InPRHA

Integrating Prediction of Precipitation and Hydrology for Early Actions

PROJECT IMPLEMENTATION PLAN

2024-2028

A research project of the World Weather Research Programme

WORLD METEOROLOGICAL ORGANIZATION

WWRP WORLD WEATHER RESEARCH PROGRAMME

Table of Contents

Executive Summary

Despite advancements in science and technology, the challenge of predicting and preparing for floods persists. Uncertainties in forecasts, influenced by the chaotic nature of atmospheric processes, uncertainties in the estimation of the hydrological response to precipitation and limited real-time observations, are compounded by communication breakdowns and barriers to information access, hindering effective early warnings in the face of an increasingly changing climate. We need to better integrate observations and predictions of precipitation and hydrology for early actions. We also need to inform the warning process with knowledge from social sciences to ensure the proper delivery and use of those predictions.

In this document, we present the purpose and research plans of a new project, **In**tegrating Prediction of **PR**ecipitation and **H**ydrology for Early **A**ctions (InPRHA), within the World Meteorological Organization's (WMO) World Weather Research Programme (WWRP). InPRHA operates under the overarching guidance of the WWRP Scientific Steering Committee and its project plan is aligned with the WWRP Implementation Plan, which is driven by the WMO strategy. The overarching aim of InPRHA is to advance the integration of precipitation forecasts, hydrology, and social science to achieve the condition in which "no one is surprised by a flood," building on the goals of the WMO Vision and Strategy for Hydrology and its associated plan of action.

Through this project, we intend to expand research and knowledge about the development of multi-hazard flood forecasting systems for early warning from minutes to days. InPRHA will focus on integrating hydrology and meteorology as well as social science approaches to identifying user needs for data and information delivery and communication. InPRHA further seeks to enhance socio-hydrometeorology through dynamic and mutually beneficial interactions between weather, water, people and citizen science.

The key research objectives of InPRHA are:

- To co-produce new knowledge with existing communities of practice to improve dissemination, communication and behavioural response along the value chain of flood forecasting and warning for end users and the scientific community.
- To integrate existing and emerging technologies (e.g. AI and machine learning), methods, knowledge, and approaches from different research disciplines, including meteorology, hydrology and social sciences, as well as local and Indigenous knowledge systems to improve the flood early warning chain.
- To improve the integrated forecasts of precipitation, hydrology, and human systems (including managed systems for decision-making) to build knowledge about interactions between the different components of early warning to reduce uncertainty.
- To bridge research and operations within flood forecasting and observing systems to improve:
    - The verification cycle (from predictions to warning dissemination and coordination)
    - The traceability of predictions and warnings
    - The quantification and communication of uncertainties
    - The understanding of the needs and constraints of operational centres
    - The incorporation of social science knowledge into operations
- To re-envision the warning process with consideration of impacts from multi-hazard interdependencies (compound and cascading flood hazards and their associated uncertainties), local vulnerability, and precipitation and hydrological forecasts in a changing climate.
- To promote capacity development in flood early warning knowledge, practice, technology and understanding in effective multi-organizational partnerships , policy and and to bridge the gap between formal, and local and Indigenous knowledge systems for more inclusive and effective flood early warnings.

To achieve the above research aims and objectives, the InPRHA Steering Group is working to enhance international interdisciplinary and transdisciplinary collaborations by developing strong linkages and generating cooperative initiatives across academia, research institutions, policy makers and operational forecasting centres. InPRHA will require transdisciplinary research that integrates physical and social sciences with practitioner perspectives. Its activities will include cooperative science research projects led by Steering Group members and the wider community, working towards shared goals, and will incorporate knowledge and findings from other global research efforts, to connect existing communities of practice in a commitment to the integration of meteorology, hydrology and social science.

The project, which will span 5 years, will bring together a diverse community of researchers, operational forecasters, policy makers, practitioners, and end users for a range of research and education activities. The project will work to ensure that scientific information is communicated effectively and is used to reduce the detrimental impacts on society despite forecasting uncertainty. It will also foster capacity development and outreach for stakeholders, including educational organizations and the research community, as well as end users of early warnings. At its essence, the project aims to support international capacity for developing integrated predictions to improve end-user decision-making and draw on lessons of experience across the different regional contexts.

The work of the project is organized into four interdisciplinary and transdisciplinary work packages: **DEFINE**, **CONSTRUCT**, **EXPERIMENT** and **ENGAGE**. **DEFINE** will set the ground level understanding of challenges and opportunities related to integration along the flood warning value chain; **CONSTRUCT** will gather case studies and experiments that will serve as the basis for evaluation; **EXPERIMENT** will involve experimentation, analysis and address communication issues along the warning value chain by addressing key scientific questions outlined in the implementation plan, which are also open for exploration and contributions from the broader research and operational community; and **ENGAGE** will involve communities of practice to advance InPRHA's research objectives and share the knowledge co-developed through the project. The project will focus its research on a collection of relevant case studies, as well as experiments and projects, either led by or with strong participation of Steering Group members, and the wider community. We anticipate that this collection of case studies and experiments will help identify successful strategies for the integration of meteorology, hydrology and social sciences in flood forecasting.

The knowledge acquired through these activities, as well as those of other researchers who connect their work to InPRHA's goals through various channels, will be synthesized to produce a range of deliverables, including a meta-database or web repository for future research, white papers, webinars, workshops, and peer reviewed publications. Key deliverables will include a compilation of micro-reviews and case studies identifying the key challenges and opportunities in this area of study, as well as guidelines for good practices for integration of these fields to support the operational and research communities. The project will run through 2028, with the possibility of a 5-year extension.

Introduction

Our rapidly changing world faces increasing challenges, with international flood records shattering and many countries experiencing recurring, catastrophic flooding events. Cutting-edge science and technology (Bauer et al., 2015; Cloke & Pappenberger, 2009) have enhanced our ability to predict and model rainfall and runoff pathways (McCabe et al., 2017; Lavers et al., 2020), yet predicting and preparing for floods remains a persistent challenge (Budimir et al., 2020; Pagano et al., 2014; Wu et al., 2020). The inherent uncertainty of flood forecasts (Cloke & Pappenberger, 2009; Troin et al., 2021), influenced by the chaotic nature of the atmosphere (Bauer et al., 2015), uncertainties in the estimation of the hydrological response to precipitation and insufficient real-time data, and a rapidly changing climate (Hirabayashi et al., 2013) are sometimes combined with communication breakdowns and barriers to information and actions even when floods are accurately forecasted (EFAS, 2021; Mohr et al., 2023; Thieken et al., 2023).

The number of disasters is on the rise due to higher levels of disaster risk derived from increasing vulnerability and exposure to hazards of diverse origins, particularly weather, climate, and water hazards (Majumdar et al., 2021). Deaths, human displacements, loss of livelihoods, damage to food and energy production systems, damage to the environment and economic losses are among the major consequences of disasters. The anticipated impacts of weather and climate change include increased temperatures, more extreme localized precipitation, shifting rainfall patterns, droughts, flooding, and an increase in pests and diseases (Harrington et al., 2023; Ludwig et al., 2023). These risks caused by climate change require both coping and adaptation measures to ensure the resilience of coastal communities, urban populations, ageing populations, businesses and industries, smallholder farmers in developing countries and biodiversity and ecosystems. IPCC (2022) on Impacts, Adaptation and Vulnerability clearly notes that vulnerability of the impacts of climate change are uneven and gendered.

Flood forecasting and warning is a wicked problem (Allison et al., 2018; Pohl et al., 2017). The integration of precipitation and hydrologic predictions with social sciences and Indigenous knowledge systems for early action requires a transdisciplinary approach. Sociohydrology, which focuses on the interactions and feedbacks between water systems and human societies, provides a framework for understanding the complex relationships between hydrological changes, societal needs, and water management (Di Baldassarre et al., 2019; Gober et al., 2015; Sivapalan et al., 2015). It addresses not only the technical and environmental dimensions of water but also the social, cultural, economic, and health impacts (Srinivasan et al., 2012; Costanza et al., 2007). This comprehensive understanding is crucial for developing early warning systems that can respond to the challenges posed by climate change, population growth, and land-use competition. A transdisciplinary approach, which integrates insights from multiple academic disciplines and non-academic stakeholders, is essential for addressing these real-world complexities (Bergmann et al., 2012; Pohl et al., 2017). By engaging with local communities, including Indigenous groups, and co-producing knowledge, this approach ensures that early action plans are not only scientifically based but also socially and culturally relevant (Menken et al., 2016).

Early Warning Systems (EWSs) and the value chain (Hoffmann et al., 2023), understood as an integrated system of monitoring hazard, forecasting and prediction, disaster risk assessment, communication, and preparedness activities, can serve as a mechanism to enable individuals, communities, governments and businesses to take timely action to reduce disaster risks. In March 2022, WMO and the United Nations announced an ambitious groundbreaking effort, the "Early Warnings for All" initiative (WMO, 2022), to ensure everyone on the planet is protected from hazardous weather, water, or climate events through life-saving early warning systems. The target is to develop a plan to ensure that EWSs are widely used within the next five years by all people worldwide and empowering and supporting aid organizations with effective early warnings. The United Nations (UN) Early Warnings for All (EW4All) action plan was launched by UN Secretary-General António Guterres during the World Leaders Summit at the UN 2022 Climate

Change Conference, COP27. EWSs must be effective in delivering the information users need in ways they can access and can trigger effective behavioural responses.

To achieve this, addressing key fundamental research and practice gaps is essential. The four conceptual themes below highlight these gaps, across physical and social science disciplines, on how to integrate predictions of precipitation, hydrology and social science for early action through EWSs:

- *Multi-directional knowledge & practice transfer* refers to gaps around collaboration and the sharing of information across disciplines, agencies, and at-risk communities, as well as the exploration of two-way coupling of models in physical sciences (Fisher & Koven, 2020; Pagano et al., 2014; Potter et al. 2021).
- *Prediction integration* involves the exploration of integrating various models, observations, forecasting tools and techniques in research and operations, taking into consideration uncertainty that arises through this cascade of integration (Abbaszadeh et al., 2022; Imhoff et al., 2020; Pappenberger et al., 2005; Zappa et al., 2011).
- *Generalizability of research findings* refers to the extent to which findings from research conducted in specific locations, sectors, and contexts (e.g. different land use types, catchment characteristics and population levels) can be compared to other contexts (Berghuijs et al., 2017; Donovan et al., 2015; Kuller et al., 2021; Lesch et al., 2009; Scolobig et al., 2015).
- *Increased data inputs & access* includes the use of alternate data collection and estimation methods and techniques to overcome limitations to data availability, as well as the increased accessibility of data throughout the warning "chain" (Kidd et al., 2017; Selker et al., 2020; Songchon et al., 2023; Tan et al., 2022).

Further, EWSs must work in the context of decision-making within communities and engage many partners along the way – from scientists doing forecasting to emergency managers issuing local guidance to residents. This early warning value chain must be effective from end to end (Hoffmann et al., 2023), with the quantification of uncertainty transmitted through the forecast process, and communicated to the end users in ways that support decision-making (Hogan Carr et al., 2016). In short, there is work to be done to make EWSs as accurate and effective as possible.

Key scientific questions

The project poses the question of how vulnerable communities exposed to weather, climate, and flood hazards might reduce the risk of disaster through improved information for early actions. It focuses on advancing flood hazard predictability (monitoring and modelling) and assessment, improving hydro-meteorological warnings, and co-developing sound communication strategies for decision-making and early warning.

We propose a set of key scientific questions across seven themes (Table 1) to the broader research and operational community, including InPRHA steering group members and WWRP working groups, focusing on current challenges related to the integration of prediction within the flood forecasting and warning value chain. These challenges are critical to addressing gaps in research and practice, and by engaging with projects and communities working on these scientific questions, InPRHA aims to provide insights into the essential elements and processes required for effective integration of predictions across the flood warning value chain.

Table 1: Key scientific questions proposed to the broader research and operational community to advance the integration of predictions of precipitation, hydrology and social science within the flood warning value chain.

1.	**State of the art for flood prediction and risk in a changing world**
1.1	What are the research needs for understanding, developing and evaluating integrated prediction systems within the flood early warning value chain? What are the successes, limitations, lessons learned and failings, and what are the reasons behind them?
1.2	What are the key relationships between the reliability of a hydrometeorological ensemble prediction system and the predictability at various temporal and spatial scales across the value chain? Specifically, how do these factors interact when predicting different types of storms (e.g. tropical cyclones, atmospheric rivers, convective storms, monsoons)? What are the implications of these relationships on the perception of forecast and trust of decision-makers?
1.3	What is the impact of a rapidly changing climate and anthropogenic land and water use on forecasting science?
1.4	What is the state of the art of impact-based forecasting? How effective are impact-based forecasts for early action for flood warnings?
2.	**Research to operation**
2.1	What are the research science and operational requirements for incorporating the most salient processes from hydrometeorology for flood forecasting?
2.2	How will an Earth systems perspective of multi-hazards embedded into flood warning value chains improve the performance, reliability and value of forecasts?
3.	**Emerging technologies**
3.1	What is the role and value of non-traditional sources of forecasts (e.g. data driven methods, such as artificial intelligence and machine learning, digital twin) in weather, hydrological modelling and the potential for emulators to handle inundation forecasting?
3.2	How will km-scale Earth system models change our ability to project flood risk in a future climate change and anthropogenic land and water use. How will this inform current flood forecasting systems?
4.	**Hydrometeorological observing and forecasting - challenges and synergies**
4.1	How can we leverage improvements in remotely sensed observations for precipitation estimation and in Earth observations of the hydrological and soil moisture states, using coherent spatial and temporal resolutions?
4.2	How can we ensure continued support and coverage for ground-based networks (of rain gauges and flow gauges) for precipitation and streamflow?
4.3	How observational networks can be leveraged through public engagements and include nonconventional sources of data?
4.4	How can the observational limitations in a rapidly changing climate - where we have yet to experience extreme hydrological events, such as those expected in a warmer climate - impact the effectiveness of the warning value chain, especially given that hydrological forecasting systems are largely empirical?
4.5	What are the current gaps in hydrometeorological observing systems (or technologies) and research, particularly in defining optimal observing systems and strategies?
4.6	How do nowcasting and short-range coupled prediction systems need to advance to accurately initialize and forecast the atmospheric (precipitation) and hydrological state through data assimilation and emerging technologies?
5.	**Socio-economic, cultural and environmental challenges**
5.1	What are the warning value chain demands and needs for communicating impacts through forecasts for multi-hazard flood events (riverine, coastal, pluvial, urban, compound events and tropical cyclones)? How do we reconcile hazard forecasts, vulnerability and exposure information to tailor messages to a variety of end-users?
5.2	How do we better understand and integrate formal and local/indigenous knowledge systems for more inclusive and effective flood early warning systems?
5.3	How do we better build and sustain trust for flood EWS evidence generation, communication and evaluation?
5.4	What are appropriate policy frameworks and behavioural interventions that support flood resilience, education and adaptation to living with risk? How best to support adaptive behavioural responses at the community and individual level?
6.	**Uncertainties throughout the value chain**
6.1	How can we realistically represent the evolution of uncertainty throughout the coupled system and value chain, and what are the impacts of observational, meteorological, and hydrological model uncertainties on hazard forecast results?
6.2	What uncertainty information is most salient and effective for integrated forecasts (weather, hydrology, hazards), decision-making and early actions?
6.3	How do domain experts ensure that uncertainty quantification is accurately propagated through the hydrometeorological forecasting chain?
6.4	What are the opportunities for co-creating and co-defining the understanding and meaning of uncertainties with local communities?
7.	**Perceptions and actions for flood risks**
7.1	What is the public and professional stakeholder perception of multi-hazards and compound threats at the same time? How do multi-hazard warning systems cope with this perception (e.g. flooding, hurricanes, tornadoes, tsunamis)?
7.2	How can uncertainty information be tiered to provide the greatest utility to stakeholders in a variety of decision-making capacities?
7.3	How does information delivery affect behavioural response, and what changes in information delivery across the value chain improve end-users' motivation to take protective actions?

To advance this aim, the InPRHA activities will specifically address the driving workflow questions:

- What insights can we gain from understanding the state of the art and the challenges of integrating components within the flood forecasting and warning value chain?

- What experiments and test-beds are necessary to advance knowledge on integration of predictions of meteorology and hydrology, communication, and early action?
- How do we involve communities in co-producing and contributing to the process?
- What can we learn about how effective integration along the value chain can improve users' motivation and understanding to take appropriate action in response to warnings?
- What are the recommendations and guidance for effective integration of predictions of precipitation, hydrology, social science, and local and Indigenous knowledge systems across the flood warning value chain?

By focusing on these driving workflow questions, the InPRHA project aims to address key scientific challenges, build frameworks for community co-production, and ultimately improve the effectiveness of flood early warning systems across different components of the value chain.

Mission Statement

In this project, we aim to advance transdisciplinary knowledge and skill in the research and development of effective multi-hazard flood early warning systems so no one is surprised by a flood. The overall mission of the project is to:

"Promote cooperative international research to improve effective warning to communities from flood hazard forecasting systems by integrating precipitation and hydrologic predictions, and social sciences in a rapidly changing world".

In our mission statement, "predictions" include both observations and forecasts. By "prediction," we refer to a broad concept that encompasses more than future forecasting. It involves anticipating what is likely to happen based on prior information and knowledge. In the context of climate change and land use change, it involves estimating how changes in these factors will influence future conditions under various assumptions. This also includes generating predictions for data already observed (e.g. estimating current states or cross-validation). Here, predictions, inclusive of observations and forecasting models, provide a framework to evaluate and improve our understanding of flood hazards quantitatively.

In our mission statement, we also emphasize the integration of social sciences, including fields such as communication, risk perception, behavioural science, governance and institutional studies, and Indigenous knowledge systems, into the flood hazard forecasting and warning chain. This approach recognizes that Indigenous or local communities often possess deep, place-based knowledge of hydrological systems and flood risks, developed over generations. Additionally, the emerging field of sociohydrology studies the dynamic interactions between human societies and hydrological systems, acknowledging that human behaviour, cultural values, and social structures—including Indigenous practices—shape flood preparedness, risk and response.

Goals and objectives

The overarching goal of InPRHA is to expand research and knowledge about the development of multi-hazard forecasting systems for early flood warning. that incorporate an integration of hydrology and meteorology, and that are informed by social science approaches to identify user needs for data and information delivery and communication. The research focus is on understanding the flow of uncertainty and decision-making, through the integrated atmospheric and hydrological system on time scales of minutes to days; exploring potential information for short-term forecasting of improving short-range information about flash flooding and coastal inundation for disaster risk reduction.

The project has the following **GOALS**:

- Engage with the diversity of the international communities of researchers, forecasters, practitioners and other stakeholders

- Foster collaboration between research and operations towards better services, within national meteorological and hydrological services (NMHSs) and beyond
- Bring together knowledge from different disciplines (meteorology, hydrology and the social sciences) and cultures, with particular consideration for the most vulnerable and least developed communities
- Rethink the flood warning process, in a non-stationary system, by taking into account anthropogenic influences and changes on climate, land and water, as well as societal interactions, considerations and perceptions.

In support of these goals, the Steering Group has established the following research **OBJECTIVES** that will drive its work plan (Figure 1):

- ❖ Bridging communities: To co-produce new knowledge with existing communities of practice to improve dissemination, communication and behavioural response along the value chain of flood forecasting and warning for end users and the scientific community.
- ❖ Bridging scientific disciplines: To integrate existing and emerging technologies (e.g. AI and machine learning), methods, knowledge, and approaches from different research disciplines, including meteorology, hydrology and social sciences, as well as local and Indigenous knowledge systems – to improve flood early warning chain.
- ❖ Bridging across the natural and human coupled systems: To improve the integrated forecast of precipitation, hydrology, and human systems (including managed systems for decision-making) to build knowledge about interactions between the different components of early warnings to reduce uncertainty.
- ❖ Bridging across research and operations: To bridge research and operations within flood forecasting and observing systems to improve:
    - o The verification cycle (from predictions to warning dissemination and coordination)
    - o The traceability of predictions and warnings
    - o The quantification and communication of uncertainties
    - o The understanding of the needs and constraints of operational centres
    - o The incorporation of social science knowledge into operations
- ❖ Bridging across types of flood hazards: To re-envision the warning process with consideration of impacts from multi-hazard interdependencies (compound and cascading flood hazards and their uncertainties), local vulnerability, and climate change on precipitation and hydrological forecasts.

- ❖ Bridging systems for capacity development: To promote capacity development in flood early warning knowledge, technology and understanding in effective multi-organizational partnerships, policy and to bridge the gap between formal, and local and Indigenous knowledge systems for more inclusive and effective flood early warnings.

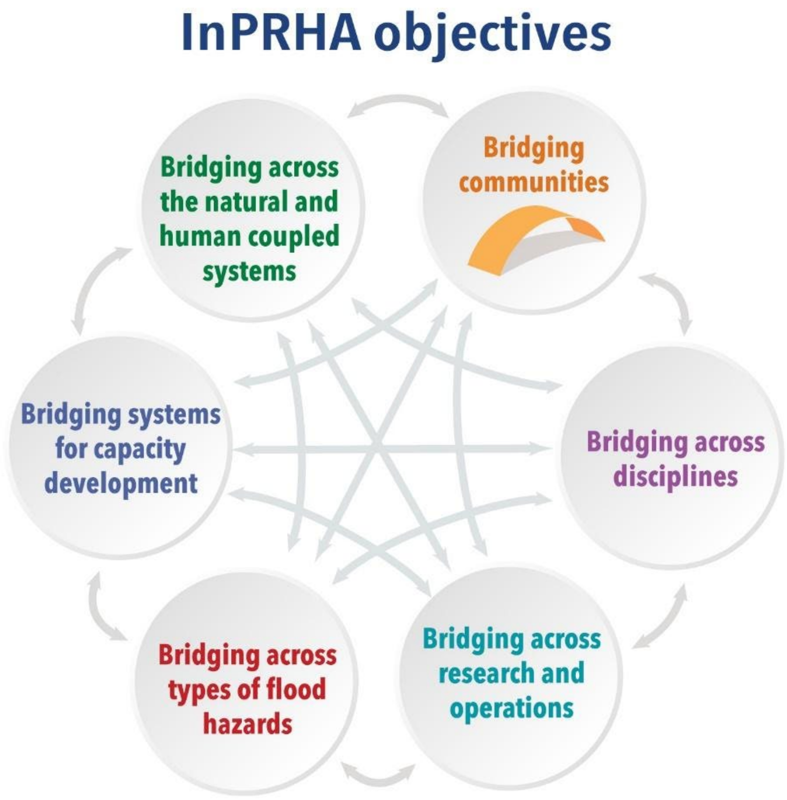

Figure 1: Interactions between InPRHA objectives

Scope

This project will focus on the shorter time scales (minutes to days), and the advancement of warning strategies associated with multi-hazards and their interdependencies that affect the water cycle. The project will work to advance the WMO goal that communities are prepared for flooding events of different types, including fluvial/riverine, pluvial and inland flooding through interaction with the built environment, freshwater flooding, coastal inundation, and mud or debris flows. Coupling the atmosphere (from near real-time to short-range time scales) using Numerical Weather Prediction (NWP) models with hydrological and land surface models is required to advance and accurately initialize the precipitation and hydrological state, and to realistically represent the evolution of uncertainty through the coupled system. This work requires a significant improvement in remotely-sensed observations for precipitation estimation, the improvement of observations of the hydrological and soil moisture state, and continued support for ground-based networks for precipitation and streamflow.

The project will also focus on integrating knowledge from the social sciences to identify user needs for information and good practices for delivery of warning messages and inherent uncertainty in the underlying predictions. Research on effective risk communication, warning dissemination, community education, behavioural response, as well as knowledge from psychology, sociology and economics fields will work to ensure that information to end users is clear and actionable, and reaches the intended audiences in a timely manner, and that it sufficiently addresses the complexities of uncertainty, cascading and compound impacts, local conditions and changing climate.

The project centres its research on addressing the needs of, and building capacity for, the most flood-vulnerable communities and especially, but not exclusively, least developed nations, targeting impact where it is most needed. Learning from previous extreme flood events as case studies will help us build knowledge on how the linkages within the value chain - more fully understood now through the research of WWRP's HIWeather project (Majumdar et al., 2021) - can be strengthened, and also what communities need in order to actualize change within their systems.

Background for Project Development

WMO has identified the establishment of effective EWSs as an essential step for all communities globally. Together with three other main partners, it leads the United Nations' Early Warnings For All (EW4All) initiative to reach this goal by 2027.

InPRHA also fully aligns with the 2021 WMO Water Declaration, which, in support of the global water agenda and the United Nations Sustainable Development Goals, acknowledges the central role of the water cycle and hydrology in the water-climate-weather continuum. It is also in harmony with the WMO Vision and Strategy for Hydrology and its associated Action Plan which targets eight long-term ambitions for operational hydrology including, "No one is surprised by a flood" and "Science provides a sound basis for operational hydrology".

Additionally, the WWRP has fixed the advancement and promotion of research activities that facilitate timely and actionable EWSs to effectively inform and influence societal actions, planning, and policy decisions as one of its top priorities. Specifically, in its revised Implementation Plan for 2024-2027, the WWRP established a series of research questions that undergird the InPRHA project, and from which InPRHA has evolved. These questions emphasize the need to engage in multi-hazards research, to communicate potential impacts from hydrometeorological impacts, to improve the quantification and communication of uncertainty, and to bridge knowledge across disciplines to improve forecast capability. Finally, InPRHA mobilizes the WWRP community to join efforts and create partnerships within the WMO Hydrological Research Strategy 2022-2030, which highlights the priority areas where research is needed to improve the delivery and use of hydrologic data, information and services.

InPRHA builds on and differs from the core WWRP HIWeather project (Majumdar et al., 2021) in multiple ways. While HIWeather primarily focuses on the warning value chain for severe weather events, InPRHA expands this scope by integrating hydrological insights and perspectives and emphasizing early action strategies for flood hazards at a short-time scale. Beyond understanding and forecasting weather, InPRHA emphasizes understanding the complex interactions and impact on the hydrological and coastal systems and implementing proactive measures to mitigate risks. InPRHA emphasizes collaboration between meteorologists, hydrologists, social scientists and relevant stakeholders to consider all perspectives in the decision-making processes for early action. By focusing on integrated prediction and nodes of integration along the value chain, new understandings and lessons should also inform meteorological forecasting advances, techniques and research focus needed to lead to more accurate and effective early warnings and early action.

Partners and Stakeholders

Linking research activities to national and international organizations, and encouraging the interface between scientific research, policymakers and society will be fundamental (World Bank, 2020). This includes liaising with NMHS (national meteorological and hydrological services), UNDRR (United Nations Office for Disaster Risk Reduction), GFP (Global Flood Partnership), UNESCO-IHP (United Nations Educational, Scientific and Cultural Organization's Intergovernmental Hydrological Programme), GEWEX (the World Climate Research Programme (WCRP) Global Energy and Water Exchanges core project), HEPEX (Hydrological Ensemble Prediction Experiment), and IAHS (International Association of Hydrological

Sciences). Partner knowledge exchange between the developing and the developed world will be encouraged.

WWRP core projects serve a diversity of audiences, both in the research and operational communities, and in the communities where early flood and multi-hazard warning systems can protect lives and property and reduce environmental damage. InPRHA has aligned its activities with the AWAR^{3}E Principles identified by WWRP to ensure the projects focus on the most vulnerable audiences, address the needs of all people, and also support the capacity of forecasters, decision-makers, and researchers to continually improve outcomes.

InPRHA's Steering Group will develop and implement activities with a wide range of stakeholders and partners in the research projects identified, including end users for social science research and testing, forecast audiences, emergency managers and other professional stakeholders, as well as larger institutions, such as research institutions, operational centres, and national agencies. Projects will intentionally engage users across a spectrum of experience and technical sophistication to gather the best knowledge and provide the clearest level of instruction and communication in flood and multi-hazard warning communication possible.

Specifically, the InPRHA research will work within rural, urban and underdeveloped communities, as well as countries with established warning systems, to advance learning across a variety of hydrologic, economic and social regimes, and to transfer learning across nations and communities. InPRHA will aim to work with EW4All communities as a priority. InPRHA recognizes the need for public education about science information and will extend its efforts to include end-user and public audiences to increase awareness of floods and resilience, multi-hazard flood forecasts, as well as to advance communication and behavioural response under uncertainty.

Research Plan

In this section, we focus on the research goals and objectives, which have been compiled into Working Packages (WPs) to allocate and distribute the work to guarantee a successful completion of the project key objectives.

Work Packages

Figure 2 illustrates the work package framework and linkages between them. The project team contributes social and physical science expertise for all work packages. The packages contribute logically one toward the next but allow for synchronous work to be completed in each. A timeline associated with each package shows the anticipated schedule of activities. Work Package, **DEFINE** sets the ground level understanding of challenges and opportunities related to integration across the flood warning value chain; this work underpins the remaining three Work Packages, but also can continue to evolve as new project work reveals evolving understanding of integration challenges. Key milestones of this WP are highlighted in Figure 3. Work Package **CONSTRUCT** will gather the case studies and experiments that will serve as the basis for evaluation. Work Package **EXPERIMENT** will involve experimentation and analysis, i) individually through members' projects, ii) collaboratively as a Steering Group and iii) collaboratively as a community. This Work Package will also include communication issues along the warning value chain, addressing issues of information delivery and its impacts on understanding, risk perception and motivation to act. Work Package **ENGAGE** aims to communicate the breadth of knowledge developed throughout InPRHA as a project, and to facilitate coordination and co-production among communities of practice to advance the research objectives and mission of InPRHA.

Work packages are designed to be interdisciplinary and transdisciplinary, reflecting the emphasis on integration that is at the heart of InPRHA; each scope of work involves considerations of hydrology, meteorology and social science bodies of knowledge, and each seeks to build knowledge across diverse stakeholder groups. The packages serve to organize the research tasks into definable elements, and to create measurable indicators of progress, described later herein.

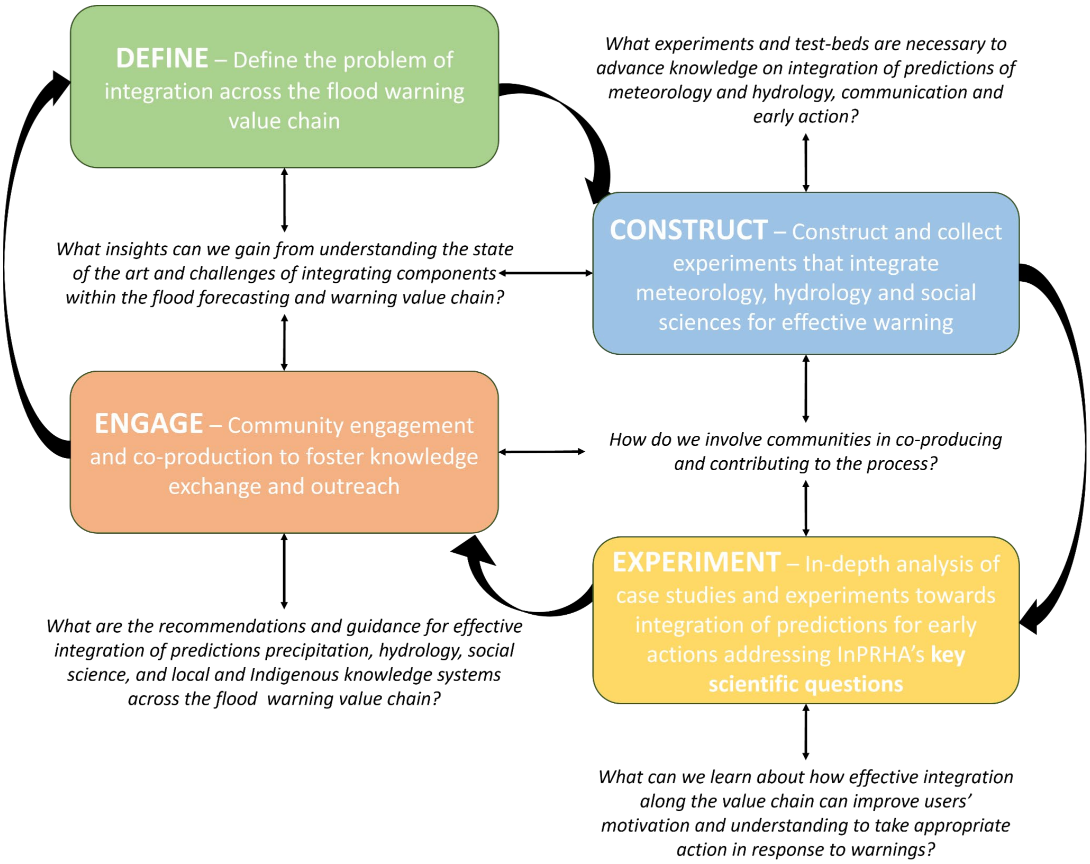

Figure 2: Interactions between InPRHA work packages, driving workflow questions (Italic) and proposed key scientific questions (Table 1) in EXPERIMENT.

DEFINE

- Mapping, inventory and needs assessment of integration
- Characterizing the complexities, enablers and barriers to integration
- Evaluating effectiveness of integration
- Formulating integration strategies and guidance for experiments

CONSTRUCT

- Designing experimental protocol
- Collecting protocol and test-beds
- Creating searchable database

EXPERIMENT

- Generating experiments, test-beds and case studies based on InPHRA's proposed key scientific questions
- In-depth analysis of experiments and test-beds, knowledge co-production
- Designing integration framework and guidance tools

COMMUNICATE

- Community co-production workshops and special conference sessions
- Exchanging knowledge
- Empowering: Educational and capacity development pilot
- Coordinating: Project reporting, monitoring and evaluation

Figure 3: Key milestones of InPRHA work packages.

WP DEFINE – Define the problem of integration across the flood warning value chain

The goal of the DEFINE work package is to develop a problem definition for better integration by collecting existing case studies across disciplines and communities through a meta-study, surveys and workshops to inform scientific inquiries, questions, and understand the state-of-the-art and challenges and opportunities for integration of disciplines and knowledges across the flood warning value chain. DEFINE will provide a review and high-level guidance regarding integration approaches of meteorology, hydrology, social science (e.g. communication, risk perception, behaviour science, decision-making processes), and local and Indigenous knowledge systems for early actions. Figure 4 provides a summary of the work package proposed activities, tasks and outputs. Each activity is described in more detail in the annex section.

	DEFINE			
Activities	**Mapping**	**Characterizing**	**Evaluating**	**Formulating**
Tasks	Write micro-reviews on state-of-the-art of InPRHA's research themes Develop web repository for micro-reviews Invite collaborations from scientists, operational centres, emergency managers and ECSs	Define problem of integration across the value chain Perform a gap analysis on micro-reviews Synthesize micro-reviews	Define evaluation criteria for effectiveness of integration Gather stakeholder feedback Synthesize findings	Formulate framework of integration strategies across the value chain Produce and iteratively update guidance to inform integration experiments
Outputs	Living repository, manuscript, StoryMap, report			

Figure 4: Activities, tasks and outputs for the work package WP1 DEFINE

WP CONSTRUCT – Construct and collect experiments that integrate meteorology, hydrology and social sciences for effective warning

In WP2, a catalogue of experiments will be designed based on findings from WP1 DEFINE. These experiments will study the integration of methods, knowledges, and approaches from various research disciplines and knowledge systems. The WWRP project HIWeather (Hoffmann et al., 2023) will provide valuable case studies and tools as a starting point. We will focus on cases and experiments that address multi-hazard interdependencies (compound and cascading hazards) and local vulnerability, including impacts of a changing climate. The purpose of the database/web repository of experiments of integration is to serve the community beyond the lifespan of the project, providing a platform for others to replicate or modify experiments or case studies, and a central location to access various meteorological and hydrological forecasts, observations, and social science related data across disciplines. Figure 5 provides a summary of the work package proposed activities, tasks and outputs. Each activity is described in more detail in the annex section.

	CONSTRUCT		
Activities	**Designing**	**Creating**	**Collecting**
Tasks	Define experimental protocol objectives and scope Develop protocol guidelines to integrate components along the value chain	Develop database/web interface to link to test-beds Define data collection protocol for test-beds Create submission platform to encourage community participation	Form review committee to evaluate proposed test-beds Curate collection of case studies for community exploration
Outputs	Documentation, database, Webinars/Presentations		

Figure 5: Activities, tasks and outputs for the work package WP2 CONSTRUCT

WP EXPERIMENT – In-depth analysis of case studies and experiments towards integration of predictions for early actions

This work package focuses on generating and sharing new findings and insights from emerging case studies, and experiments addressing physical and social scientific questions (Table 1) about the integration of predictions into early actions along the information value chain. Some of the proposed experiments may include prototypes of operational forecast products or services that demonstrate the direct application of

InPRHA for operations and services. Experiments will also address communication and delivery of the forecast, including issues related to audience and users, cultural factors, capacity for messaging and dissemination across communities, as well as factors including product design, behaviorial response and risk communication barriers and strategies. Figure 6 provides a summary of the work package proposed activities, tasks and outputs. Each activity is described in more detail in the annex section.

	EXPERIMENT		
Activities	**Experimenting**	**Analyzing**	**Designing**
Tasks	Set up experiments to test key research questions (Table 1) related to integration of predictions and early actions Form Task Teams to conduct surveys on the use of probabilistic river forecasts in research and operations Find funding and partnerships	Analyze experiment results to identify patterns for improvement in integration challenges and opportunities Host workshops/webinars to disseminate experiment findings and promote co-production Synthesize findings to derive insights of effective integration nodes along the value chain Publish, disseminate findings	Facilitate webinars and workshops to obtain feedback from the research and operation communities Develop serious games Formulate a good practice integration framework, recommendations and guidance tools
Outputs	Reports, publications, Webinars/Workshops		

Figure 6: Activities, tasks and outputs for the work package WP3 EXPERIMENT

WP ENGAGE – Community engagement and co-production to foster knowledge exchange and outreach

Here, we will oversee the coordination of the first three work packages within the project, as well as engaging and co-producing knowledge and exchange with WMO, international and national initiatives, and the broader research, practitioner, and end-user communities. Figure 7 provides a summary of the work package proposed activities, tasks and outputs. Each activity is described in more detail in the annex section.

	ENGAGE			
Activities	**Co-producing**	**Exchanging**	**Empowering**	**Coordinating**
Tasks	Organize InPRHA workshops/sessions Facilitate stakeholder discussions for co-productions and feedback Refine guidance on an effective integration framework	Develop InPRHA website Host webinar series on findings and experiments Publish newsletters and project updates Coordinate Journal issue on aspects of integration of the flood warning value chain	Pilot education material to enhance capacity development to inform future outreach services Establish InPRHA student prize of integration (of disciplines, knowledge systems, emerging technologies, research to practice) Prepare presentation material to inform WMO guidance	Facilitate project meetings with members Monitor progress Seek external funding to support project activities
Outputs	Conference sessions, workshops, interviews, Journal Special Issue, Presentations			

Figure 7: Activities, tasks and outputs for the work package WP4 ENGAGE

Strategies for Execution

Tasks and Milestones for Work Packages

The four Work Packages will produce an integrated series of outputs designed to build new knowledge and share existing knowledge across communities of practice. These outputs will include:

- A repository for relevant case studies for use by the research community (e.g. database of experiments)
- StoryMap illustrating successful integration
- Manuscripts, including micro-review summary
- Webinars that share the findings of experiments and studies
- Workshops for sharing and co-production of knowledge
- White papers, reports and peer reviewed publications sharing findings and good practices
- The development of prototype end-user and stakeholder educational materials for evaluation,
- Conference sessions
- Journal special issue with guidance for good practice for integration

Of these outputs, two major legacy deliverables will emerge. Namely, within DEFINE, the Steering Group will produce a **compilation of findings from micro-reviews on a range of research challenges related to InPRHA's mission;** this micro-review summary, anticipated for peer-review publication, will define the state-of-the art of integration within the early warning value chain for flood and multi-hazard events, noting challenges and opportunities for improvement. We anticipate this paper to establish a basis for sustained future research, helping to engage communities of practice around integration. This deliverable will also underpin the development of the rest of the project's work, helping to frame parameters for case studies, experiments, and development of social science research.

The second legacy deliverable for the project will occur within the ENGAGE work package and is the **issuance of guidance for good practices in integration of meteorology, hydrology, social science and knowledge systems as identified throughout the course of the project.** This guidance will be delivered as part of a larger journal special issue organized by InPRHA, and as a standalone report.

In addition to these tasks, a set of administrative activities will undergird the project. For instance, the International Coordination Office (ICO) will develop and maintain a website that will offer general information, news, and relevant links pertaining to the InPRHA Project. The website will serve as an archive and repository for the case studies, findings from experiments, outcomes of workshops, recording of webinars and other critical information. Care will be taken to ensure the platform enhances and does not replicate existing resources and information elsewhere. Additionally, monitoring, evaluation and learning activities will occur throughout the project.

Details on the anticipated sequence and timing of these core deliverables can be found in the implementation schedule below (Figure 8). Each of these outputs are designed to engage multiple research domains, and are expected to inform multiple of the research outcomes.

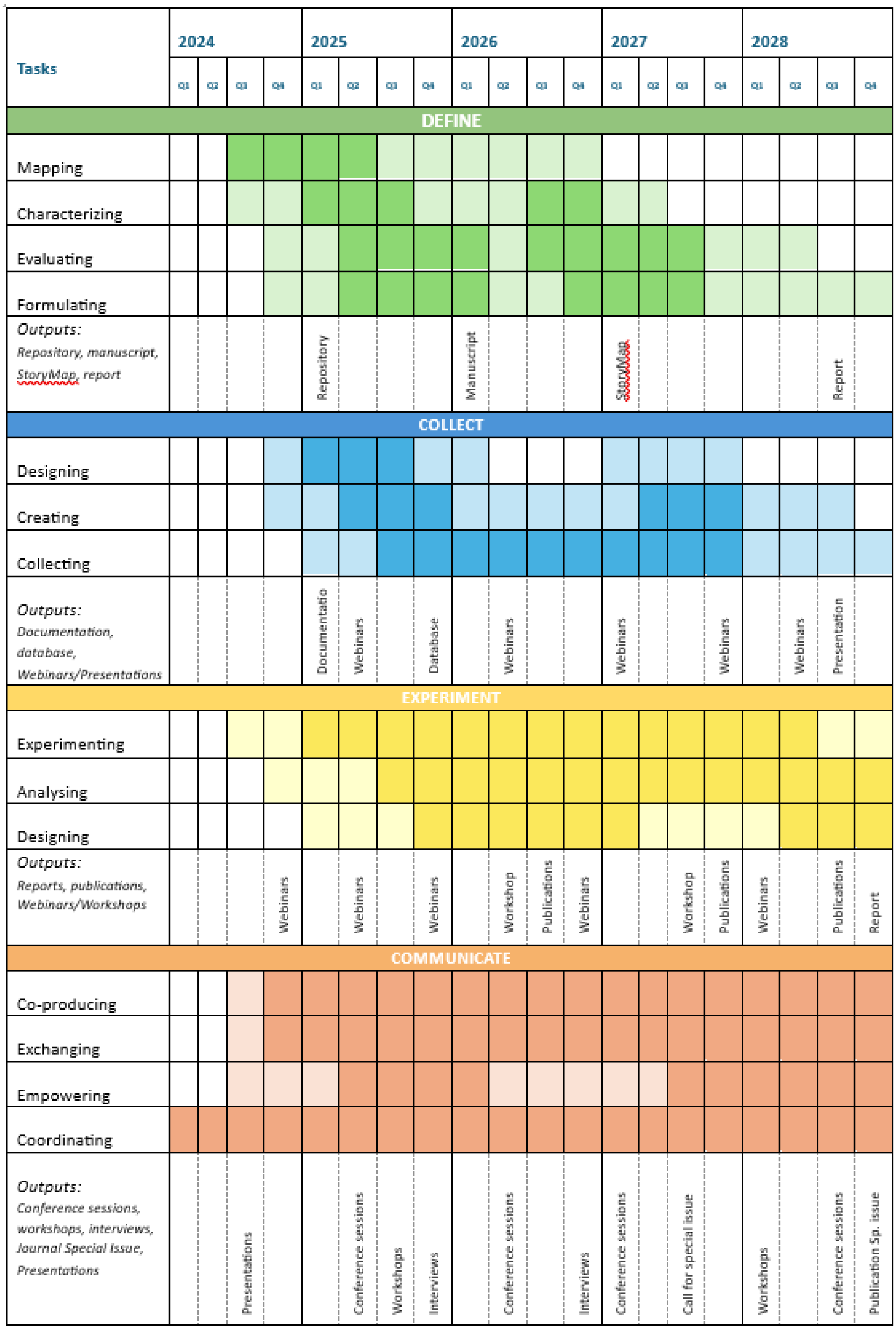

Figure 8: Project tasks and outputs timeframe.

Leveraging and linking with other initiatives

Ultimately, InPRHA intends to build a network of researchers committed to the goal and objectives identified. The existing WWRP working groups, such as the WWRP/WGNE Joint Working Group pn Forecast Verification Research (JWGFVR), and projects, such as URBAN, Progressing EW4All Oriented to Partnerships and Local Engagement (PEOPLE) and Polar Coupled Analysis and Prediction for Services Project (PCAPS), will support InPRHA through their expertise and direct involvement in related activities. Importantly, InPRHA will also be taking stock of recommendations of projects that are sunsetting, like HIWeather.

We intend to collaborate and share knowledge with other national and international efforts to address complementary goals, including the United States' NOAA's Precipitation Prediction Grand Challenge Strategy (NOAA, 2020), the UNESCO-IHP, the HEPEX (Hydrological Ensemble Prediction Experiment), the WCRP's Global Precipitation Experiment (GPEX) Lighthouse Activity. We will also work with other WMO groups including the Research Board Task Team on Hydrology, the Services Commission's (SERCOM) Standing Committees on Hydrological Services (SC-HYD) and Disaster Risk Reduction and Public Services (SC-DRR), the Infrastructure Commission's (INFCOM) Joint Expert Team on Operational Weather Radar (JET-OWR), Joint Expert Team on Earth Observing System Design and Evolution (JET-EOSDE), and the UN Ocean Decade project "Predicting the Global Coastal Ocean" (CoastPredict). We will also engage with the WMO Task Team on Implementation of Products from Non-traditional Sources (TT-NTS) in the WMO Integrated Processing and Prediction System (WIPPS) riverine flood products from machine learning models.

We further anticipate working with and learning from humanitarian organizations such as the Red Cross, who also focus on disaster risk reduction, and public-private partnerships such as the Google Flood Hub. The mechanisms for establishing robust connections will include: (i) coordinating closely between the WWRP HIWeather, URBAN, PCAPS and PEOPLE projects; (ii) ensuring open consultation and active involvement in the ongoing implementation plan and project activities; (iii) organizing workshops to evaluate the scientific aspects and plan future activities; and (iv) participating in cross-membership initiatives as deemed suitable.

One of the key mechanisms to enable stronger partnerships and growth of a community involved in InPRHA is the WWRP endorsement process. This process formally recognizes research aligned with the WWRP Implementation Plan and supporting the InPRHA's goals, as described in this project plan. This approach can benefit both InPRHA and the endorsed projects or institutions by allowing them to use the WWRP endorsement in their funding proposals, while also expanding the number of projects contributing to InPRHA's overall mission. Fostering and sustaining a robust community of endorsed projects aligned with InPRHA will be critical to its success. Therefore, InPRHA will actively promote the endorsement of relevant projects, programs, and initiatives that align with its goals and objectives, as well as the WWRP Implementation Plan.

Governance and Management:

Integrating Predictions of **PR**ecipitation and **H**ydrology for Early **A**ction (InPRHA) is a core project within the World Weather Research Programme (WWRP) of the WMO (Figure 9). It operates under the overarching guidance of the WWRP Scientific Steering Committee (WWRP SCC).

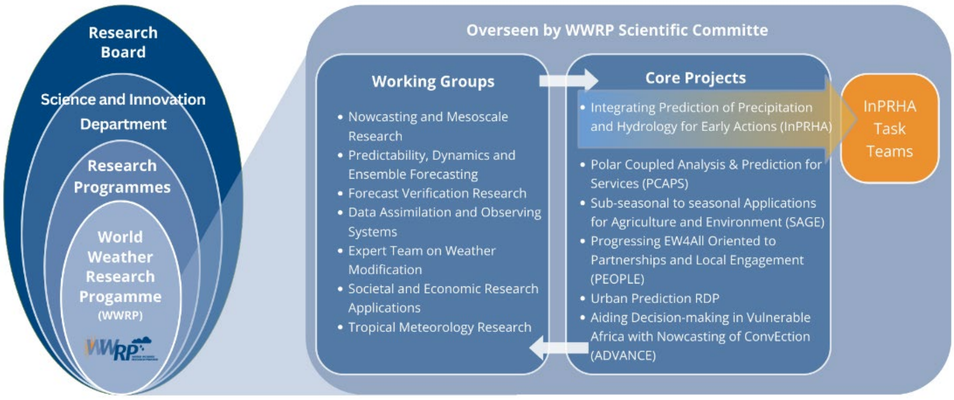

Figure 9: Linkages of InPRHA within the World Weather Research Programme

The InPRHA Steering Group is composed of physical and social scientists working in countries spread across all six WMO regions (Figure 10), with a range of specialty and expertise in hydrology, meteorology, and hazard communication. The Steering Group members have identified a series of project ideas that will advance the research goal and objectives, described further herein.

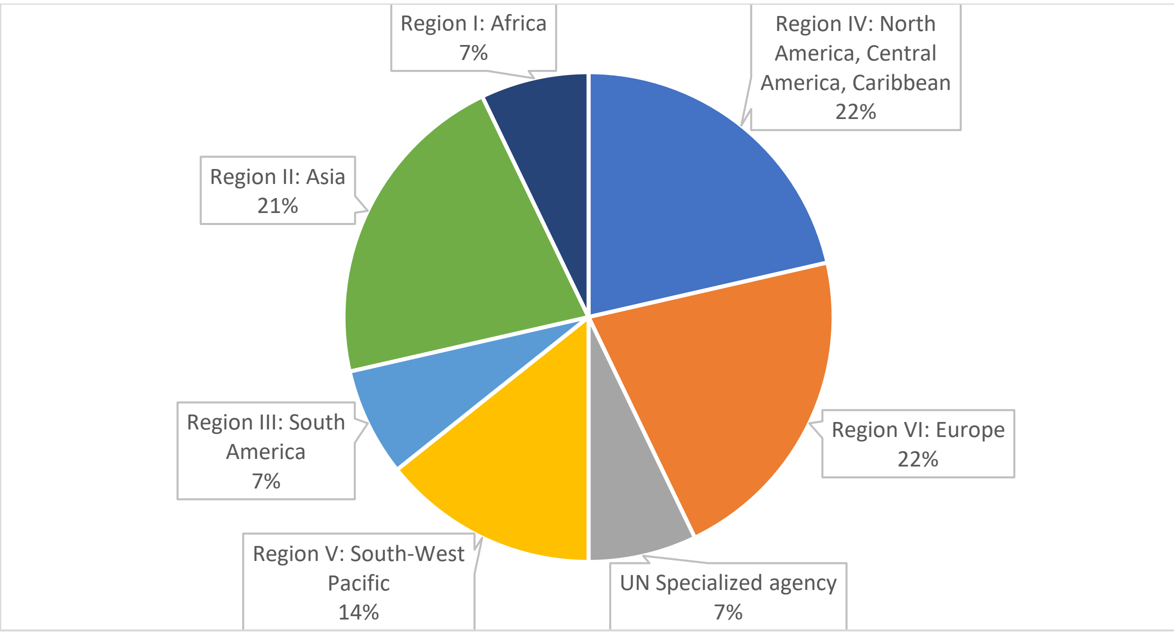

Figure 10: InPRHA Steering Group distribution across the six WMO regions

The project Steering Committee includes members from WCRP and WWRP groups, from groups of the WMO's Services Commission, academia and public sector communities. Representing all six regions, the steering group conducts monthly working meetings to advance coordination, and is led by the co-chairs with support from the scientific officer. The steering group holds an annual meeting to provide an in-person working session.

The International Coordination Office (ICO) for InPRHA is being carried out by the United States National Oceanic and Atmospheric Administration's (NOAA) Office of Oceanic and Atmospheric Research (OAR), through its Weather Program Office (WPO), and specifically under the direction of the division chiefs of the Science, Technology and Society, and Earth System Research and Modelling divisions. The ICO will provide administrative and logistical support and research assistance through the expertise of its staff and access to its institutional resources.

Like other WWRP projects, team members and their host organizations dedicate time to the project to align with their scientific and organizational research objectives. WMO has allocated four months of salary support for an early career scientist to contribute to the initial stages of working package 1 to coordinate literature reviews from members.

External funding will be required to complete the project, particularly for the development and implementation of the case study/testbed database of predictions of precipitation and hydrology for early actions. Additional funding for post-doctoral and PhD positions focused on targeted experiments of integration would accelerate project outcomes. Team members will actively be seeking funding opportunities to secure resources for the project.

InPRHA Members

Co-chairs:

- Celine Cattoën-Gilbert, NIWA (National Institute of Water and Atmospheric Research), New Zealand
- Rachel Hogan Carr, Nurture Nature Center, USA

Members:

- James Bennett, CSIRO, Australia
- Erin Dougherty, NCAR, USA
- Vincent Fortin, Environment and Climate Change Canada (ECCC), Canada
- Ruben Imhoff, Deltares - Netherlands
- Gyuwon Lee, Kyungpook National University, South Korea
- Yali Luo, Chinese Academy of Meteorological Sciences - Nanjing University of Information Science & Technology (NUIST)
- Everisto Mapedza, Int'l Water Mgmt. Institute (IWMI), Pretoria, South Africa
- Thara PRABHAKARAN, Indian Institute of Tropical Meteorology, Pune, India
- Jan Polcher, CNRS, France
- Luca Rossi, UNDRR, Switzerland
- Andrea Taylor, University of Leeds, UK
- Jose Valles Leon, Ministry of Environment. National Directorate of Water (DINAGUA), Uruguay

International Coordination Office (ICO) staff:

- Jessie Carman, NOAA, US
- Gina Eosco, NOAA, US

Liaisons of the InPRHA Steering Group

- Daryl Kleist, NOAA, US
- Maria-Helena Ramos, INRAE, France

WWRP Scientific Officer:

- Nico Caltabiano, WMO, Switzerland

Ethics

Improving the delivery of early flood warnings globally requires careful attention to the needs of a diverse range of users. Effective research must engage across social science disciplines to consider factors such as individual risk perception and decision-making, as well as community-level considerations such as social cohesion, past disaster experience and cultural response to hazards. Such research must respond to the cultural contexts in which warnings are delivered and received, and the range of knowledge systems including formal, informal and Indigenous in which warnings will be interpreted. Research must also recognize the technological resources of communities, the chains of information exchange that are already extant, the experience of populations with hazards, and the relationships of populations to land and technology, among other considerations. InPRHA projects and experiments will be designed to carefully consider a wide range of populations and associated needs, including in the least developed communities, and will engage the appropriate disciplines and expertise to address the research questions at hand: communication, economics, risk management, sociology, anthropology and psychology. InPRHA will ensure that experiments engaging populations follow appropriate research protocols for the protection of communities and participants.

Monitoring, Evaluation and Learning

Theory of Change

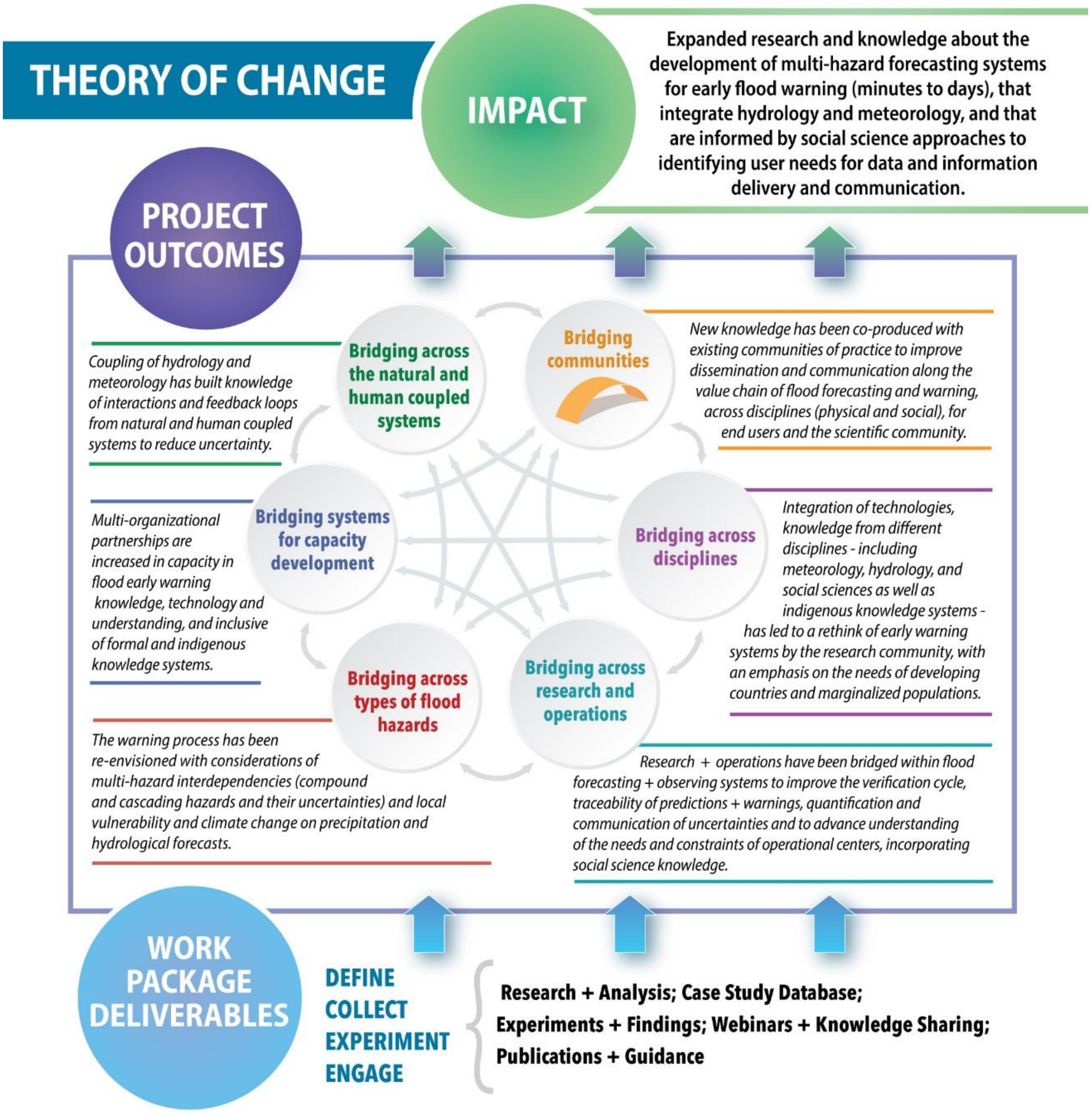

Figure 11: Theory of change for InPRHA.

IMPACT: It is anticipated that InPRHA’s work will result in expanded research and knowledge about the development of multi-hazard forecasting systems for early flood warning (minutes to days), that integrate hydrology and meteorology, and that are informed by social science approaches to identifying user needs for data and information delivery and communication. At the project’s end, we expect a lasting collection of research and case studies available for future use by researchers, as well as guidance for the research and operational community on good practices for integration of hydrology, meteorology and social science knowledge. We intend to connect communities of practice around InPRHA’s aims, sustained by collaborative research projects funded through multinational efforts sparked by InPRHA’s incipient efforts. We anticipate also developing a revised set of research questions to be advanced by future WMO initiatives.

OUTCOMES To guide this work, we have identified six outcomes (see Figure 11), which build upon each other in both linear and multidirectional fashion. Notably, the first, ***Bridging Communities***, which seeks to work within existing communities to build and exchange knowledge, is both a requirement for the remainder of the outcomes, as well as its own outcome – a lasting, enduring body of knowledge seekers that exists beyond the life of the project. For each of the outcomes, we have identified the necessary pre-conditions that must exist in order to achieve the outcome – that is, what is the knowledge or information that is needed, or the support that must exist, to improve the science and communication of multi-hazard early warning systems? As this graphic reflects, the activities within our Work Packages are designed to achieve these necessary preconditions and achieve our outcomes. Our outcomes were designed to align with WWRP's three key objectives, as well as the WWRP's AWAR^{3}E Principles. A complete Monitoring, Evaluation and Learning plan has been developed, which provides detail on the baseline conditions for each of these outcomes and provides a rationale for how we expect our work to build toward the outcomes.

Monitoring

The indicators below have been developed with input from the InPRHA's Steering Group members and WWRP SSC liaisons as well as the professional monitoring, evaluation and learning consultant engaged by WWRP. These reflect a series of practical, measurable progress metrics we can assemble that will alert us to any challenges we may be facing in achieving our outcomes. While our research questions, objectives and outcomes are scientifically complex and engage a wide range of actors to achieve, our indicators reflect the progress the Steering Group and its work can make toward an established and growing knowledge base that supports each individual outcome. Measures look at the reach and distribution of knowledge through tactical activities such as webinars and workshops and journal publications - all needed for building the central outcome of engaging communities of practice. These measures also include substantive evaluation of the project findings to ensure that the work of the projects is properly addressing the core research needs related to topics such as multi-hazards, local conditions in a changing climate, communication and quantification of uncertainty, and the coupling of human and natural systems.

INDICATORS:

- Endorsed WWRP projects to InPRHA that integrate multi-disciplines to identify a growing interest in projects with an integration theme
- Newsletter and website uptake and growth
- Project visibility and exposure to international audiences
- Number of publications bridging across disciplines
- InPRHA workshops and conference sessions linking to stakeholders and other projects
- Support for early career researchers in international science
- Number of and reach of online webinars or workshops on natural + human coupled systems
- Analysis of project findings (case studies)
- Instances of integration of project results or research into operational forecasting systems or early warning chains
- InPRHA-influenced partnerships across multiple organizations or institutes or WMO projects traditionally focusing on different hazards
- Participation in activities and outputs bridging across multi-hazards
- Partner assessment of project impact

Evaluation and Learning

A Theory of Change is by definition an evolving set of assumptions, and it will be the job of the Steering Group to gather and reflect upon the indicators on an annual basis, and compare our progress to this Theory of Change, and consider what adaptations need to be made in our expectations, research goals, and the activities that our projects and Steering Group itself are pursuing. Our annual meetings will include a time for shared review, which will be documented by the Scientific Officer and Co-chairs, and used to determine if any modifications are required to the Theory of Change and associated data collection.

Our indicators include feedback from our project partners and stakeholders, in various ways, which will be used to evaluate our progress toward our outcomes. Elements such as surveys will help to provide both quantitative and qualitative assessment of progress, and compilations of endorsements and testimonials will help provide reflection on InPRHA's impact. We anticipate this feedback to be formative into the evolution of the Theory of Change as well.

Acknowledgements

The InPRHA Steering Group would like to thank Simone Phillips for the work done with the micro-reviews, which was fundamental in identifying key challenges and opportunities, and contributed to the development of this project plan.

References

Abbaszadeh, P., Muñoz, D. F., Moftakhari, H., Jafarzadegan, K., & Moradkhani, H. (2022). Perspective on uncertainty quantification and reduction in compound flood modeling and forecasting. *iScience*, *25*(10), 105201. https://doi.org/https://doi.org/10.1016/j.isci.2022.105201

Allison, A. E. F., Dickson, M. E., Fisher, K. T., & Thrush, S. F. (2018). Dilemmas of modelling and decision-making in environmental research. *Environmental Modelling & Software*, *99*, 147-155. https://doi.org/https://doi.org/10.1016/j.envsoft.2017.09.015

Bauer, P., Thorpe, A., & Brunet, G. (2015). The quiet revolution of numerical weather prediction [Review Article]. *Nature*, *525*, 47. https://doi.org/10.1038/nature14956

Berghuijs, W. R., Aalbers, E. E., Larsen, J. R., Trancoso, R., & Woods, R. A. (2017). Recent changes in extreme floods across multiple continents. *Environmental Research Letters*, *12*(11), 114035. https://doi.org/10.1088/1748-9326/aa8847

Bergmann, Matthias, Julie Thompson Klein, and Ronald C. Faust. 2012. Methods for Transdisciplinary Research: A Primer for Practice. English ed. Frankfurt ; New York: Campus-Verlag.

Budimir, M., Donovan, A., Brown, S., Shakya, P., Gautam, D., Uprety, M., Cranston, M., Sneddon, A., Smith, P., & Dugar, S. (2020). Communicating complex forecasts: an analysis of the approach in Nepal's flood early warning system. *Geosci. Commun.*, *3*(1), 49-70. https://doi.org/10.5194/gc-3-49-2020

Cloke, H. L., & Pappenberger, F. (2009). Ensemble flood forecasting: A review. *Journal of Hydrology*, *375*(3), 613-626. https://doi.org/http://dx.doi.org/10.1016/j.jhydrol.2009.06.005

Costanza, Robert, Brendan Fisher, Saleem Ali, Caroline Beer, Lynne Bond, Roelof Boumans, Nicholas L. Danigelis et al. "Quality of life: An approach integrating opportunities, human needs, and subjective well-being." *Ecological economics* 61, no. 2-3 (2007): 267-276.

Di Baldassarre, G., Sivapalan, M., Rusca, M., Cudennec, C., Garcia, M., Kreibich, H., et al. (2019). Sociohydrology: Scientific challenges in addressing the sustainable development goals. Water Resources Research, 55, 6327–6355. https://doi.org/10.1029/2018WR023901

Donovan, S. M., O'Rourke, M., & Looney, C. (2015). Your Hypothesis or Mine? Terminological and Conceptual Variation Across Disciplines. *Sage Open*, *5*(2), 2158244015586237. https://doi.org/10.1177/2158244015586237

EFAS. (2021). *European Flood Awareness System Bulletin June - July 2021 Issue 2021 (4)*

Fisher, R. A., & Koven, C. D. (2020). Perspectives on the Future of Land Surface Models and the Challenges of Representing Complex Terrestrial Systems. *Journal of Advances in Modeling Earth Systems*, *12*(4), e2018MS001453. https://doi.org/https://doi.org/10.1029/2018MS001453

Gober, P., & Wheater, H. S. (2015). Debates—Perspectives on sociohydrology: Modeling flood risk as a public policy problem. Water Resources Research, 51, 4782–4788. https://doi.org/10.1002/2015WR016945

Harrington, L. J., Dean, S. M., Awatere, S., Rosier, S., Queen, L., Gibson, P. B., Barnes, C., Zachariah, M., Philip, S., & Kew, S. (2023). The role of climate change in extreme rainfall associated with Cyclone Gabrielle over Aotearoa New Zealand's East Coast.

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., & Kanae, S. (2013). Global flood risk under climate change. *Nature Climate Change*, *3*, 816. https://doi.org/10.1038/nclimate1911

Hoffmann, D., Ebert, E. E., Mooney, C., Golding, B., & Potter, S. (2023). Using value chain approaches to evaluate the end-to-end warning chain. *Adv. Sci. Res.*, *20*, 73-79. https://doi.org/10.5194/asr-20-73-2023

Hogan Carr R., Montz, B., Maxfield, K., Hoekstra, S., Semmens, K., & Goldman, E. (2016). Effectively communicating risk and uncertainty to the public: Assessing the National Weather Service's flood forecast and warning tools. Bulletin of the American Meteorological Society, 97(9), 1649-1665. DOI: https://doi.org/10.1175/BAMS-D-14-00248.1

Imhoff, R. O., Overeem, A., Brauer, C. C., Leijnse, H., Weerts, A. H., & Uijlenhoet, R. (2020). Rainfall Nowcasting Using Commercial Microwave Links. *Geophysical Research Letters*, *47*(19), e2020GL089365. https://doi.org/https://doi.org/10.1029/2020GL089365

IPCC, 2022: Summary for Policymakers [H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (eds.)]. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3–33, doi:10.1017/9781009325844.001.

Kidd, C., Becker, A., Huffman, G. J., Muller, C. L., Joe, P., Skofronick-Jackson, G., & Kirschbaum, D. B. (2017). So, How Much of the Earth's Surface Is Covered by Rain Gauges? *Bulletin of the American Meteorological Society*, *98*(1), 69-78. https://doi.org/https://doi.org/10.1175/BAMS-D-14-00283.1

Kuller, M., Schoenholzer, K., & Lienert, J. (2021). Creating effective flood warnings: A framework from a critical review. *Journal of Hydrology*, *602*, 126708. https://doi.org/https://doi.org/10.1016/j.jhydrol.2021.126708

Lavers, D. A., Ramos, M.-H., Magnusson, L., Pechlivanidis, I., Klein, B., Prudhomme, C., Arnal, L., Crochemore, L., Van Den Hurk, B., Weerts, A. H., Harrigan, S., Cloke, H. L., Richardson, D. S., & Pappenberger, F. (2020). A Vision for Hydrological Prediction. *Atmosphere*, *11*(3), 237. https://www.mdpi.com/2073-4433/11/3/237

Lesch, M. F., Rau, P.-L. P., Zhao, Z., & Liu, C. (2009). A cross-cultural comparison of perceived hazard in response to warning components and configurations: US vs. China. *Applied Ergonomics*, *40*(5), 953-961. https://doi.org/https://doi.org/10.1016/j.apergo.2009.02.004

Ludwig, P., Ehmele, F., Franca, M. J., Mohr, S., Caldas-Alvarez, A., Daniell, J. E., Ehret, U., Feldmann, H., Hundhausen, M., Knippertz, P., Küpfer, K., Kunz, M., Mühr, B., Pinto, J. G., Quinting, J., Schäfer, A. M., Seidel, F., & Wisotzky, C. (2023). A multi-disciplinary analysis of the exceptional flood event of July 2021 in central Europe – Part 2: Historical context and relation to climate change. *Nat. Hazards Earth Syst. Sci.*, *23*(4), 1287-1311. https://doi.org/10.5194/nhess-23-1287-2023

Majumdar, S. J., Sun, J., Golding, B., Joe, P., Dudhia, J., Caumont, O., Chandra Gouda, K., Steinle, P., Vincendon, B., Wang, J., & Yussouf, N. (2021). Multiscale Forecasting of High-Impact Weather: Current Status and Future Challenges. *Bulletin of the American Meteorological Society*, *102*(3), E635-E659. https://doi.org/https://doi.org/10.1175/BAMS-D-20-0111.1

McCabe, M. F., Rodell, M., Alsdorf, D. E., Miralles, D. G., Uijlenhoet, R., Wagner, W., Lucieer, A., Houborg, R., Verhoest, N. E. C., Franz, T. E., Shi, J., Gao, H., & Wood, E. F. (2017). The future of Earth observation in hydrology. *Hydrol. Earth Syst. Sci.*, *21*(7), 3879-3914. https://doi.org/10.5194/hess-21-3879-2017

Menken, Steph, Machiel Keestra, Lucas Rutting, Ger Post, Mieke de Roo, Sylvia Blad, and Linda de Greef, eds. 2016. An Introduction to Interdisciplinary Research: Theory and Practice. Perspectives on Interdisciplinarity, Volume 2. Amsterdam: Amsterdam University Press.

Mohr, S., Ehret, U., Kunz, M., Ludwig, P., Caldas-Alvarez, A., Daniell, J. E., Ehmele, F., Feldmann, H., Franca, M. J., Gattke, C., Hundhausen, M., Knippertz, P., Küpfer, K., Mühr, B., Pinto, J. G., Quinting, J., Schäfer, A. M., Scheibel, M., Seidel, F., & Wisotzky, C. (2023). A multi-disciplinary analysis of the exceptional flood event of July 2021 in central Europe – Part 1: Event description and analysis. *Nat. Hazards Earth Syst. Sci.*, *23*(2), 525-551. https://doi.org/10.5194/nhess-23-525-2023

NOAA (2020). Precipitation Prediction Grand Challenge Strategy. Web: https://www.noaa.gov/sites/default/files/2022-01/PPGC-Strategy_FINAL_2020-1030.pdf

Pagano, T. C., Wood, A. W., Ramos, M. H., Cloke, H. L., Pappenberger, F., Clark, M. P., Cranston, M., Kavetski, D., Mathevet, T., Sorooshian, S., & Verkade, J. S. (2014). Challenges of Operational River Forecasting [Article]. *Journal of Hydrometeorology*, *15*(4), 1692-1707. https://doi.org/10.1175/jhm-d-13-0188.1

Pappenberger, F., Beven, K. J., Hunter, N. M., Bates, P. D., Gouweleeuw, B. T., Thielen, J., & de Roo, A. P. J. (2005). Cascading model uncertainty from medium range weather forecasts (10 days) through a rainfall-runoff model to flood inundation predictions within the European Flood Forecasting System (EFFS). *Hydrology and Earth System Sciences*, *9*(4), 381-393.

Pohl, C., Truffer, B., & Hirsch-Hadorn, G. (2017). Addressing Wicked Problems through Transdisciplinary Research. In R. Frodeman (Ed.), *The Oxford Handbook of Interdisciplinarity* (pp. 0). Oxford University Press. https://doi.org/10.1093/oxfordhb/9780198733522.013.26

Potter, S., Harrison, S., & Kreft, P. (2021). The Benefits and Challenges of Implementing Impact-Based Severe Weather Warning Systems: Perspectives of Weather, Flood, and Emergency Management Personnel. *Weather, Climate, and Society*, *13*(2), 303-314. https://doi.org/10.1175/wcas-d-20-0110.1

Scolobig, A., Prior, T., Schröter, D., Jörin, J., & Patt, A. (2015). Towards people-centred approaches for effective disaster risk management: Balancing rhetoric with reality. *International Journal of Disaster Risk Reduction*, *12*, 202-212. https://doi.org/https://doi.org/10.1016/j.ijdrr.2015.01.006

Selker, J. S., Selker, F., Llamas, R., Kruger, A., Niemeier, J., Najm, M. R. A., van de Giesen, N., Hut, R., van Emmerik, T., Lane, J. W., Rupp, D. E., Lintz, H., Stewart, R. D., & McCulloh, K. (2020). Lessons in New Measurement Technologies: From Instrumenting Trees to the Trans-African Hydrometeorological Observatory. In D. F. Levia, D. E. Carlyle-Moses, S. i. Iida, B. Michalzik, K. Nanko, & A. Tischer (Eds.), *Forest-Water Interactions* (pp. 131-144). Springer International Publishing. https://doi.org/10.1007/978-3-030-26086-6_6

Srinivasan, V., Lambin, E. F., Gorelick, S. M., Thompson, B. H., & Rozelle, S. (2012). The nature and causes of the global water crisis: Syndromes from a meta-analysis of coupled human-water studies. Water Resources Research, 48, W10516. https://doi.org/10.1029/2011WR011087

Sivapalan, M., & Blöschl, G. (2015). Time scale interactions and the coevolution of humans and water. Water Resources Research, 51, 6988–7022. https://doi.org/10.1002/2015WR017896

Songchon, C., Wright, G., & Beevers, L. (2023). The use of crowdsourced social media data to improve flood forecasting. *Journal of Hydrology*, *622*, 129703. https://doi.org/https://doi.org/10.1016/j.jhydrol.2023.129703

Tan, M. L., Hoffmann, D., Ebert, E., Cui, A., & Johnston, D. (2022). Exploring the potential role of citizen science in the warning value chain for high impact weather. Frontiers in communication, 7, 949949.

Thieken, A. H., Bubeck, P., Heidenreich, A., von Keyserlingk, J., Dillenardt, L., & Otto, A. (2023). Performance of the flood warning system in Germany in July 2021 – insights from affected residents. *Nat. Hazards Earth Syst. Sci.*, *23*(2), 973-990. https://doi.org/10.5194/nhess-23-973-2023

Troin, M., Arsenault, R., Wood, A. W., Brissette, F., & Martel, J.-L. (2021). Generating Ensemble Streamflow Forecasts: A Review of Methods and Approaches Over the Past 40 Years. *Water Resources Research*, *57*(7), e2020WR028392. https://doi.org/https://doi.org/10.1029/2020WR028392

World Meteorological Organization. (2022). Early Warnings For All: The UN Early Warning Initiative for the Implementation of Climate Adaptation - Executive Action Plan 2023-2027. WMO. Geneva. (56 pp.). https://library.wmo.int/idurl/4/58209

World Bank (2020). *The Power of Partnership: Public and Private Engagement in Hydromet Services*. World Bank, https://alliancehydromet.org/wp-content/uploads/2021/07/The-Power-of-Partnership-Public-and-Private-Engagement-in-Hydromet-Services.pdf

Wu, W. Y., Emerton, R., Duan, Q. Y., Wood, A. W., Wetterhall, F., & Robertson, D. E. (2020). Ensemble flood forecasting: Current status and future opportunities. *Wiley Interdisciplinary Reviews-Water*, *n/a*(n/a), e1432. https://doi.org/ARTNe143210.1002/wat2.1432

Zappa, M., Jaun, S., Germann, U., Walser, A., & Fundel, F. (2011). Superposition of three sources of uncertainties in operational flood forecasting chains. *Atmospheric Research*, *100*(2-3), 246-262.

Annexes

Annex 1: Supplemental Work Package Information

WP1 DEFINE – Define the problem of integration across the flood warning value chain

Mapping, inventory and needs assessment of integration

We will document and evaluate the integration status across flood early warning value chains, aiming to identify existing research, practices, stakeholder needs, and integration gaps, with a focus on transdisciplinary aspects. It includes mapping interactions and feedback loops, documenting case studies of successful integrations, and reviewing research needs and best practices for effective integration. This investigation will be based on a review of academic and grey literature, understanding needs from operational flood forecasting centers, and workshops. Description of integration of the flood early warning chain encompasses various aspects including:

- Disciplines engaged and their degree of interconnection
- Coupling level between components like meteorology, hydrology, the diversity of modelling and observation types utilized
- Feedback mechanisms between physical and social sciences
- Integration of cascading uncertainty in physical and social sciences
- Multi-directional knowledge and practice transfer across the value chain
- Modes and level of complexity of communication channels within the warning system
- Level of integration of local knowledge systems and of needs of marginalized communities
- Behavioural responses to warnings across individual, collective, and organizational levels.

Tasks include:

- Write micro-reviews across key research themes of InPRHA
- Create a web repository of short micro-reviews for and by academic researchers, operational forecasters/hydrologists, and Early Career Scientists (ECS). Operational forecasters/hydrologists and ECSs will be invited to contribute via workshops and webinars.
- Develop an expandable web repository allowing the community to contribute with their micro-reviews.

Characterizing complexities of enablers and barriers to integration

Based on the inventory and needs assessment, we will identify and characterize nodes of complexities to define the problem of integration across the flood warning value chain. We will conduct a gap analysis to understand the state-of-the-art, enablers and barriers in terms of their impact on the warning value outcomes like the integration of observation and model interoperability, physical and social processes, consideration for local knowledge and vulnerable populations.

Tasks include:

- Conduct gap analysis of inventory and define the problem
- Write a scientific manuscript consisting of the information in the micro-reviews highlighting gaps, challenges and opportunities, as highlighted by the gap analysis, for integrating meteorology, hydrology and social science for flood early action with a focus on transdisciplinarity
- Create a StoryMap documenting feedback loops and examples of good practices, using a matrix of administrative structures vs. earth systems

Evaluating effectiveness of integration

We will explore the effectiveness and impact of integrating components of the flood warning value chain by considering perspectives of multiple disciplines, existing and emerging technologies, methods, and process understanding. An evaluation framework with criteria and metrics that consider aspects of accuracy, reliability, uncertainty, inclusivity and user-friendliness will be conceptualized. The assessment will consider the role and integration of various knowledge systems, including Indigenous, operational, and local practices, in enhancing flood warning systems.

Tasks include:

- Define evaluation criteria by interviewing SG members and conduct surveys/workshops with stakeholders and services
- Gather stakeholder feedback to assess practicality and effectiveness of integration approaches, emphasizing research to operation perspectives
- Synthesize findings to inform next stages
- Iteratively update as project progresses and feedback gathered from stakeholders and other work packages

Formulating integration strategies and guidance for experiments

This stage involves formulating a framework of strategies, guidance and good practice to design integration experiments across the flood warning value chain. Building on previous findings, we will propose recommendations and design strategic initiatives tailored to different types of flood hazards, value chain components and involved sectors and communities.

Tasks include:

- Develop a high-level framework of integration strategies
- Produce and iteratively update a guidance tool on integrating approaches considering multiple research disciplines, emerging technologies, inclusive of Indigenous knowledge systems to improve flood early warning systems

WP2 CONSTRUCT – Construct and collect experiments that integrate meteorology, hydrology and social sciences for effective warning

Designing experimental protocol

We will develop a protocol for experiments aimed at exploring and evaluating integration across the flood warning value chain. This protocol will guide the collection and analysis of data, ensuring both physical and social science aspects. The protocol will emphasize at least two components of the value chain. We will invite the research and practitioner communities to identify and propose case studies that fit these criteria, facilitating a collaborative approach.

Tasks include:

- Conduct a collaborative team activity to define objectives and scope of experimental protocol of integration
- Develop guidelines for the experimental protocol (data collection, social science surveys, modelling requirements) to integrate components along the value chain.

Creating searchable database/repository

Drawing from the experience of the HIWeather database, and working closely with relevant groups in WMO's Infrastructure Commision, we aim to establish to create, pending funding availability, a searchable database/repository housing collected data (including observations, forecasts, warnings, communication, behavioural responses, and impacts).

Tasks include:

- Develop a database and web interface for adding new cases and entries, facilitating user-defined searches and displays based on requirements.
- Collaborate with researchers and practitioners to determine requirements for a database, IT infrastructure, and web-based access tool for the collected data.
- Define a data collection protocol to meet experiment needs and design test-beds linked to InPRHA questions, challenges, and objectives
- Create a submission platform, organize informational webinars or workshops to explain the experimental protocol, gather feedback, and encourage community participation and involvement.

Collecting experiments and test-beds

We will collect and document success and failure stories, along with learning opportunities, to directly improve National Meteorological and Hydrological Services (NMHSs) and bridge research to operations by targeting NMHS research needs.

Tasks include:

- Form a review committee to evaluate proposed experiments and case studies
- Curate a collection of case studies and experimental data for community exploration and further research.

WP3 EXPERIMENT – In-depth analysis of case studies and experiments towards integration of predictions for early actions

Generating experiments and case studies

This stage focuses on the implementation and generation of experiments of integration following WP CONSTRUCT. This will include conducting field observations, modelling simulations, survey-based social science experiments to assess how different ways of presenting flood information, forecasts and warnings are interpreted and acted upon. We will also develop protocols for experiment sharing, facilitating community involvement, co-production, and further exploration.

Tasks include:

- Set up experiments to test key research questions related to the integration of predictions and early actions.
- Iteratively refine protocols for storing and sharing data online to facilitate further community exploration.
- Form a crosscutting working group to design and conduct a workshop, followed by a survey, to understand the use of probabilistic river forecasts in research and operations.
- Focus funding and partnership opportunities with priority to Early Warnings 4 All communities and early warning forums

In-depth analysis of experiments and test-beds, knowledge co-production

We will conduct a comprehensive analysis of patterns and key findings from experiments and test-beds, identifying factors influencing success or failure and deriving insights. The objective is to relate challenges of integration from physical and social research questions to effective flood predictions, warnings and early action. Questions and research for experiments are listed, but not limited to, in the *Section Key scientific questions* across the themes of:

- State of the art for flood prediction and risk in a changing world

- Research to operation
- Emerging technologies
- Transdisciplinary synergies
- Hydrometeorological forecasting challenges
- Socio-economic, cultural and environmental challenges
- Uncertainties throughout the value chain
- Perceptions and actions for flood risks

Tasks include:

- Analyse experiment results to identify patterns, key factors, and areas for improvement in integration challenges and opportunities.
- Host regular workshops and webinars to disseminate experiment findings and promote knowledge-co-production and collaboration.
- Synthesize findings to derive insights, recommendations and identify benefits of effective and integration nodes along the value chain.
- Publish findings in reports, peer-reviewed journal articles.

Designing an integration framework and guidance tools

Based on previous stages and outcomes, we will develop a comprehensive integration framework and accompanying guidance tools for enhancing the effectiveness of flood warning systems and value chains. By synthesizing insights from in-depth analyses of experiments and emerging case studies, the framework will facilitate transdisciplinary learning, enabling multi-directional knowledge and practice transfer. The objective is to identify effective integration strategies, across the whole flood warning value chain, with all our expertise, identifying findings, lessons and good practice that apply across contexts (i.e., are generalisable) versus those that apply to specific contexts (e.g., countries), drawing on where appropriate on approaches and resources developed in the HIWeather Value Chain Project.

Tasks include:

- Facilitate discussions and feedback webinars or workshops on insights of integration, proposed framework's practicality, and effectiveness.
- Develop and/or adapt serious games for early action and disaster risk reduction, drawing on for instance approaches developed HEPEX[1] and by the Red Cross Red Crescent Climate Centre[2,3]
- Finalize recommendations and guidance tools on integrating approaches considering multiple research disciplines, emerging technologies, research to application challenges, inclusive of Indigenous knowledge systems to improve flood early warning systems

WP4 ENGAGE – Community engagement and co-production to foster knowledge exchange and outreach

Community co-production workshops and special conference sessions

These events will mature and establish an interdisciplinary network of researchers and public and private organizations committed to advancing integrated hydrometeorological forecasting and flood warnings, including raising awareness of InPRHA's goals and activities.

Tasks include:

[1] https://hepex.org.au/resources/hepex-games/

[2] https://www.climatecentre.org/priority_areas/innovation/climate-games

[3] https://www.stopdisastersgame.org/

- Plan, schedule and organize InPRHA workshops and special conference sessions in collaboration with key stakeholders and community representatives (such as round-table sessions at conferences on risk communication)
- Facilitate interviews with stakeholders, interactive discussions and activities, including games, to gather input, feedback and share experiences
- Conduct validation testing, and refine an integration guidance framework and recommendations

Exchanging knowledge

We will facilitate knowledge exchange through regular newsletters, webinars, and a special issue publication, ensuring widespread dissemination of findings and best practices, and fostering community engagement.

Tasks include:

- Develop a robust website, guided by the ICO, to serve as an information repository and archive.
- Host webinar series on project research findings, including one communication-focused webinar per year.
- Publish newsletters containing event announcements and project updates.
- Coordinate a journal special issue or collection on aspects of integration of the flood warning value chain.

Empowering: educational and capacity development pilot

This pilot study aims to expand knowledge within existing communities of practice by testing educational materials focused on guidance of integration of flood prediction across the flood warning value chain, recognising the importance of cultural considerations and Indigenous knowledge systems in the development of Flood Early Warning Systems (FEWS). It will target researchers, including researchers in less developed or resourced countries, to develop knowledge and skill in integrated forecast approaches. It will also target experts, end-users, and the public, covering the integration of disciplines, information dissemination, and public education on flood forecasting and early actions.

Tasks include:

- Pilot educational material to enhance capacity development to inform future outreach services including WMO guidance.
- Establish an InPRHA student prize of integration (of disciplines, knowledge systems, emerging technologies, research to practice) to ensure no one is surprised by a flood.
- Prepare presentation material to inform WMO report or guidance.

Coordinating: Project reporting, monitoring and evaluation

This stage involves coordinating project meetings, reporting to the WWRP SSC annually, and securing external funding. Key tasks include organizing regular project meetings, preparing progress reports, and monitoring project milestones and outcomes.

Tasks include:

- Schedule and facilitate project coordination and steering group meetings.
- Prepare and submit progress reports to WWRP for dissemination, monitoring and evaluation.
- Identify and apply for external funding opportunities to support project activities.

Annex 2: Supplemental Theory of Change Information

Our Theory of Change has identified six outcomes and articulated the knowledge and conditions needed for the achievement of that outcome. We explain the baseline conditions, and our rationale for how the activities within our Work Packages will contribute to meeting the knowledge and conditions needed. We also align each outcome to the WWRP Goals and AWAR^{3}E Principles.

BRIDGING COMMUNITIES: *New knowledge has been co-produced with existing communities of practice to improve dissemination and communication along the value chain of flood forecasting and warning, across disciplines (physical and social), for end users and the scientific community.* **Alignment:** WWRP Goal 3 and AWAR^{3}E PRINCIPLE 3 and 5

NEEDED KNOWLEDGE AND CONDITIONS:

- Expanded education for experts and public related to the flood early warning systems (including formal education about the integration of meteorology and hydrology, and dissemination of information, as well as public education related to hydrology, meteorology, flooding forecasts and appropriate early actions)
- Matured and established interdisciplinary network of researchers and public and private organizations committed to advancing integrated hydrometeorological forecasting

BASELINE CONDITIONS and RATIONALE:
Fostering collaboration between researchers, practitioners, and stakeholders to develop and implement innovative solutions for early warnings can be an ad hoc process. Institutional barriers, such as funding constraints and competing priorities, present further challenges to sustained collaboration.

We anticipate that by structuring regular and diverse opportunities for interaction, anchored by resources from the ICO, including a website and newsletter for the consistent sharing of content, that we can overcome this "ad hoc" approach to collaboration and build sustained relationships and information-sharing. Our indicators for this outcome chart growth in collaboration and public education.

BRIDGING ACROSS DISCIPLINES**:** *Integration of knowledge from different disciplines - including meteorology, hydrology, and social sciences as well as Indigenous knowledge systems - has led to a rethink of early warning systems by the research community, with an emphasis on the needs of developing countries and marginalized populations.* **Alignment**: WWRP goals 1 & 2 and AWAR^{3}E Principles 2, 4 and 5

NEEDED KNOWLEDGE AND CONDITIONS:

- Defined research needs and good practices for developing and evaluating a successful integrated prediction systems within the flood early warning value chain, now and in a rapidly changing climate and land use regime
- Advanced understanding of the needs of economically and socially disadvantaged, marginalized and underserved communities for early flood warning forecast information
- Documented success stories (and learning opportunities), and functional database of case studies, of integrations of meteorology, hydrology and social science that address early warning challenges in research and operations.

BASELINE CONDITIONS, RATIONALE and DATA COLLECTION
Currently, much international research related to hydrology and meteorology is siloed without integration, and with little input from social science, particularly in smaller and less resourced nations. Research feedback between disciplines is limited (Journal audiences tend to be siloed into disciplines). Incorporating social science research to understand human behaviour and decision-making during flood events for both flood responders and the public is lacking. We aim to increase this interdisciplinary and transdisciplinary research effort through multiple channels, including the publication of peer-reviewed articles, educational and information workshops, and the generation of new projects as a result of shared information.

BRIDGING ACROSS THE NATURAL AND HUMAN COUPLED SYSTEMS: *Coupling of hydrology and meteorology has built knowledge of interactions and feedback loops from natural and human coupled systems to reduce uncertainty.* **Alignment:** WWRP goals 1, 2 and 3 and AWAR^{3}E Principle 4

NEEDED KNOWLEDGE AND CONDITIONS:

- Advanced understanding of observational data gaps, limitations, and needs for short-term hydrometeorological and multi-hazard forecasting
- Advanced understanding of research modelling key processes in a coupled Human and Earth system prediction improving integration and interconnectedness throughout the entire early warning chain and considering a changing climate.

BASELINE CONDITIONS AND RATIONALE:
Key advancements include the development of coupled hydro-meteorological models, the integration of real-time monitoring data, the utilization of remote sensing technologies, and the implementation of community-based early warning systems. Furthermore, efforts are being made to enhance resilience through risk assessment, land-use planning, infrastructure design, and community engagement. Ongoing challenges include improving forecast skill to accurately initialize the precipitation and hydrological state, and to realistically represent uncertainties in model predictions, enhancing communication and decision support tools, and promoting equitable access to early warning information, especially in vulnerable communities.

With the first two outcomes in progress to support the transfer of knowledge across disciplines, we expect that the work within this outcome will come through the efforts of early career researchers working together. We expect information sharing to happen largely through online webinars and workshops that facilitate knowledge transfer on these topics, but also via in-person meeting (e.g., sessions at conferences). Such opportunities will be necessary for sharing knowledge of coupled systems.

BRIDGING ACROSS RESEARCH AND OPERATIONS *Research and operations have been bridged within flood forecasting and observing systems to improve the verification cycle, traceability of predictions and warnings, quantification and communication of uncertainties and to advance the understanding of the needs and constraints of operational centres, incorporating social science knowledge.* **Alignment:** WWRP Goal 3 & AWAR^{3}E Principles 1 and 4

NEEDED KNOWLEDGE and CONDITIONS:

- Established research science and operational requirements for incorporating hydrometeorological, Earth systems and multi-hazard key driving processes into warning value chains, including the need for communicating impacts from multi-hazard flood events (riverine, coastal, pluvial, compound events and tropical cyclones)
- Advanced understanding of types of uncertainty information most effective and salient for integrated modelling, decision-making and early actions

BASELINE CONDITIONS AND RATIONALE:
Communicating uncertainty is an important research focus with the advancement of probabilistic forecasts and ensemble technology, but fewer studies have addressed how the various sources of scientific uncertainty along the warning value chain interact and are received in messages between forecasters, practitioners and to users. Gaps between research advancements and their practical implementation in operational forecasting systems stem from issues like funding constraints, institutional barriers, and differing priorities between researchers and forecasters. Sustaining long-term collaboration between research institutions, operational agencies, and end-users can be challenging.

With the first three outcomes striving to bridge information transfer on integration of precipitation, hydrology and social science, this outcome is focusing on the specific area of verification, traceability, communication and quantification of uncertainty. We anticipate the project work, and specifically the development of case studies, will reveal continual progress in knowledge transfer on these topics, and will reveal evidence of an evolution of a bridged research and operations environment internationally. To measure this success we will need to analyse the case study compilation, review the information sharing that occurs through our own communication channels such as newsletter and blog posts, and survey SG members about the status of their own project findings.

BRIDGING ACROSS TYPES OF FLOOD HAZARDS *The warning process has been re-envisioned with considerations of multi-hazard interdependencies (compound and cascading hazards and their uncertainties) and local vulnerability and climate change on precipitation and hydrological forecasts.* **Alignment**: WWRP Goal 2 and AWAR^{3}E Principles 2, 3 and 4

NEEDED KNOWLEDGE AND CONDITIONS:

- Advanced research on effective governance, institutional structures and mandates needed to enable integrated predictions for early action
- Advanced understanding of public perception of multi-hazards and compound threats as well as how uncertainty information influences development of early warning systems
- Established research science and practice to integrate precipitation and hydrology, and multi-hazards into existing warning value chains using multi-source data, models and communication.

BASELINE CONDITIONS AND RATIONALE:
FEWS are an established concept but increasingly there is recognition that precipitation and hydrology events, combined with other severe weather events such as preceding droughts, high-winds, tornadoes and storm surges, can create compound and cascading hazards, as can the specific vulnerabilities of a region or locality. A shift is needed to a more comprehensive multi-hazard understanding of warning systems and how a changing climate interacts with predictions. Leveraging commonalities in hazard modelling, risk assessment and resilience strategies are limited. We anticipate that the outputs of the preceding outcomes will undergird the need for, and support our outcome related to, a cross-disciplinary emphasis on multi-hazards research. We expect an increase in the quantity and frequency of research projects and educational opportunities on these topics, both for the research community and end users.

BRIDGING SYSTEMS FOR CAPACITY DEVELOPMENT: Multi-organizational partnerships are increased in capacity in flood early warning knowledge, technology and understanding, and inclusive of formal and Indigenous knowledge systems. **Alignment**: WWRP Goal 3 and AWAR^{3}E Principle 5

NEEDED KNOWLEDGE AND CONDITIONS:

- Expanded opportunities for researchers, including in less developed countries, to develop knowledge and skill in integrated forecast approaches
- Expanded recognition of the importance of cultural considerations and Indigenous knowledge systems in FEWS development

BASELINE CONDITIONS AND RATIONALE:

Resources for developing flood and multi-hazard early warning systems are not equitably distributed, with developing countries often lacking access to technology and infrastructure required for effective implementation. But efforts to transfer knowledge and resources from developed countries cannot simply move technology into new regions without careful attention to local conditions, cultures, institutional practices, constraints and local priorities and preferences. Systems must recognize the value of, and incorporate, Indigenous knowledge systems, and build upon existing capacity while promoting expansion of warning system capabilities. This project will work to encourage new capacity for integrated forecasts.