describe the information they provide to the other users (for example, flood forecasters provide information on flood stage to emergency services). By comparing what is *needed* with what is actually *provided* and *received*, it is possible to identify the gaps in the information flows in the value chain, consider the possible causes of those gaps and what could be done to address them. Allow about 90 minutes for the activity and group discussion.

Preparation: Create a set of blank tables similar to the one shown below, with one blank table for each pair of actors who are adjacent in the value chain. Additional tables can be created for non-adjacent actors if desired.

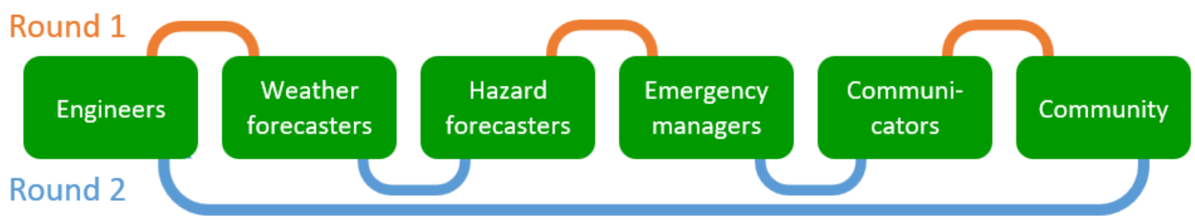
Activity: Allow two 30-minute rounds, one for each pair of adjacent users and providers in the value chain, similar to the example shown below. Allow additional rounds (and additional time) if non-adjacent pairings are included.

Round 1:

1. Choose someone to be the notetaker and someone to report back to the main group.
2. Actors in the user group agree on 3-4 types of essential data or information that they need to get from the provider group in order to do their job well.
3. For each type of data/information, discuss what is actually provided, any gaps or necessary improvements, barriers to the information being transferred, potential solutions to address the barriers, and the benefits of receiving the additional information.

Round 2: Repeat with different pairings. Round 1 users become providers in Round 2, and Round 1 providers become users in Round 2.

Group discussion: What did the providers learn about unmet users' needs? What did the users learn about the difficulty of providing certain data or information? What opportunities were identified for providing new data or information? What are some ideas for overcoming the barriers that prevent effective flow of information? How would that make the value chain more effective?



<table>
<tr><td colspan="6">Information flow between __________[user]____________ and _________[provider]_________ in the value chain for ________[hazard]_________</td></tr>
<tr><td>Users: What data / information do we really need?</td><td>Providers: What data / information do we provide to these users?</td><td>What improvement is needed in information content and/or flow?</td><td>What are the barriers to the right data / information reaching the users?</td><td>Suggestions to address the barriers</td><td>Benefit of improving</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

e. Logic model

A logic model is a concise visual representation that outlines the inputs (resources), activities (what is done), outputs (immediate results), outcomes (short and long-term changes), and impacts (broader societal changes) of a program or planned intervention. It provides a clear and structured framework for understanding how a change is expected to lead to improved outcomes over the short and long term. Its focus on the causal pathway complements the information value chain's focus on the information flow and supports a theory of change.

A logic model can form a basis for developing an evaluation plan by identifying key performance indicators and outcomes that should be measured. If monitoring and evaluation show gaps between the expected (target) and actual outcomes then adjustments can be made to the system to improve its performance.

A generic logic model template with an evaluation focus is given below.

<table>
<tr><th>Situation</th><th>Resources/ Inputs</th><th>Activities</th><th>Outputs</th><th>Outcomes</th><th>Impacts</th></tr>
<tr><td rowspan="3">Problem statement, including who is affected. Establishes a baseline for comparison after the change has been implemented.</td><td>People, expertise, partners, funds, infrastructure, facilities, etc.</td><td>What will be done to implement the change? E.g. activate a new channel for warning messages</td><td>Numerical data based on the activities. Estimating outputs before making the change helps with review and evaluation.</td><td>What will the change achieve? Ideally also measurable. E.g. enhanced response to warnings</td><td>Long-term benefits, e.g. reduced loss of life</td></tr>
<tr><td colspan="2">Assumptions</td><td colspan="3">External factors</td></tr>
<tr><td colspan="2">What is needed for the change to be effective?</td><td colspan="3">What might prevent the change from being effective?</td></tr>
</table>

- - - - - Planned change - - - - - -   - - - - - - - - Intended results - - - - - - - -

A1.4 Valuing improvements in a service

a. Cost-benefit analysis

Cost-benefit analysis (CBA) assesses the economic and financial implications of introducing a change by quantifying and balances the costs of implementing improvements against the anticipated benefits that will accrue over time. The Harvard Business School blog gives a friendly basic explanation of CBA:

Stobierski, T. (2019). *How to do a cost-benefit analysis and why it's important.* https://online.hbs.edu/blog/post/cost-benefit-analysis

CBA can be implemented using specialized software or spreadsheets. The New Zealand Treasury has developed a spreadsheet-based CBAx tool (https://www.treasury.govt.nz/information-and-services/state-sector-leadership/investment-management/investment-planning/treasurys-cbax-tool) that aids in social cost-benefit analysis and decision-making by helping agencies monetize impacts and compare different options. The tool was designed for social sector agencies but can be used for various initiatives, including the net benefits from improving and creating an early warning service.

When to use it: Use the CBAx tool when you need to conduct a cost-benefit analysis to compare different options, and to take a consistent and rigorous approach to assessing societal impacts, costs, and benefits.

How to use it:

1. Familiarize yourself with the CBAx tool and its components.
2. Gather relevant data and evidence about the impacts of your initiative.
3. Use the tool to quantify impacts and success rates, considering both monetized and unmonetized impacts.
4. Apply the tool's assumptions and values consistently to ensure transparency and informed decision-making.
5. Consider all impacts, including those that can be monetized using the tool and those that cannot.
6. Use the tool's database of impact values or add your own values as needed.
7. Discuss the results of the analysis, considering all factors, and use them to inform value-for-money advice and decision-making.

Pros:

- Helps agencies take a consistent approach to cost-benefit analysis.
- Encourages a long-term view of impacts.
- Makes assumptions explicit and values costs and benefits consistently.
- Provides a basis for informed choices between different options.

Cons:

- Requires quantification of impacts and success rates, which may be challenging.
- Assumes values for impacts, which may vary in different contexts.
- Users should apply subjective well-being values with care to avoid overestimating impacts.

b. Multi-criteria analysis

Multi-criteria analysis (MCA) or Multi-criteria decision analysis (MCDA) is a decision-making tool for evaluating and comparing multiple options or alternatives based on various criteria. Unlike methods that focus solely on economic costs and benefits, MCA considers a broad range of factors, including qualitative and quantitative criteria, to provide a more comprehensive and transparent assessment. Criteria are assigned different weights based on their importance, with the criteria and weights often selected by stakeholders. Each option is scored against each criterion, then these scores are weighted and aggregated to yield an overall ranking of the options.

MCA enables users to understand the trade-offs involved in choosing one option over another. For example, a cell phone-based warning might be more expensive than a siren-based warning system but have much greater reach.

Some friendly online resources for learning more about MCDA are:

Donnellan, A. (2022). *Introducing multiple criteria decision analysis* (video format). https://www.csiro.au/en/news/all/articles/2022/september/introducing-multiple-criteria-decision-analysis

Government Analysis Function (2024). *An Introductory Guide to Multi-Criteria Decision Analysis (MCDA)*. https://analysisfunction.civilservice.gov.uk/policy-store/an-introductory-guide-to-mcda/.

c. Value of Information Characterization and Evaluation (VOICE)

This organizing framework enables better understanding of how actors in an information value chain create, translate, communicate, and use weather-related information to produce value (Lazo and Mills 2021). It uses an “economics” approach to identify at each node what the objective of the actor is, what their constraints are, and what resources they have. This may help to better identify how they intake, transform, and pass on the information or use the information in decision-making. Understanding their objectives may help understand why they do what they do with the information, and understanding their constraints may facilitate improving that information.

The information that the actors use and produce at each node can be characterized by its content and quality attributes such as precision, accuracy, timeliness, reliability, and so on. As information flows through the value chain each actor transforms and enhances it by applying their knowledge and resources.

See Chapter 4 for the VOICE template and a description of how to use it as an evaluation tool.

d. Weather Service Chain Analysis

Weather Service Chain Analysis (WSCA; Perrels *et al.* 2012, 2013; see also Chapter 4) explores how weather information progressively loses value due to the compounding effects of imperfect attributes: forecast accuracy, customer orientation (information appropriateness), access, comprehension, ability to respond, and response effectiveness. WSCA can be applied qualitatively using the table below to describe the current state and suggest what type of improvement(s) might lead to the greatest benefit.

Quantitative WSCA involves estimating the efficacy P_i, the percent of the maximum attainable performance of each attribute i. This can be done from available data and/or expert opinion (see

Perrels *et al.* 2012 for approaches they used). Multiplying the efficacies (as fractions) across all (n=6) attributes gives the overall efficacy, that is, the percent of the potential benefit that is realized.

$$P = \prod_{i=1}^{n} P_i$$

If the average annual losses associated with the hazard are known with (L_W) or without (L_0, the baseline) the early warning service being in place, then the direct value of the weather information can be estimated as the difference between the losses with and without the warnings:

$$\begin{aligned} \text{Value} &= L_0 - L_W \\ &= P \cdot L_0 \\ &= [\, P / (1-P) \,] \cdot L_W \end{aligned}$$

It is quite common in practice that only the average annual losses with the warning system in place are known (L_W). In this case, one has to take care to standardise the damage figures with respect to contextual changes in the period between the baseline and current years(s), such as population growth, change in property value, etc. In the fortunate case that both L_0 and L_W are known, there is an opportunity for cross-validation, which can raise the reliability of the estimated fractions within WSCA.

The increase in value from improving one of the attributes is easily calculated by applying the improved efficacy P_i and computing the difference between the old and new value. Some efficacies may be monitored, such as forecast accuracy and access to weather information, but for the remainder estimates have to be obtained by means of surveys, behavioural lab experiments, or from earlier studies using benefit transfer.

i	**Filtering stage (attribute)**	**Recommendations for weather service provider**	**Current state (qualitative)**	**Efficacy (%) (quantitative)**
1	*Weather forecast accuracy*	Up-to-date and well maintained weather observation and forecasting system; adequate and 24x7 staffing; monitoring and evaluation of forecast accuracy.		P_1
2	*Customer orientation of the information*	Provision of technical forecast information in textual and pictorial formats meeting information needs of targeted user groups; well-tended and lasting customer relations.		P_2
3	*Access to weather information*	Weather / hazard information distributed through diverse media channels to maximise reach to different users; emergency back-up; technical and economic access to media channels.		P_3
4	*Comprehension of the information*	Easy to grasp representation of information using standard terms; trust (including possibilities and limits of forecasts); further education via schools, media and customer relations.		P_4

5	*Ability to respond effectively in a timely manner*	Timely availability of weather / hazard information (related to 24 x 7 staffing and agreement with media channels on access).		P_5
6	*Actual effectiveness of responses*	Largely outside the realm of influence of the weather service provider, but promotion of education on (use of) weather / hazard information will help (step 4).		P_6
	Overall efficacy = Percent of potential value that is realized			$P = \mathbf{\Pi} P_i$

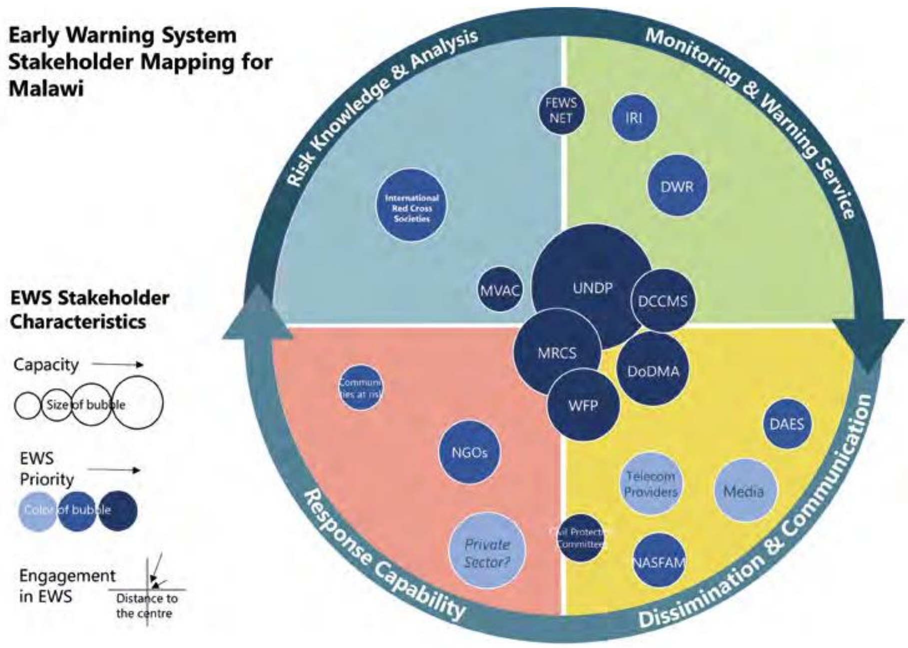
A1.5 Co-designing a new service

a. Stakeholder mapping

Description: A stakeholder map is a diagram that aims at clarifying roles and relationships. It is useful during the project planning, implementation and evaluation phases. When created together with stakeholder representatives it builds shared understanding and helps manage expectations.

Activity: Start by brainstorming a list of all of the stakeholders, both those involved in the project/service delivery, and those who may be affected by the service or have an influence on it. On a large piece of paper, whiteboard, or electronic collaboration tool, draw a set of three concentric circles, with the inner circle to hold the most engaged stakeholders and the next two "layers" to hold progressively less engaged stakeholders. Group the most critical stakeholders according to their role similarities, perhaps representing each group using a different colour. Then place the critical stakeholders on the map based on their roles and their level of engagement. Relationships and exchanges between stakeholders/groups can be shown with connecting lines and descriptors.

The activity described above is one of many different ways to map stakeholders. The example below uses quadrants to group the roles according to where they fit in a multi-hazard early warning system. Different shades and sizes of stakeholder labels represent early warning system priority and stakeholder capacity, respectively.



Stakeholder mapping in Malawi (from International Federation Red Cross/Red Crescent 2021)

b. Impact-based warning verification

Verifying an impact-based warning involves looking at the performance of several nodes in the warning value chain. The UK Met Office objectively verifies weather and hazard forecasts against observations using a variety of metrics. Subjective verification of the impact-based warning and communication uses the template below.

UK Subjective Verification Form (form as of March 2015)

1. Warning summary

Add details of the warning being assess or, if no warning issued, add details of the medium or high impacts observed including the area and period over which they were observed for the purposes of assessing a potential "miss".

Issue Date/Time *(if warning issued)*			
Valid From *(or earliest time of observed impacts)*			
Valid Until *(or latest time of observed impacts)*			
Summary of the area of risk *(Give a brief summary of the area highlighted in the warnings or, if no warning was issued by medium or high impacts were observed, give details of the area(s) over which the impacts were observed.)*			
Matrix Information *(Indicate in the boxes below where the tick appeared in the matrix of the warning. If no warning was issued give only the levels of impacts recorded.)*			
Likelihood *(VL, L, M, H)*		Impact *(VL, L, M, H)*	
Brief Summary of Impacts Observed			

(Highlight some of the main impacts observed and provide an assessment of the level – very low, low, medium or high – of those impacts.)	

Other Information *(Please add any other comments you may wish to be taken into consideration when assessing this warning/event, e.g. YLO warnings already in force and considered adequate at the time, discussions with FFC/SFFS/Advisors which influenced the issue, any discussions with other local agencies, government departments, etc.)*	

Now complete the assessment below. Only Section 2 counts toward the PWS target. Sections 3, 4 and 5 are noted for the purposes of continuous improvement both in terms of forecasting practice and service delivery.

2. Assessment of Issued Warning

Impact Levels	
3	*Impact column ticked in warning is consistent with impacts experienced*
2	*Impact column ticked in warning is within one level of impacts experienced, e.g. if warning indicated "medium" impacts while those experienced were "low"*
1	*Impact column ticked in warning is within two levels of impacts experienced, e.g. if warning indicated "medium" impacts while those experienced were "very low"*
0	*Impacts were reported and no warning was issued or no impacts were reported*
Comments as necessary *(Add any further information which influenced your marking.)*	
Assessment Score for Impact Level *(0, 1, 2 or 3)*	

Area Affected	
3	*All impacts noted were within the warning area*
2	*The impacts occurred generally within the area indicated but the area is deemed to be too large or slightly too small*
1	*The area is generally displaced from the main impacts but a few impacts occurred within it*
0	*No warning was issued or there were no reported impacts in the area identified by the warning*
Comments as necessary *(Add any further information which influenced your marking.)*	
Assessment Score for Area *(0, 1, 2 or 3)*	

Validity Time	
3	*All the impacts were noted within the warning validity time and the warning was issued at least 2 hours before the start validity time*
2	*Most of the impacts occurred within the validity time while others were no more than 2 hours outside the period*
1	*Some of the impacts occurred within the validity time but most occurred within 2 hours either side of the period*
0	*No warning was issued none of the impacts identified occurred within the validity time period*
Comments as necessary *(Add any further information which influenced your marking.)*	
Assessment Score for Validity Time *(0, 1, 2 or 3)*	

Total Score *(out of 9)*		
Overall Marking Assessment		
0-2	Very Poor Guidance	A missed warning or false alarm, i.e. either at least "medium" impacts were observed without any warning being in place, or a warning was in place but no impacts were observed.
3-5	Poor Guidance	A warning was issued, but it was either issued too late after the onset of the event, or the impact level, area and/or validity time were significantly different to those observed so that the warning was of limited use to responders and the public.
6-7	Good Guidance	Generally the warning was of use to responders and the public, but could have provided more accuracy of usefulness in terms of impact levels, area covered, validity time and/or timeliness of issue.
8-9	Excellent Guidance	The impacts, area, and validity time of the warning were closely in line with what was observed, and the warning was issued in good time before the onset of the event.

3. Warning issues more than 24 hours ahead?

Please note here if a warning was issued more than 24 hours ahead of the event. Although this is not formally part of the assessment process, information in this section may be used to inform overall marking decisions in warning situations.

Was an alert issued more than 24 hours ahead?		Yes/No?
Comments as necessary *(Add any further information which you feel may be useful)*		

4. Wording of the Warning

Please assess and comment on the wording of the warning (both main section and Chief Forecaster's Assessment) so that feedback can be provided to Chiefs on good practice, etc.

Wording of the Warning	
Very Good	*The wording of the warning was clear and very helpful to the reader with a good explanation of uncertainties, reasons for changes from previous issues, etc.*
Good	*The wording of the warning was reasonably clear but some areas were identified which could have improved it*
Poor	*The wording might have caused some confusion to the reader and/or was too brief*
Very Poor	*The wording of the warning was obscure or too technical and generally unhelpful to the reader*
Comments as necessary *(Add any further information which influenced your marking.)*	
Assessment Score for Wording *(VG, G, P, VP)*	

5. Lessons Learned

Please summarize any learning points you feel come out of this warning either in relation to the issuing of the warning or in relation to the assessment.

Annex 2. Economic valuation methods

This annex provides further guidance on the methods listed in Table 4.1 for valuing improvements in early warning systems, following WMO *et al.* (2015) and Lazo and Mills (2021). It highlights the resources and steps that are required for each valuation method and, where possible, suggests a case study from the literature.

The aim is to inform agencies looking to justify, design, and enhance early warning systems through rigorous economic valuation.

A2.1 Contingent valuation method (CVM)

- **Definition:** A survey-based economic valuation method that gauges individuals' willingness to pay (WTP) for a hypothetical improvement in services, such as improved accuracy or faster dissemination of warnings.
- **Idealized case study:** A coastal city plans to upgrade its tsunami early warning system with better precision and user-friendly alerts. A survey reveals high WTP among residents for the proposed enhancements.
- **Monetization outcome:** The aggregated WTP provides a monetary value, directly informing funding and prioritization of early warning system improvements.
- **Requirements for implementation:**
    - **Resources:** Economists, survey designers, data analysts.
    - **Technology:** Survey software, statistical analysis tools.
    - **Data sources:** Population demographics, previous WTP studies.
    - **Social and political checks:** Stakeholder engagement, ethical considerations in survey design.
    - **Step-by-step:** Design the survey, disseminate, analyze responses, aggregate WTP.
- **Reported case study:** Joseph et al. (2015) highlighted the significant WTP for flood warning system improvements in England and Wales.
- **More information:**
    - Brief introduction: https://www.youtube.com/watch?v=__xzmIG4L8s
    - A practical guide provided by the Asian Development Bank outlines steps for measuring WTP for non-market benefits like those provided by early warning systems. This includes designing effective sampling strategies and contingent valuation questionnaires, ensuring comprehensive stakeholder engagement, and managing and analyzing data to inform early warning system funding and prioritization. https://www.adb.org/publications/valuation-nonmarket-benefits-project-economic-analysis-guide
    - The OECD provides further insight into applying the CVM within environmental economics, emphasizing its flexibility and broad application range for non-market goods. For more detailed exploration, the OECD iLibrary's "Cost-Benefit Analysis and the Environment: Further Developments and Policy Use" offers an in-depth look at good survey design and valuation within CVM, highlighting its relevance across a

wide range of non-market changes.
https://read.oecd-ilibrary.org/environment/cost-benefit-analysis-and-the-environment/contingent-valuation-method_9789264085169-7-en#page1
https://www.oecd-ilibrary.org/sites/9789264085169-7-en/index.html?itemId=/content/component/9789264085169-7-en

A2.2 Conjoint analysis

- **Definition:** A method that evaluates how individuals value different attributes of a service through choices made in survey scenarios. It entails some form of ranking of preferred attributes.
- **Idealized case study:** An inland community frequently affected by flash floods evaluates preferences for alert lead times vs. accuracy in warnings.
- **Monetization outcome:** Preferences quantified reveal prioritization for longer lead times, influencing budget allocations toward forecasting technology.
- **Requirements for implementation:**
  - **Resources:** Market research experts, conjoint analysis specialists.
  - **Technology:** Advanced survey and conjoint analysis software.
  - **Data sources:** Detailed early warning system attributes, user preference studies.
  - **Social and political checks:** Inclusivity in survey population, transparency in attribute selection.
  - **Step-by-step:** Develop survey, conduct conjoint analysis, apply findings to early warning system improvements.
- **Reported case study:** Lee *et al.* (2014) explored public preferences for a pollen forecast system in South Korea through conjoint analysis.
- **More information:**
  - Brief introduction: https://www.youtube.com/watch?v=vQKlHnOeSyY
  - For implementing conjoint analysis in early warning systems, several tools are available, each with unique features and pricing models. Qualtrics DesignXM, OpinionX, SurveyMonkey, and Sawtooth Software offer conjoint analysis capabilities. https://www.opinionx.co/research-method-guides/conjoint-analysis-tools

A2.3 Averting behaviour method/avoided cost method

- **Definition:** Estimates the value of service improvements by observing expenses or actions taken by individuals to mitigate potential impacts.
- **Idealized case study:** Farmers in a drought-prone area invest in irrigation systems following early drought warnings, aiming to safeguard crops.
- **Monetization outcome:** Investments in irrigation and resultant yield improvements provide a quantifiable economic benefit of early drought warnings.
- **Requirements for implementation:**
  - **Resources:** Agricultural economists, community surveys.

- **Technology:** Data collection and analysis tools.
- **Data sources:** Agricultural productivity records, investment costs in averting actions.
- **Social and political checks:** Ethical considerations in data collection, community consent.
- **Step-by-step:** Identify averting actions, collect cost and benefit data, analyze economic value.

- **Reported case study:** Van Ginkel and Biradar (2021) linked farmers' investments in response to drought early warnings to economic benefits in crop yield improvements in Kenya.
- **More information:**
  - Brief introduction: https://www.youtube.com/watch?v=hOX6WrR79Ao
  - Software for risk assessment (hazard, exposure and vulnerability/resilience, scenarios with and without the early warning system): RiskScape, Oasis, GEM

A2.4 Hedonic pricing method

- **Definition:** Assesses how different early warning system attributes influence market prices, typically real estate, providing a direct valuation.
- **Idealized case study:** A city with an advanced earthquake early warning system shows higher property values in areas covered by the system compared to those without.
- **Monetization outcome:** The premium on properties within the system's coverage area quantifies the early warning system's economic value.
- **Requirements for implementation:**
  - **Resources:** Real estate economists, GIS specialists.
  - **Technology:** GIS software, statistical analysis packages.
  - **Data sources:** Real estate prices at different points in time (prior and posterior to events), early warning system coverage data, other land-use (change) data to correct for disturbing effects on response measurement
  - **Social and political checks:** Consideration of market dynamics, data privacy concerns.
  - **Step-by-step:** Collect property data, correlate with early warning system features, apply regression models.
- **Reported case study:** In the US, properties in flood-prone areas with better early warning systems have shown increased values, demonstrating the value of such systems.
- **More information:**
  - Brief introduction: https://www.youtube.com/watch?v=LkXVCQam5kw
  - Statistical software: Open source (R, Python), licensed (SPSS, STATA)

A2.5 Ecosystem services

- **Definition:** Nature, through its functioning, provides services that have also economic significance. The four main categories of ecosystem services are provisioning services (e.g. timber, fish stocks), regulating services (e.g. soil life, pollination), cultural services (e.g. scenic beauty, relaxation amidst natural sounds only), and supporting services (e.g. nutrient cycle, water cycle). Some of these outputs have (almost) directly a transaction value (price), in other cases the economic value of changes in an ecosystem service can be inferred from the price of man-made substitutes or the effects on human activities.

- **Idealized case study**: Wildfire warning service in a certain region and its effect on prevented loss of ecosystem services
- **Monetization outcome:** Estimated (monetized) values of prevented ecosystem service losses
- **Requirements for implementation:**
  - **Resources:** Environmental economists, biologists, GIS specialists, engineers
  - **Technology**: Ecosystem modelling, GIS software, statistical analysis packages.
  - **Data sources**: GIS land use data, species counting, observed ingoing and outgoing fluxes (of nutrients, water, products, etc.)
  - **Social and political checks:** Check for possible confounding factors regarding occurrence and decrease of damage
  - **Step-by-step:** Identify affected ecosystem services. Collect data on ecosystem service levels prior and after (warned) events, infer unit-cost (implied prices) of affected ecosystem services, assess value of avoided ecosystem service loss(es)
- **Reported case study:** Mehvar *et al.* (2018) provide a review of the value of coastal ecosystem services.

A2.6 Benefit transfer method

- **Definition:** Utilizes economic values estimated in one context to approximate values in a new, but similar, context.
- **Idealized case study:** Implementing an early warning system for volcanic activity on a small island, using valuation data from similar geographic contexts to estimate benefits.
- **Monetization outcome:** Adapted valuations facilitate investment by demonstrating expected benefits
- **Reported case study:** Hallegatte (2012) estimated the potential benefits of providing early warning services of developed-country standards services in developing countries.
- **More information:**
  - Brief introduction: https://www.youtube.com/watch?v=xpXvnbNeOEo

A2.7 Difference-in-differences (DiD) method

- **Overview**: DiD is an econometric technique used to estimate the causal impact of an intervention by comparing the changes in outcomes over time between a treatment group and a control group. This method helps isolate the effect of the intervention from other factors that might influence the outcome.
- **Definitions**:
  - **Intervention**: An action or policy introduced to achieve a specific outcome.

- **Treatment group**: The group that receives the intervention or treatment being evaluated.
- **Control group**: The group that does not receive the intervention or treatment. The control group serves as a benchmark to compare the changes observed in the treatment group.

- **Step-by-step:**
  1. **Define the treatment and control groups:** The treatment group and control group are exactly the same in all their attributes except for the existence of the intervention (for example, implementation of an early warning system). This assumption, which needs to be tested statistically, enables making causal statements of the effect of the intervention.
  2. **Collect data:** Records of outcomes spanning several years before and after the intervention or treatment.
  3. **Variables**
     - **Outcome variables**: Outcome levels are observed before and after the event for both treatment and control groups.
     - **Control variables**: Factors that could influence the outcome variables, such as population density, economic sectors, and capital stock.
  4. **Conduct the DiD analysis**
     a. Calculate the average outcome levels in both the treatment and control groups (for example, regions) before the intervention.
     b. Calculate the average outcome levels in both regions after the intervention.
     c. Determine the changes in outcomes for the treatment group by subtracting pre-intervention averages from post-intervention averages.
     d. Determine the changes in outcomes for the control group in the same way.
     e. Compute the DiD estimate as the difference between the changes in the treatment group and the changes in the control group.
     DiD = $(\underline{Y}_{post,treatment} - \underline{Y}_{pre,treatment}) - (\underline{Y}_{post,control} - \underline{Y}_{pre,control})$
     where $\underline{Y}$ is the outcome.
  5. **Interpretation of results**
     - A significant DiD estimate indicates the causal impact of the early warning system on employment levels.
     - Positive DiD estimates suggest a beneficial impact of the early warning system, while negative estimates would indicate an adverse effect.
     - A challenge in DiD is neutralization of other interfering factors, as the use of DiD implies that the assumption there have no other notable changes in factors that can affect the studied behavioural responsiveness. For responsiveness to an early warning system it could be, for example, significant changes in conditions of indemnity insurance. This means that in very dynamic communities DiD may not produce meaningful results.

- **Worked example**: Early warning system for tropical cyclones
  - **Scenario**: Two coastal cities, City A (treatment group) and City B (control group), are both prone to tropical cyclones. City A implements a new early warning system to provide warnings for tropical cyclones. City B does not implement the new early

warning system. The outcome to be evaluated is the reduction in disruption of employment as a result of having an early warning system.

- **Collect** and process employment records from the tax agency for several years before and after the early warning system implementation.
  - City A (treatment group):
    - Pre-intervention average employment level: 100,000 jobs
    - Post-intervention average employment level: 98,000 jobs
  - City B (control group):
    - Pre-intervention average employment level: 95,000 jobs
    - Post-intervention average employment level: 94,500 jobs
- **Calculate** differences in employment levels before and after early warning system implementation for both cities, use those differences to compute the DiD estimate.

  DiD estimate (employment) = (98,000 - 100,000) - (94,500 - 95,000)
  = -2,000 - (-500)
  = -1,500
- **Outcome**: The DiD estimate of -1,500 jobs indicates a reduction in employment disruption by 1,500 jobs attributable to the early warning system.
- **Conclusion**: Applying the DiD method allows for a robust evaluation of the impact of the early warning system (with imperfectly forecasted tropical cyclones) on reducing employment disruptions. This structured approach provides valuable insights into the effectiveness of the early warning system, aiding policymakers to make evidence-based decisions.

Annex 3. Further examples of value chain analysis

When deciding to adopt a value chain approach it is often useful to review what others have done. This annex references several studies that have applied value chain methodologies to understand, improve, value, design and compare early warning systems (or in some cases, aspects of early warning systems such as communication between partners).

Value chain studies in the refereed and grey literature are rarely laid out neatly in terms of their nodes, actors and flows, evaluation methods and value indicators. Many relevant studies use value chain approaches implicitly without reference to the term "value" or "value chain". This makes them more difficult to identify in literature searches, for example. The recent acceleration of activities to enhance early warnings, inspired by the Early Warnings for All initiative, means that new studies and case study examples are becoming available all the time.

Table A3.1 provides an extensive list of studies from 2015 onward that have used value chain approaches in hydrometeorology and, to a lesser extent, geophysical hazards. They are classified according to their primary purpose for the value chain analysis: strategic awareness, operational management support, post-event analysis, investment decision, comprehensive service renewal, new service co-design, and comparative studies (refer to Chapter 1).

Table A3.1. Selected studies demonstrating value chain analysis in hydrometeorology and geoscience.

Purpose	***References***
Strategic awareness	**Identifying the impact-related data uses and gaps for hydrometeorological impact forecasts and warnings**. Harrison, S. E., Potter, S. H., Prasanna, R., Doyle, E. E., & Johnston, D. *Weather, Climate, and Society*, 14, (2022): 155-176. https://doi.org/10.1175/WCAS-D-21-0093.1
	The value of weather and climate information to the Tanzanian disaster risk reduction sector using nonmonetary approaches. Msemo, H.E., Taylor, A.L., Birch, C.E., Dougill, A.J. & Hartley, A. *Weather, Climate, and Society*, 13, (2021): 1055-1068. https://journals.ametsoc.org/view/journals/wcas/13/4/WCAS-D-21-0005.1.xml
	Improving tropical cyclone forecast communication by understanding NWS partners' decision timelines and forecast information needs. Morss, R.E., Vickery, J., Lazrus, H., Demuth, J. & Bostrom, A. *Weather, Climate, and Society*, 14, (2022): 783-800. https://doi.org/10.1175/WCAS-D-21-0170.1
Operational management support	**Evaluation of the end-users of disaster risk warnings in Brazil**. Saito, S.M., de Lima, G.R.T. & de Assis Dias, M.C. *Sustainability in Debate*, 10, (2019): 38-53. https://doi.org/10.18472/SustDeb.v10n2.2019.24908
	Building resilience from the grassroots: The Cyclone Preparedness Programme at 50. Haque, A., Haider, D., Rahman, M.S., Kabir, L. & Lejano, R.P. *International. Journal of Environmental Research and Public Health*, 19, (2022): 14503. https://doi.org/10.3390/ijerph192114503
	Quantifying the effectiveness of early warning systems for heavy air pollution based on public responses. Wang F. & Fei, S. *IOP Conference Series: Earth and Environmental Science*, (2021): 657 012065. https://doi.org/10.1088/1755-1315/657/1/012065
	Quantifying the effectiveness of early warning systems for natural hazards. Sättele, M., Bründl, M. and Straub, D. *Nat. Haz. Earth System Sci.*, 16, (2016): 149-166. https://doi.org/10.5194/nhess-16-149-2016

	Indian Ocean Wave Tsunami Exercise 2020. Indian Ocean Tsunami Information Centre. (2020). https://iowave.org/indian-ocean-wave-tsunami-exercise-2020/
Post-event analysis	**NWS Service Assessments.** (2024). https://www.weather.gov/publications/assessments
	Recommendations to improve the interpretation of global flood forecasts to support international humanitarian operations for tropical cyclones. Speight, L., Stephens, E., Hawker, L., Baugh, C., Neal, J., Cloke, H., Grey, S., Titley, H., Marsden, K., Sumner, T. & Ficchi, A. *Journal of Flood Risk Management*, (2023): e12952. https://doi.org/10.1111/jfr3.12952
	Emergency flood bulletins for Cyclones Idai and Kenneth: A critical evaluation of the use of global flood forecasts for international humanitarian preparedness and response. Emerton, R., and coauthors. *International Journal of Disaster Risk Reduction*, 50, (2020): 101811. https://doi.org/10.1016/j.ijdrr.2020.101811
	Lessons learned from the tragedy during the 100 km ultramarathon race in Baiyin, Gansu Province on 22 May 2021. Zhang, Q., Ng, C. P., Dai, K., Xu, J., Tang, J., Sun, J., & Mu, M. *Advances in Atmospheric Sciences*, 38, (2021): 1803-1810. https://doi.org/10.1007/s00376-021-1246-0
Investment decision	**Benefits of economic assessment of cyclone early warning systems - A case study on Cyclone Evan in Samoa**. Fakhruddin, B. S. H. M. H. M., & Schick, L. *Progress in Disaster Science*, 2, (2019): 100034. https://doi.org/10.1016/j.pdisas.2019.100034
	The monetary benefit of early flood warnings in Europe. Pappenberger, F., Cloke, H.L., Parker, D.J., Wetterhall, F., Richardson, D.S., & Thielen, J. *Environmental Science and Policy*, 51, (2015): 278-291. https://doi.org/10.1016/j.envsci.2015.04.016
	A framework for comparing permanent and forecast-based flood risk-reduction strategies. Bischiniotis, K., de Moel, H., van den Homberg, M., Couasnon, A., Aerts, J., Nobre, G.G., Zsoter, E. & van den Hurk, B. *Science of the Total Environment,* 720, (2020): 137572. https://doi.org/10.1016/j.scitotenv.2020.137572
	Lives saved versus time lost: Direct societal benefits of probabilistic tornado warnings. Ugarov, A. *Weather, Climate and Society*, 15, (2023): 587-602. https://doi.org/10.1175/WCAS-D-22-0139.1
	Strengthening Hydromet and Early Warning Systems and Services in Tunisia. A roadmap. (2022). World Bank. https://www.gfdrr.org/sites/default/files/publication/Tunisia Hydromet Roadmap_ENG_web.pdf
Comprehen-sive service renewal	***The Socio-Economic Benefits of the WISER Programme***. Watkiss, P., & Cimato, F. (2021). https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/business/international/wiser/wiser-seb-results_final-web.pdf
	Application of the Total Warning System to Flood. Australian Institute for Disaster Resilience. (2022). 22 pp. https://knowledge.aidr.org.au/media/9243/aidr_flood_warning_companion_2022.pdf
	Impact-based decision support services and the socioeconomic impacts of winter storms. Lazo, J. K., Hosterman, H. R., Sprague-Hilderbrand, J. M., & Adkins, J. E. *Bulletin of the American Meteorological Society*, 101, (2020): E626-E639. https://doi.org/10.1175/BAMS-D-18-0153.1
	The Natural Hazards Partnership: A public-sector collaboration across the UK for natural hazard disaster risk reduction. Hemingway, R. & Gunawan, O., *International Journal of Disaster Risk Reduction*, 27, (2018): 499-511. https://doi.org/10.1016/j.ijdrr.2017.11.014
New service co-design	**Taking the HIGHWAY to save lives on Lake Victoria**. Roberts, R.D. and co-authors. *Bulletin of the American Meteorological* Society, 103, (2021): E485-E510. https://doi.org/10.1175/BAMS-D-20-0290.1
	A pilot forecasting system for epidemic thunderstorm asthma in south-eastern Australia. Bannister, T. and co-authors. *Bulletin of the American Meteorological* Society, (2021): E399-E420, https://doi.org/10.1175/BAMS-D-19-0140.1

	Building the SUN4CAST system. Haupt, S. E., and co-authors. *Bulletin of the American Meteorological Society*, 99, (2018): 121–135. https://doi.org/10.1175/BAMS-D-16-0221.1
	Hydromet Gap Report 2024. Alliance for Hydromet Development. (2024). https://alliancehydromet.org/wp-content/uploads/2024/06/Hydromet-Alliance-Gap-Report-2024_en.pdf
Comparative studies	**An evaluation of availability and adequacy of Multi-Hazard Early Warning Systems in Asian countries: A baseline study**. Aguirre-Ayerbe, I., Merino, M., Aye, S.L., Dissanayake, R., Shadiya, F., & Lopez, C. M.. *International Journal of Disaster Risk Reduction*, 49, (2020): 101749. https://doi.org/10.1016/j.ijdrr.2020.101749
	Preparing for the unprecedented. Golding, B., Ebert, E., Hoffmann, D. & Potter, S. *Advances in Science and Research*, 20, (2023): 85-90, https://doi.org/10.5194/asr-20-85-2023.
	What the weather will do – results of a survey on impact-oriented and impact-based warnings in European NMHSs. Kaltenberger, R., Schaffhauser, A., & Staudinger, M. *Advances in Science and Research*, 17, (2020): 29–38. https://doi.org/10.5194/asr-17-29-2020

Annex 4. Glossary[2]

Accuracy	The closeness of a prediction to the actual outcome, with small errors indicating better prediction.
Actor	Actors in a value chain encompass a diverse range of individuals, organizations, and entities engaged in creating, using, transforming and transmitting information. Often described as agents, experts, stakeholders, and producers, actors play crucial roles in various parts of a warning value chain, and are characterized by dynamic qualities like objectives, resources and constraints.
Baseline	The current state against which the effects of changes or interventions can be measured.
Benefit	(1) A positive outcome or advantage resulting from the implementation of an early warning system or improvements in it. This may include the reduction of potential risks, the mitigation of adverse impacts, improved preparedness and response capabilities, and ultimately the protection of lives, property, and the environment. (2) Benefits may concern effects that are monetary, such as avoided repair cost, as well as those that are non-monetary, such as well-being effects related to human health or the environment. The latter type may be monetizable in many cases, e.g. the incidence of injuries can be converted into care costs and costs of temporary or permanent loss of the ability to work.
Capacity	The combination of all the strengths, attributes and resources available within an organization, community or society to manage and reduce disaster risks and strengthen resilience. Capacity may include infrastructure, institutions, human knowledge and skills, and collective attributes such as social relationships, leadership and management.
Club good	Club goods are a type of public good that is partially excludable. Access is restricted to those who belong to a "club," but once admitted, users do not compete for the resource. Membership can be based on specific qualifications (e.g., certain professionals) or entry fees. While this model can help ensure high-quality service, it may raise concerns about fairness.
Common pool resource	Common pool resources are public goods that are difficult to restrict access to but have rival features (their use by one group reduces availability for others beyond a certain point). Examples include natural resources like lakes or satellite orbits in space. The solution for preventing exhaustion or serious quality reduction is to either regulate access (club goods) or to price the usage.
Co-design	Process of working with clients, stakeholders and collaborators to design the objectives, activities and scope of a project before commencing. It can extend beyond the initial phases in some cases where the design is adaptive to feedback.
Co-production	An umbrella term for research engagement (which typically incorporates some or all of co-design, co-development, and co-delivery, often sequentially) that brings diverse knowledges together to create new knowledge, tools or products, activities, processes and/or outcomes.

[2] Definitions are given in the context of how they may be used to understand, describe or analyze a value chain for early warnings.

Community	A group of people in a defined area with shared culture, values, and social structures. Members derive their identity from common beliefs, norms, and values developed over time, fostering a sense of group awareness and a commitment to fulfilling shared needs.
Costs	(1) The total amount of priced and unpriced resources allocated to accomplish a task or produce an early warning service. It can encompass purchased goods and services, labor effort (working hours), use of goods from inventory, use of equipment, models and buildings (capital stock) and use of public goods and non-monetized resources. (2) The damage toll caused by hazardous weather including foregone welfare, which may entail loss of income, loss of earning capacity due to ailments, loss of good health, etc. Some of these elements are monetary, others would need to be monetized if cost-benefit analysis is used. Avoided costs constitute the benefits of early warnings systems (see "benefits").
Cost/benefit analysis	Cost-benefit analysis quantifies the overall social costs and benefits of a policy or project, including direct monetary factors as well as public goods and externalities. This method, often used to compare alternatives, helps justify subsidizing projects with total social benefits exceeding costs and preventing those where costs outweigh benefits, utilizing criteria like benefit-cost ratio, net present value, and internal rate of return.
Damage	The physical destruction, harm, or impairment inflicted on structures, infrastructure, natural environments, and personal property as a direct result of a natural hazard.
Decision making	In an early warning context, decision-making is the process of using available information to assess risks and choose effective actions to enhance preparedness and reduce harm. It involves timely responses based on coordinated efforts among stakeholders in response to received warnings and alerts.
Disaster	A significant disruption to the functioning of a community or society caused by hazardous events interacting with exposure, vulnerability, and capacity conditions. This results in losses across human, material, economic, and environmental dimensions, often requiring external assistance due to its widespread and enduring impact that may surpass the affected community or society's coping capacity.
Early warning system	A comprehensive framework integrating hazard monitoring, risk assessment, forecasting, communication, and preparedness activities to enable timely action in reducing disaster risks before hazardous events occur.
Evaluation	The systematic assessment of the effectiveness, efficiency, and impact of each stage and component within the value chain. It involves analyzing the performance of hazard monitoring, risk assessment, communication, and preparedness activities to determine the overall success of the early warning system. Evaluation provides insights into strengths, weaknesses, and areas for improvement, contributing to continuous enhancement and optimization of the warning value chain.
Ex-ante (evaluation)	An ex-ante evaluation assesses the benefits and costs of a new service before it has gotten operational, usually in the planning phase of the new service. This means that estimates of the uptake and sustained use of the service are to be based in interviews.

Ex-post (evaluation)	An ex-post evaluation assesses the benefits and costs of a new service some time (1~2 years) after it has gotten operational. It informs whether a service is indeed as beneficial as assessed in an ex-ante evaluation. Information of service uptake and use is available, but for reliable effect attribution it is important to account for other changes in the use context. Ex-post results can help to provide default parameter values in ex-ante studies, e.g. regarding service uptake.
Exposure	The presence of people, infrastructure, housing, and other tangible assets in hazard-prone areas.
First mile	The initial stage of community engagement or involvement in the planning, design, and implementation of a warning system where communities take ownership of the process and identify their needs and priorities.
Forensic analysis	A thorough investigation of each stage of the warning system after a high-impact weather event to identify and understand factors contributing to its performance, aiming to uncover insights and improve overall efficiency.
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.
Impact	The occurrence of loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation due to the realization of a hazard.
Indicator	A specific, observable, and measurable accomplishment or change that shows the progress made toward achieving a specific output or outcome.
Information flow	The movement of data, alerts, and communications through each stage of the value chain. It involves the transmission of relevant information from hazard monitoring and assessment to public communication.
Infrastructure	The essential physical and organizational elements that support the monitoring, communication, and response to hazards and emergencies in an early warning system. This includes technological systems, communication networks, monitoring equipment, and other critical components that enable the effective functioning of the early warning system.
Intervention	An action or policy introduced to achieve a specific outcome.
Last mile	The final link between warning dissemination and community response of a warning system by delivering warnings directly to at-risk communities, ensuring they receive timely information and take appropriate actions to mitigate risks.
Lead-time	The period between issuing a warning and the expected onset of a hazardous event which allows for preparatory actions and enhances readiness before the hazard occurs.
Local/indigenous knowledge	Locally sourced information that has grown over many years and passed down through generations.
Loss	The reduction in value, destruction, or impairment of assets, infrastructure, environment, livelihoods, and well-being of individuals and communities. Economic losses include both actual financial losses and anticipated future losses, such as loss of profits, loss of business opportunities, and costs incurred to mitigate or repair the harm.

Node — Essential points in a value chain where information and knowledge are conceived, produced, translated, transformed, disseminated, and utilized. Examples of nodes include weather forecasting, warning creation, and decision-making, serving as foundational elements that define the roles and responsibilities of actors in the value chain.

Partnership — A collaborative and mutually beneficial relationship between different actors (entities, organizations, or stakeholders) involved in various stages of the value chain.

Public goods — Pure public goods are non-excludable (meaning no one can be denied access) and non-rival (one person's use doesn't reduce availability for others). As a result, they are typically free and provided by public organizations. Some public goods, like road networks, may face limits on non-excludability or non-rivalry under high demand. Early warning systems and many weather services are usually public goods, though add-ons may be offered as private or club goods. Non-pure public goods include common pool resources and club goods.

Reliability — Reliability in early warning systems signifies the consistent and accurate issuance of timely alerts, fostering trust and confidence. A reliable system ensures stakeholders and communities can depend on accurate information for effective preparedness and response.

Response — Coordinated actions undertaken to address and mitigate the impacts of a hazardous event, encompassing search and rescue, medical aid, evacuation, and provision of essential services to minimize harm and facilitate recovery.

Service provider — An entity responsible for delivering timely and accurate warnings, notifications, and support services to individuals or communities at risk of hazardous events or emergencies.

Socioeconomics — The study and analysis of the interaction between social factors and economic activities, including how societal structures, behaviours, and norms influence economic outcomes and vice versa.

Theory of change — A framework that explains how certain actions or efforts are expected to lead to specific results or improvements in a particular situation.

Timeliness — The quality of occurring or being done at the right time, often emphasizing the importance of promptness or efficiency in addressing a situation.

Uncertainty — Uncertainties in forecasting stem from measurement errors, model limitations, and the intrinsic unpredictability of atmospheric conditions, which affect the accuracy and reliability of forecasts. Uncertainty in benefit generation of a service is rooted in societal and behavioural complexities. On top of the inherent behavioural and societal uncertainty evaluation results exhibit uncertainties owing to sample size restrictions and simplifying assumptions.

User — An individual, community, organization, or entity that receives, interprets, and potentially acts upon warnings issued by the warning system. Users are typically the intended beneficiaries of the early warning information and are directly affected by the hazardous event.

Value	(1) The effectiveness of each stage of the value chain, and overall, in changing the outcomes. Early warnings produce value when they (help) reduce the hazard-related losses to communities and individuals. (2) The total benefits (both monetary and non-monetary) the user receives from the early warning service minus the total costs (both monetary and non-monetary) of using the early warning service.
Valuation	The process of determining the financial worth or economic value of an asset, investment, or entity.
Value chain	A framework for characterizing relationships, processes, inputs, contributions, operational contexts of stakeholders, and associated value. A value chain can also be used to describe actual hazardous events.
Value of information	A change in benefit to a decision maker resulting from the use of new information.
Verification	A process for determining the accuracy of a weather or climate forecast (or prediction) by comparing the predicted weather with the actual observed weather or climate for the forecast period.
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
Warning service	A system or process designed to detect, monitor, and disseminate information about potential hazardous events and risks to users.

Additional definitions of terms in the context of early warning/action and disaster risk resilience can be found in

- REAP glossary: https://www.early-action-reap.org/sites/default/files/2022-10/REAP_Glossary%20of%20Early%20Action%20terms_2022%20edition_FINAL.pdf
- UNDRR glossary: https://www.undrr.org/drr-glossary
- HIWeather Value Chain glossary: http://hiweather.net/Uploads/keditor/file/20211108/20211108120611_16170.pdf