

Integrating Prediction of Precipitation and Hydrology for Early Actions: The InPRHA Project within the World Weather Research Programme

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KEYWORDS:

Hydrometeorology;
Ensembles;
Forecasting;
Short-range
prediction;
Decision making;
Emergency
preparedness

ABSTRACT: Despite advancements in science and technology, flood prediction and preparedness remain challenging due to uncertainties in forecasting atmospheric and hydrologic processes, limited real-time data, and communication barriers. The Integrating Prediction of Precipitation and Hydrology for Early Actions (InPRHA) project, a 5-yr initiative under the WMO's World Weather Research Programme, is the first to bring together meteorology, hydrology, and social sciences within a steering committee to address these challenges. Building on knowledge from the High Impact Weather (HiWeather) project, InPRHA focuses on multihazard flood forecasting across the entire warning value chain from minutes to days, in a rapidly changing world. A key emphasis is understanding flood predictability and how uncertainties cascade through forecasting systems and are perceived, communicated, and acted upon by diverse stakeholders. This includes bridging research and operations, examining socioeconomic, cultural, and environmental challenges that influence risk perception and response. We propose key scientific questions across seven themes that address critical gaps in integrating predictions along the flood warning value chain. Addressing these gaps requires collaboration across disciplines and agencies. The project is structured into four work packages: DEFINE (identifying challenges), CONSTRUCT (gathering case studies), EXPERIMENT (scientific evaluations), and ENGAGE (community collaboration). Research will span rural, urban, and underdeveloped regions as well as countries with established warning systems, ensuring broad applicability. We invite scientists and practitioners from meteorology, hydrology, hydraulics, impacts, communication, human behavior, and economics to collaborate. By integrating disciplines and fostering transdisciplinary research, InPRHA aims to advance the science and practice of flood forecasting and early warnings to better protect vulnerable communities at risk.

DOI: 10.1175/BAMS-D-24-0332.1

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Manuscript received 10 December 2024, in final form 9 April 2025, accepted 27 April 2025

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SIGNIFICANCE STATEMENT: InPHRA is a 5-yr project aimed at promoting international co-operation and advancing research to enhance flood hazard forecasting systems and warnings. By integrating precipitation and hydrologic predictions with social sciences, it seeks to improve early warning for communities in a rapidly changing world. InPRHA aims to envision the warning process by addressing flood multihazard interdependencies, local vulnerability, and climate change impacts on precipitation and hydrology forecasts. InPRHA calls on the broader research and operational community to collaborate on addressing key scientific questions and fostering transdisciplinary research across academia, research institutions, policymakers, and operational forecasting centers.

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1. Introduction, motivations, and major issues

Flood forecasting and warning is considered a wicked problem (Allison et al. 2018; Pohl et al. 2017), characterized by complexity, interconnected and dynamic challenges, and the involvement of multiple actors and stakeholders. Flood forecasts are inherently uncertain (Cloke and Pappenberger 2009; Troin et al. 2021; Wu et al. 2020), 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. In addition to uncertainty, aspects of both atmospheric and hydrological systems may exhibit chaotic or unpredictable behavior, particularly where the system structure is highly complex or poorly observed. For example, the influence of preferential flow paths, evolving soil properties, and subsurface heterogeneity challenges our ability to fully characterize hydrological responses, even with high-resolution data. While meteorology has long acknowledged fundamental limits to predictability, similar questions are increasingly being explored in hydrology, raising important considerations for the role of model structure, scale, and observational constraints in flood forecasting. Even when floods are accurately forecasted, effective warnings can be compromised by communication breakdowns and barriers to information and actions (European Flood Awareness System 2021; Mohr et al. 2023; Thielen et al. 2023; Budimir et al. 2020). Climate change, driven by altered atmospheric composition, is further shifting rainfall patterns, intensifying extremes, and increasing evaporative demand, with cascading effects on the water cycle, flood frequency, and associated ecological and societal impacts (Hirabayashi et al. 2013; Harrington et al. 2023; IPCC 2022; Ludwig et al. 2023; WMO 2024).

Effective flood warnings integrate precipitation and hydrologic predictions with social sciences and local and Indigenous knowledge systems. In short, averting flood disasters requires a transdisciplinary approach with an unprecedented international coordinated, cooperative research effort. 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 and Wheeler 2015; Sivapalan and Blöschl 2015). It addresses not only the technical and environmental dimensions of water but also the social, cultural, economic, and health impacts (Costanza et al. 2007; Srinivasan et al. 2012). 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 nonacademic stakeholders, is best placed to address these real-world complexities (Bergmann 2012; Pohl et al. 2017). By engaging with local communities, including Indigenous groups, and coproducing knowledge, this approach ensures that early action plans are not only scientifically based but also socially and culturally relevant and effective (Menken and Keestra 2016).

Early warning systems (EWSs) within the value chain (Hoffmann et al. 2023) are understood as an integrated system of hazard monitoring, forecasting and prediction, disaster risk assessment, communication, and preparedness activities. Early warning systems can serve as a mechanism to enable individuals, communities, governments, and businesses to take timely action to reduce disaster risks. In March 2022, the World Meteorological Organization (WMO) and the United Nations (UN) announced the ambitious the “Early Warnings for All” (EW4All) initiative (WMO 2022). It aims to ensure that everyone on the planet is protected from hazardous weather, water, or climate events through life-saving early warning systems and anticipatory actions. The target is to develop a plan to ensure that early warning systems are widely used within the next 5 years by all people worldwide and empowering and supporting aid organizations with effective early warnings. The EW4All action plan was launched by the UN Secretary-General António Guterres during the World Leaders Summit at the 2022 Climate Change Conference, COP27. Early warning systems must be effective in delivering the information users need in ways they can access and can trigger effective behavioral responses.

To achieve this, addressing gaps in fundamental research and practice 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:

- Multidirectional knowledge and practice transfer refers to gaps in collaboration practices 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 and 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; Cattoën et al. 2025; 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).

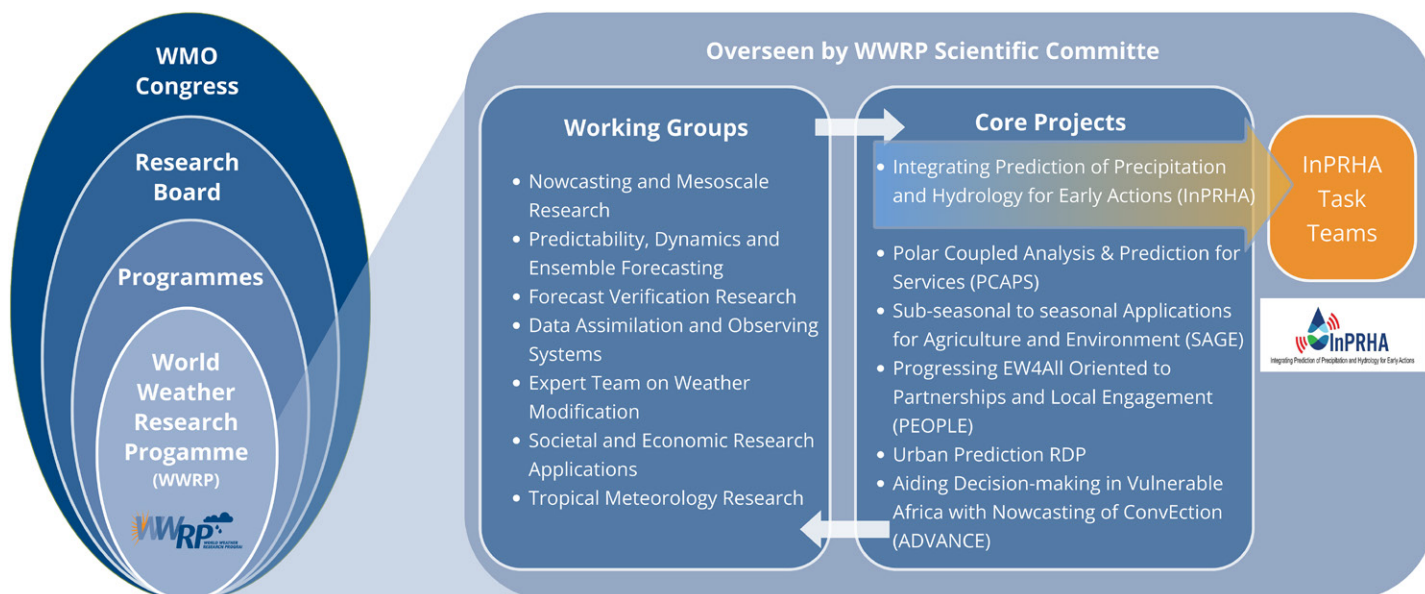


FIG. 1. Placement and linkages of InPRHA within the WWRP of the WMO.

- Increased data inputs and access include 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; McCabe et al. 2017).

Further, early warning systems must function within decision-making frameworks in communities, engaging a range of partners—from scientists developing new methods to operational agencies generating forecasts and emergency managers issuing local inclusive guidance to residents. This value chain must be effective end to end (Hoffmann et al. 2023), with uncertainty quantified throughout the forecast process, and communicated to end users in ways that support decision-making (Hogan Carr et al. 2016). In short, work remains to make early warning systems as effective and as inclusive as possible to benefit vulnerable communities.

In this article, we present the purpose and research plans of a new project, Integrating Prediction of Precipitation and Hydrology for Early Actions (InPRHA). The overarching aim of InPRHA is to advance the integration of precipitation forecasts, hydrology, and social science with a transdisciplinary approach, to achieve the condition in which “no one is surprised by a flood.” InPRHA builds on the goals of the WMO Vision and Strategy for Hydrology and its associated plan of action. InPRHA operates under the guidance of the World Weather Research Programme (WWRP) Scientific Steering Committee and its project plan is aligned with the WWRP Implementation Plan (Fig. 1).

2. 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, predictions (monitoring and modeling), and assessment, improving hydrometeorological warnings, and codeveloping 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, focusing on current challenges related to the integration of prediction within the flood forecasting and warning value chain. Addressing these gaps requires collaboration across disciplines. While each field has its own challenges

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 system's perspective of multihazards 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 nontraditional sources of forecasts (e.g., data-driven methods, such as AI, digital twin) in weather, hydrological modeling, and the potential for emulators to handle inundation forecasting?
3.2) How will kilometer-scale Earth system models (including surface representation) 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 (e.g., rain and flow gauge and weather radars) for precipitation and streamflow?
4.3) How can observational networks 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) Socioeconomic, cultural, and environmental challenges
5.1) What are the warning value chain demands and needs for communicating impacts through forecasts for multihazard 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 EWSs?
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 behavioral interventions that support flood resilience, education, and adaptation to living with risk? How best to support adaptive behavioral 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, hazards, and impact-based forecasting chain?
6.4) What are the opportunities for cocreating and codefining 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 multihazards and compound threats at the same time? How do multihazard 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 behavioral response, and what changes in information delivery across the value chain improve end-users' motivation to take protective actions?

to address, InPRHA, as a transdisciplinary initiative, emphasizes integration to advance flood forecasting and early warning systems beyond discipline-specific solutions. By engaging with projects and communities working on these scientific questions, InPRHA aims to identify the essential elements and processes required for effective integration of predictions across the value chain.

To advance this aim, InPRHA project 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 testbeds are necessary to advance knowledge on integration of predictions of meteorology and hydrology, communication, and early action? What verification methods are needed to systematically evaluate experiments and testbeds?
- How do we involve communities in coproducing 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 coproduction, and ultimately improve the effectiveness of flood early warning systems across different components of the value chain.

3. Mission statement, goals, and objectives

a. Mission statement. The InPRHA project aims to advance transdisciplinary knowledge and skill in the research and development of effective multihazard 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 forecasting the future. 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, behavioral 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 behavior, cultural values, and social structures—including Indigenous practices—shape flood preparedness, risk, and response.

b. Goals and objectives. Following from the mission statement, the project goals are to

- engage with the diversity of the international communities of researchers, forecasters, practitioners, and other stakeholders;
- foster collaboration between research and operations toward better services and tailored research, within National Meteorological and Hydrological Services (NMHSs) and beyond;
- bring together knowledge from different disciplines (climatology, meteorology, hydrology, and the social sciences) and cultures, with particular consideration for the most vulnerable and least developed communities; and
- rethink the flood warning process, in a nonstationary 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 (Fig. 2):

- *Bridging communities*: To coproduce new knowledge with existing communities of practice to improve dissemination, communication, and behavioral 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. artificial intelligence (AI)], methods, knowledge, and approaches from different research disciplines, including meteorology, hydrology, and social sciences, as well as local and Indigenous knowledge systems—to understand the flow of uncertainty and decision-making and improve the flood early warning chain.
- *Bridging across natural and human coupled systems*: To improve 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 warnings to reduce uncertainty.
- *Bridging across research and operations*: 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,

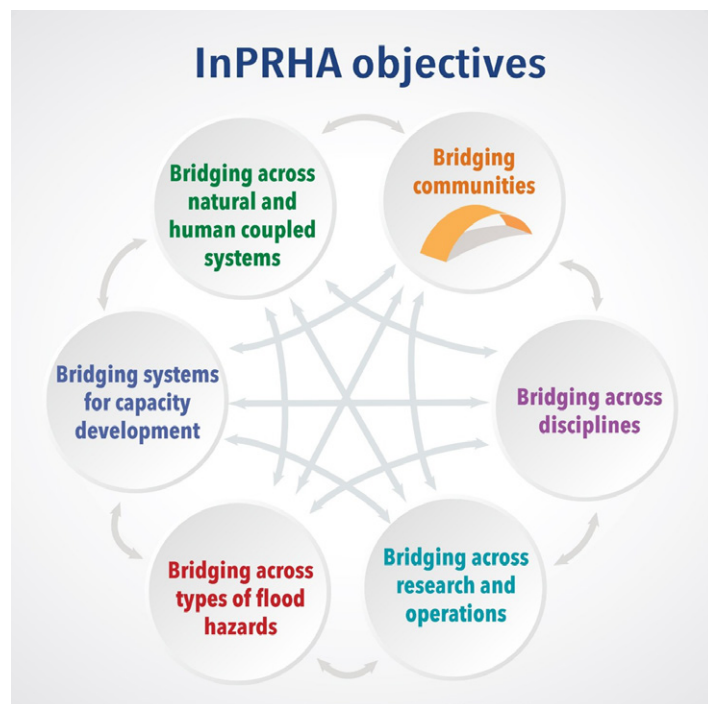


FIG. 2. Complex feedback interactions between InPRHA objectives.

- the quantification and communication of uncertainties,
- the understanding of the needs and constraints of operational centers, and
- the incorporation of social science knowledge into operations
- *Bridging across types of flood hazards*: To envision the warning process with consideration of impacts from multihazard 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 multiorganizational partnerships and policy and to bridge the gap between formal and local and Indigenous knowledge systems for more inclusive and effective flood early warnings.

c. Scope. This project will focus on shorter time scales (from minutes to days) and the advancement of warning strategies associated with hydrometeorological multihazards and their interdependencies. 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 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 state of the surface and subsurface, and continued support for ground-based networks for precipitation, streamflow, and other variables important to cryogenic-influenced systems.

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, behavioral response, and knowledge from psychology, sociology, and economics fields will work to ensure that information to end users is clear and actionable. This information should reach the intended audiences in a timely and simplified manner, which can be translated for easy dissemination and communication, and should sufficiently address the complexities of uncertainty, cascading and compound impacts, local conditions, and changing climate to enable effective action.

The project centers its research on addressing the needs of and building capacity for the most flood-vulnerable communities and especially, but not exclusively, lowest income nations or least developed countries in terms of early warning systems, while also considering disaster exposure in areas with high population density, such as urban flash floods. The goal is to target 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 the HIWeather project (Majumdar et al. 2021)—can be strengthened and also what communities need to actualize change within their systems.

4. Research plan

We have compiled InPRHA's research goals and objectives into work packages to allocate and distribute the work to successfully complete the project key objectives.

Figure 3 illustrates the work package framework and linkages between work packages. The project team contributes social and physical science expertise for all work packages. Work package DEFINE sets the ground level understanding of the state of the art, challenges, and

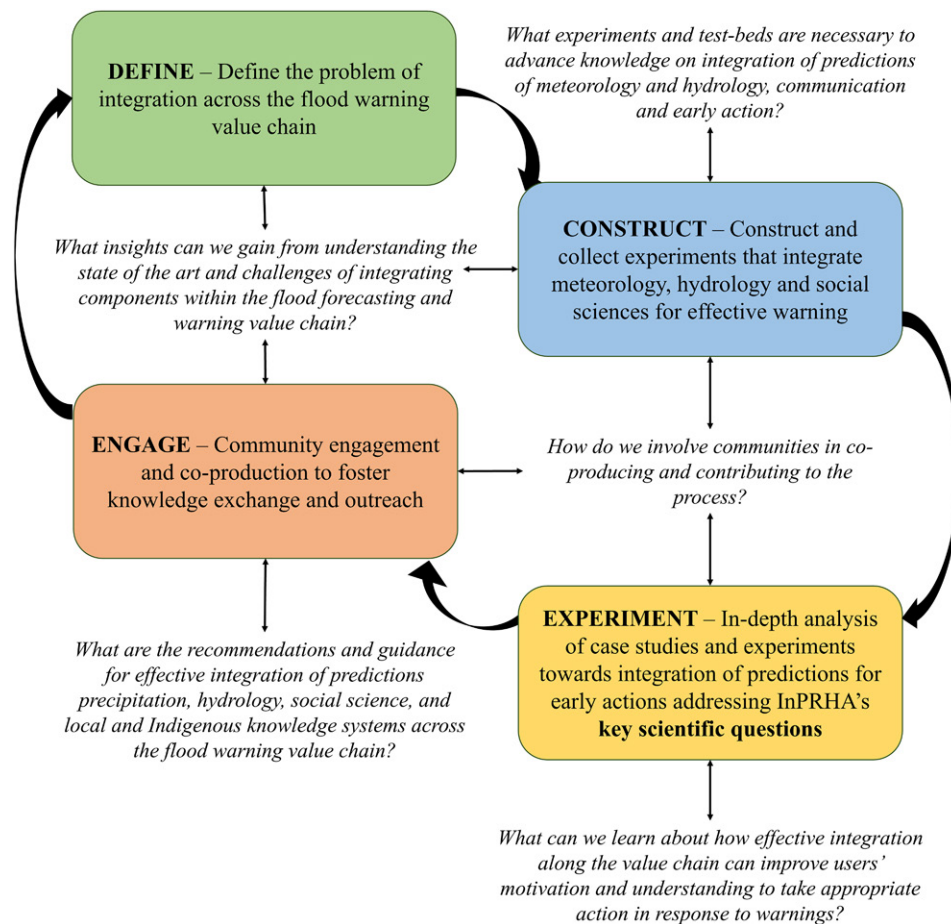


FIG. 3. Interactions between InPRHA's WPs, driving workflow questions (italic) and proposed key scientific questions (Table 1) to be addressed in the EXPERIMENT WP.

opportunities related to integration across the flood warning value chain; this work not only underpins the remaining three work packages but can also continue to evolve as new project work reveals evolving understanding of integration challenges. Key milestones of this and the other work packages are highlighted in Fig. 4. 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 InPRHA members' research projects, (ii) collaboratively as a Steering Group, and (iii) collaboratively as

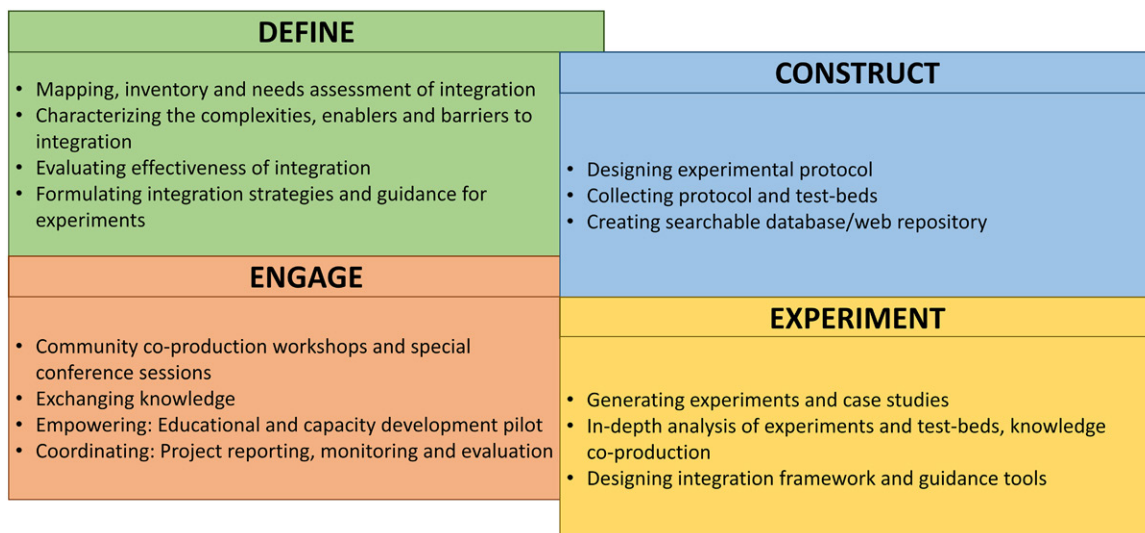


FIG. 4. Key milestones of InPRHA WPs.

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 coproduction among communities of practice to advance the research objectives and mission of InPRHA. For example, ENGAGE will codevelop knowledge to implement protocols for the food forecasting value chain.

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.

a. Work package 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 metastudy, surveys, and workshops to inform scientific inquiries and 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, behavior science, decision-making processes), and local and Indigenous knowledge systems for early actions. Table 2 provides a summary of the work package proposed activities, tasks, and outputs.

b. Work package CONSTRUCT—Construct and collect experiments that integrate meteorology, hydrology, and social sciences for effective warning. In this work package, a catalog of experiments will be designed based on findings from work package (WP) DEFINE. These experiments will study the integration of methods, knowledge, and approaches from various research disciplines and knowledge systems. The 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 multihazard interdependencies (compound and cascading hazards) and local vulnerability, including impacts of a changing climate and evolving land and water use. 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

TABLE 2. Activities, tasks, and outputs for the WP DEFINE.

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

TABLE 3. Activities, tasks, and outputs for the WP CONSTRUCT.

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

data across disciplines. Table 3 provides a summary of the work package proposed activities, tasks, and outputs.

c. Work package EXPERIMENT—In-depth analysis of case studies and experiments toward 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, behavioral response, and risk communication barriers and strategies. Table 4 provides a summary of the work package proposed activities, tasks, and outputs.

d. Work package ENGAGE—Community engagement and coproduction to foster knowledge exchange and outreach. ENGAGE will oversee the coordination of the first three work packages, while also building a strong interdisciplinary network through community coproduction workshops, conference sessions, and knowledge exchange initiatives like webinars and newsletters. It will engage and coproduce knowledge with WMO, international and national initiatives, as well as the broader research, practitioner, and end-user communities. It will foster collaboration across researchers, stakeholders, and public and private organizations, focusing on integrated hydrometeorological forecasting and flood warnings. Additionally, the work package emphasizes educational and capacity development,

TABLE 4. Activities, tasks, and outputs for the WP EXPERIMENT.

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

TABLE 5. Activities, tasks, and outputs for the WP ENGAGE.

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

especially in less-resourced communities, promoting knowledge sharing and cultural inclusion. Key tasks include organizing workshops, creating educational materials, hosting events, and coordinating project reporting and funding efforts. Table 5 provides a summary of the work package proposed activities, tasks, and outputs.

5. International context, partnerships, and next steps

InPRHA was approved by the Research Board of the World Meteorological Organization. Linking research activities to national and international organizations and encouraging the interface between scientific research, policymakers, and society will be fundamental (Suwa et al. 2019). This includes liaising with National Meteorological and Hydrological Services, the United Nations Office for Disaster Risk Reduction (UNDRR), the Global Flood Partnership (GFP), the United Nations Educational, Scientific and Cultural Organization's Intergovernmental Hydrological Program (UNESCO-IHP), the World Climate Research Programme Global Energy and Water Exchanges project (GEWEX), the Hydrological Ensemble Prediction Experiment (HEPEX), and the International Association of Hydrological Sciences (IAHS). Partner knowledge exchange between the developing and the developed world will be encouraged.

World Weather Research Programme core projects serve a diversity of audiences, both in the research and operational communities, and in the communities where early flood and multihazard warning systems can protect lives and property and reduce environmental damage. InPRHA has aligned its activities with the WMO Advancing Weather Research to Reduce Risk to Societies (AWAR³E) principles (Table 6) to ensure the projects focus on the

TABLE 6. WMO AWAR³E principles identified by the WWRP. AWAR³E consists of actionable research aimed not only at providing weather information but also ensuring that information is used to attenuate weather impacts on society.

Principle	Example measures of success
1) Ensure all stakeholders are aware of threats and mitigation efforts.	Evidence that fewer surprises occur or fewer poor decisions are made due to inadequate information.
2) Be aware of people and their needs.	Increased availability of weather research and applications for developing countries.
3) Make society aware of our science.	Evidence that capacity development and training include various groups in society.
4) Increase the awareness of forecasters and decision-makers of appropriate tools, data, and techniques.	Workshops designed with, and for, forecasters and decision-makers to raise awareness of new tools and provide training to make their work more effective.
5) Ensure research are aware of each other's work.	Projects started or continued with multiple partners such as WMO initiatives, member services, academia, operational centers, and other relevant bodies with special emphasis on regional bodies, to raise awareness.

most vulnerable audiences, address the needs of all people, and also support the capacity of forecasters, decision-makers, and researchers to continually improve outcomes.

In the ENGAGE work package, we invite the international community to share national and regional flood forecasting activities that support InPRHA's goal of integrated early warning systems bridging geophysical and social sciences. This feedback from the community will help identify gaps in transdisciplinary integration (DEFINE), develop long-term case studies (CONSTRUCT), and guide activities in EXPERIMENT and ENGAGE.

We also welcome researchers and practitioners to bring their projects to InPRHA, with a willingness to engage in cross-disciplinary collaboration. In 2025, InPRHA Task Teams will form to lead activities, such as arranging webinars, gathering case studies, developing story maps, and outlining next steps (Tables 2–5). Details on timelines and activities will be available through InPRHA's website (<https://wpo.noaa.gov/inprha/>). While InPRHA does not provide direct funding, it offers a strong support network through workshops, knowledge exchange, and structured engagement to refine research and analysis across disciplines. Efforts will also be made to secure external funding opportunities for further collaborations.

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 centers, 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 multihazard 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, multihazard flood forecasts, as well as to advance communication and behavioral response under uncertainty.

6. Concluding remarks

The InPRHA Implementation Plan for the coming 5 years highlights key scientific research questions across seven themes, focusing on current challenges in integrating precipitation and hydrologic predictions with social sciences for early actions. By engaging with research and operational 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. InPRHA's Steering Group is extending an invitation to the broader community to contribute to the project, encouraging engagement through our website or by reaching out to the cochairs. This unprecedented international effort seeks to advance our understanding and research, to improve effective warning to communities from flood hazard forecasting systems. The priority moving forward will be to set up task teams in 2025 to advance the four work packages DEFINE, CONSTRUCT, EXPERIMENT, and ENGAGE. Furthermore, we are seeking anchor projects/experiments of integration from the community that fit within InPRHA's vision of integrating precipitation and hydrologic predictions and social sciences in a rapidly changing world.

Acknowledgments. C. C. was supported by the New Zealand Ministry of Business and Innovation and Employment under Contract C01X1703. Yali Luo acknowledges support from the National Natural Science Foundation of China (42030610) and the Startup Foundation for Introducing Talent of Nanjing University of Information Science and Technology (2023r121). Thanks to Keri Maxfield, Nurture Nature Center, for contributions to the InPRHA logo in Fig. 2. This article was published with financial support of the World Meteorological Organization (WMO). The views, findings, interpretations, and conclusions presented are those of the authors and do not necessarily represent the opinions of WMO or its members.

Data availability statement. No datasets were generated or analyzed during the current study.

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