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The Needs, Challenges, and Priorities for Advancing Global Flood Research

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ABSTRACT

In recent years, numerous flood events have caused loss of life, widespread disruption, and damage across the globe. These devastating impacts highlight the importance of a better understanding of flood generating processes, their impacts, and their variability under climate and landscape changes. Here, we argue that the ability to better model flooding is underpinned by the grand challenge of understanding flood generation mechanisms and potential impacts. To address this challenge, the World Meteorological Organization-Global Energy and Water Exchanges (GEWEX) Hydrometeorology Panel (GHP) aims to establish a Global Flood

Crosscutting project to propagate flood modeling and research knowledge across regions and to synthesize results at the global scale. This paper outlines a framework for understanding the dynamics and impacts of runoff generation processes and a rationale for the role of a Global Flood Crosscutting project to address these challenges. Within this Global Flood Crosscutting project, we will establish a common terminology and methods to enable the global research community to exchange knowledge and experiences, and to design experiments toward developing actionable recommendations for more effective flood management practices and policies for improved resilience. This harmonization of rich perspectives across disciplines will foster the co-production of knowledge primed to advance flood research, particularly in the current period of heightened climate variability and rapid change. It will create a new transdisciplinary paradigm for flood science, wherein different dimensions of mechanistic understanding and processes are rigorously considered alongside socioeconomic impacts, early warning communications, and longer-term adaptation to alleviate flood risks in society.

1 | Introduction

Extreme weather events are becoming more frequent, intense, and severe because of climate and environmental change. Among weather extremes, flooding stands as the most destructive worldwide in terms of economic damage and deaths (Windheuser et al. 2023). Floods are the overland flow of water, over land that is normally dry, and can be pluvial, snowmelt, coastal, or a combination. While studying different types of flooding is important from scientific and impact assessment perspectives, the focus of this advanced review paper is on riverine flood (hereafter flood) only and how different processes modulate runoff generation mechanisms of this type of flooding across various spatiotemporal scales and nonstationary drivers.

Global flood events from 2002 until the end of Q3 2022 caused total economic losses estimated at $227 billion, with the US accounting for the highest percentage ($114 billion; ~50%), followed by Asia-Pacific and Europe ($56 billion) and the Middle East and Africa ($40 billion; EM-DAT 2023). From 2022 to 2023, nearly every global region was impacted by floods, with particularly devastating losses of human life on September 10, 2023 medicane-induced flood in Derna, Libya (> 10,000 deaths and economic damage of > US$19 billion; Fowler et al. 2024) and in the June–September 2022 Pakistan floods (1739 deaths and economic damage of US$15 billion; EM-DAT 2023). Flood risk and damage are of concern for many nations, with governments making substantial efforts to find appropriate solutions for controlling flood hazards, risk, and societal impacts. It is further becoming clear that historical research efforts are biased toward studying hydro-hazards in wealthy nations, despite greater losses of life in poorer ones (Stein et al. 2024). Fortunately, momentum is gathering to address flooding risks and impacts. The US federal government has made investments in flood assessment by focusing on a new Federal Flood Risk Management Standard to improve our understanding of the processes governing flood probability, incidence, and impacts. In Europe, the city of Copenhagen has implemented advanced water management systems to mitigate flooding and demonstrated a multipurpose solution for building resilience while also making these urban systems more attractive. Global initiatives also continue to evolve, such as Hydrologic Ensemble Prediction Experiment (HEPEX; Schaake et al. 2006) which seeks to advance hydrological ensemble prediction, and the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP; Frieler et al. 2024) which seeks to create consistent frameworks for model evaluation. Thus, an unprecedented opportunity now exists for a collaborative approach that brings together the global research community to both advance flood science and to help better manage the consequences of flooding across regions.

The World Climate Research Programme (WCRP)-Global Energy and Water Exchanges (GEWEX) Hydrometeorology Panel (GHP) plans to establish a Global Flood Crosscutting project to identify opportunities where the outcomes of regional and global studies can be synthesized to accelerate more impactful flood research—improving our modeling and monitoring of flooding as well as our understanding of the processes that govern flooding. A Global Flood Crosscutting project will enable a community-driven approach toward answering important scientific questions such as: (i) What physical and hydrological factors dominate flood generation mechanisms across scales? How might these factors differ in their combined flood generation mechanisms across different landscapes, for example, coastal, urban, mountain, and rural environments? (ii) To what extent do landscape systems and changes therein control the spatiotemporal variability of flooding? and (iii) What is the likely interplay between changes in climate and physical catchment characteristics (e.g., indicators of abrupt system shifts) on flood occurrence and predictability? How do changes in climate and land use systems (e.g., dam-induced land use changes, etc.) co-evolve and cascade from the atmosphere to the land surface and affect catchment susceptibility to flooding? How do the sensitivity and uncertainty of flood simulations increase under non-stationarity in climate and land use systems? The first step toward facilitating a global initiative to answer these questions is to set out the rationale for addressing them and to discuss the terminology and methods needed to enable global research communities in different disciplines to efficiently exchange knowledge and experiences toward the development of actionable recommendations for more effective flood control, resilience policies, and impact assessment.

2 | Challenges Associated With Flood Risk and Impact Assessment

Flooding occurs over a range of temporal and spatial scales and arises from complex hydrological processes whose nonlinear interactions challenge conventional approaches to short-term forecasting for emergency response and to longer-term assessments of risk for spatial planning and climate change adaptation policies. Predicting the spatiotemporal variability and magnitude of floods as well as managing the large volumes of overland flow produced is hugely challenging, as floods occur when the drainage capacity of channel networks is being overwhelmed and catchment responses to extremes are rapid and highly nonlinear (Phillips et al. 2018, 2022). Catchment response often varies with rainfall intensity and magnitude (e.g., Fowler, Lenderink, et al. 2021) and is modified by changes in land surface processes (e.g., He and Hogue 2012; Barros et al. 2014; Samadi and Meadows 2017) caused by physical catchment changes (e.g., dam construction, canalization) as well as by climate variability and change (e.g., Friedrich et al. 2016).

Despite the importance of understanding flooding from both a scientific and impact-centric perspective, we currently lack: (i) a complete understanding of flood generation mechanisms across different regions and a comprehensive assessment of changes; (ii) a complete assessment of how climatic features modulate extreme precipitation and snowmelt and how these variations influence flood occurrence, predictability, and clustering; and (iii) a thorough understanding of how flooding shapes catchment susceptibility as it evolves under non-stationary changes in climate and land use conditions. These limitations also highlight a knowledge gap in understanding how catchments respond to external forcing (e.g., high-intensity precipitation events), the flashiness of runoff, seasonality effects, and the impact of vegetation dynamics. Addressing these limitations can help identify "at-risk" areas to flooding events across a range of catchment types (e.g., urban vs. rural vs. coastal). This can include determining the sensitivity of different catchment parameters to climate and land use changes, defining the response of catchment systems (flashy vs. slow), and identifying the representation of rapid surface runoff through mechanistic understanding of rainfall-runoff processes across small (headwater streams) to large scale catchments. The above factors that impact flood generation and subsequent assessment of flood risk are summarized in Figure 1. While this list is not exhaustive, it serves to provide a basis (and hence common terminology and vision) by which we can start to discuss flood generation variability and the research gaps that exist. In the following sections, we unpack and summarize these aspects, focusing on the hydrologic factors controlling flood generation mechanisms, the causative mechanisms behind spatiotemporal variability in flooding, and their interplay with climate and land use—with the aim of harmonizing our knowledge and experiences across disciplines, as well as identifying future challenges.

2.1 | Hydrologic Factors Controlling Flood Generation Mechanisms

What physical and hydrological factors control flood generation mechanisms across space and time scales? How might these control mechanisms be altered by changing boundary conditions driven by climate and land-surface changes? And how might these be different in the combined flood generation mechanisms across different coastal, urban, mountainous, plains, and rural landscapes? These are just some of the questions we currently lack evidence on in the context of flood generation mechanisms. A comprehensive review of our current understanding of flood generation mechanisms can be found in Jafarzadegan et al. (2023). Recent studies have focused on developing classifications of flood generation mechanisms, as well as static and dynamic basin attributes applicable to large data samples

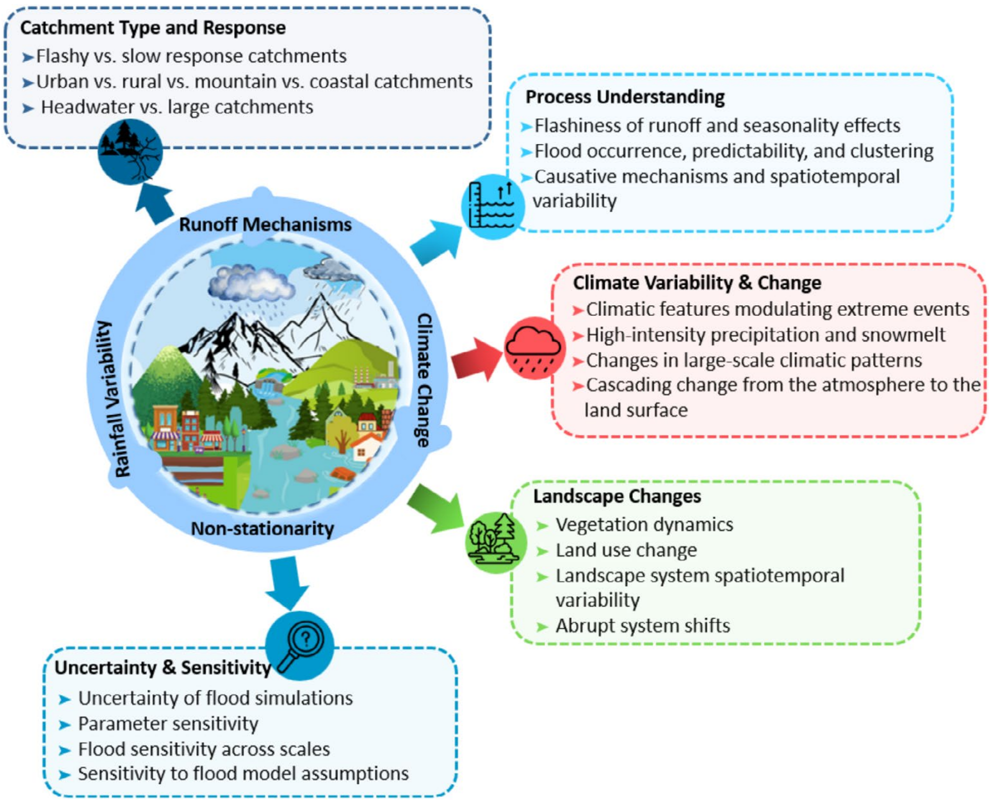

FIGURE 1 | A summary of the challenges associated with understanding flood generation mechanisms. Flood processes vary with catchment response and causative mechanisms and are impacted by atmospheric drivers, climate change and variability, and landscape changes, with our understanding of flood processes being influenced by uncertainty sources and sensitivities that vary across scales.

of hydrologic catchments (Li et al. 2023; Liu et al. 2020; Stein et al. 2019; Tarasova et al. 2019). Such classifications can help us to understand what mechanisms dominate at the subbasin or hydrological response unit scale (Stein et al. 2021; Chen et al. 2023), and how they might change under future climate scenarios (Jiang et al. 2024). While significant uncertainties exist around the most extreme floods and their generating mechanisms, which are mostly different from more common 'nuisance' flood events (Merz et al. 2021), we might still be able to estimate what floods might be possible in a location using similarity principles (Bertola et al. 2023).

Currently, fine-scale runoff generation mechanisms and the dynamics of runoff generation processes are yet to be further discovered and regionalized under current and projected future conditions. Available variables and parameters are limited in their ability to meaningfully characterize hydrologic systems, for example, we lack reliable subsurface descriptors (Tarasova et al. 2024). Not surprisingly, current models reveal significant differences in their estimates of flood magnitudes (e.g., Devitt et al. 2021). Missing observations often include the spatiotemporal variability of causative precipitation, antecedent soil moisture and groundwater, snowpack, and broader land surface states, discharge along the river network, as well as catchment attributes—especially related to subsurface properties. New observational systems, often based on remote-sensing techniques, are regularly put into place, such as the recent Surface Water Ocean Topography (SWOT; Biancamaria et al. 2016) launched at the end of 2023, and upcoming NASA-ISRO Synthetic Aperture Radar (NISAR; Kellogg et al. 2020) satellite missions, with an anticipated launch in March 2025. These systems provide the capability to reduce scale gaps in observations, thus allowing us to evaluate, and possibly even constrain, model predictions. While new observations cannot fill in gaps during historic flood events, they can be used to advance our physical and causal understanding of combined flood-generating mechanisms across scales; and then to inform models in reconstructing past events and to provide guidance on future hydrological behavior under climate change. However, there is still a need to advance observational measurements of extreme rainfall, especially in topographically challenging areas (e.g., Gnann et al. 2025).

The impacts of past flood events, and the potential impacts of future floods in a changing world, are also poorly known and quantified (Kreibich et al. 2022). Robust and comprehensive data on flood hazard impacts are rare, which undermines any detailed analysis of flood risk. The potential impacts of flooding on society are diverse, ranging from immediate threats to life and property to long-term effects including diseases or mental health issues, poor municipal water quality, and increasing costs to rebuild. Social vulnerability and its spatiotemporal variability are important themes, and their intersections with flood hazards must be considered to assess and predict potential impacts (Terti et al. 2015). Flood inundation mapping using approaches such as explicit hydrodynamic modeling, machine learning, and filling low-lying areas according to a digital elevation model has recently emerged as tools for planning, designing, and forecasting in the face of flooding (Nobre et al. 2011; Sampson et al. 2015; Bomers et al. 2019; Bates et al. 2021; Windheuser et al. 2023). Yet, uncertainties in these maps must also be incorporated into decision-making, given the sensitivity of simulation results to errors in inputs and model assumptions (Savage et al. 2016; Najafi et al. 2024). Alternative or complementary observational strategies are required to increase the robustness of information for decision-makers and policymakers. One alternative strategy is to use stress testing to model the flood system in response to a range of plausible changes in the system's drivers/stressors to quantify how many people would increasingly be exposed, instead of relying on a single flood estimate based on a chosen return period or a climate scenario (Devitt et al. 2023). Performing such testing across systems allows for the identification of the most vulnerable systems or sub-systems. It also allows decision makers to identify possible actions in response to a particular stressor.

2.2 | Causative Mechanisms and Spatiotemporal Variability of Flooding

Understanding the causative climatic, meteorological, hydrologic, and hydrodynamic flood-generating processes that control the spatiotemporal characteristics of flooding requires both atmospheric and watershed perspectives (Schelf et al. 2019; Jafarzadegan et al. 2023). Climatic elements such as the intensity and distribution of precipitation, temperature fluctuations, and atmospheric circulation patterns (see Figure 2) play significant roles in determining flood timing and location (Schelf et al. 2019; Fowler, Lenderink, et al. 2021). These factors then interact with regional hydrological processes, which again vary depending on when and where the precipitation has occurred (Merz et al. 2011; Jung et al. 2011), creating variability in the flood response arising from the wide range of hydrological drivers. Urban areas, for example, often experience pluvial flooding due to intense, short-duration rainfall on poorly drained, impervious surfaces, while rural areas may encounter prolonged riverine flooding (Merz et al. 2011; Wu et al. 2021) resulting from the combined effects of one or more rainstorms, high soil moisture, and in many cases, snowpack and snowmelt, and storm tides in coastal areas (Berghuijs et al. 2019; Tarasova et al. 2019; Wasko et al. 2021). Soil antecedent moisture dynamics play a significant role in the risk, severity, and spatial extent of flooding (Wasko and Nathan 2019; Ran et al. 2022; Brunner and Dougherty 2022). All these flood "ingredients" not only vary geographically but also seasonally, meaning that understanding these spatiotemporal differences in flood physics is crucial for identifying vulnerable regions, creating accurate flood prediction models and early warning systems, and allocating scarce resources (Wu et al. 2014; Blöschl et al. 2019).

Recent technological advancements have significantly improved our ability to document, analyze, and understand flood events locally, regionally, and globally. Remote sensing technologies, such as satellite imagery and airborne Light Detection and Ranging (LiDAR), are crucial in capturing high-resolution data on flood extents and dynamics (Brakenridge et al. 2012). High-resolution gridded precipitation datasets from ground-based weather radars such as NEXRAD, space-based instruments, and numerical weather and climate models have proven crucial for understanding, predicting, and projecting the spatiotemporal dynamics of floods (e.g., Giannoni et al. 2003; Villarini et al. 2010; Wright 2018; Yu et al. 2020), enabling large-sample hydrological studies to assess flood variability between regions. In conjunction with the

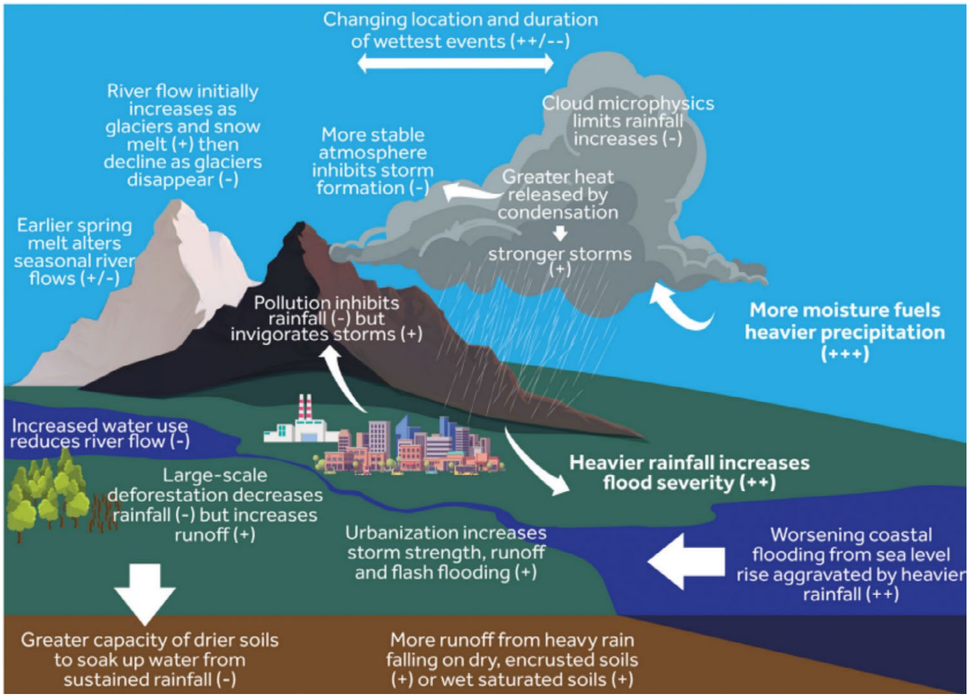

FIGURE 2 | Schematic illustrating factors important in determining changes in heavy precipitation and flooding (adapted from Allan et al. 2020).

development of distributed hydrologic models, these products have allowed for the accurate translation of rainfall space–time variability into flood responses (e.g., Cunha et al. 2012; Wright et al. 2014) in a variety of applications ranging from forecasting to long-term frequency analysis. For example, NASA's Global Flood Monitoring System (GFMS) integrates satellite data with hydrological models to detect and map floods worldwide (Wu et al. 2014). Crowd-sourced data and social media analytics have also emerged as valuable complementary approaches, enriching traditional flood inventories with real-time, on-the-ground information (Fohringer et al. 2015; Donratanapat et al. 2020; Huang et al. 2021). The benefits of crowd sourcing data, for example through citizen science, are twofold: the collection of additional data helps improve modeling efforts and flood estimates resulting in reduced uncertainty, but also, the engagement of citizens improves the individual capacity to adapt to and cope with natural disasters (Ferri et al. 2020).

Despite these advances, deriving reliable high-resolution historical distributions of flood frequency, intensity, and duration remains a core challenge due to the scarcity and often limited quality of flood data (Teng et al. 2017), limitations of remote sensing data, and the uneven distribution of ground-based observations (Brakenridge et al. 2012). Additionally, processing and verifying unstructured data from crowdsourcing adds another layer of complexity (Fohringer et al. 2015; Pally and Samadi 2022). The advent of climate change further compounds our ability to understand flood dynamics by altering precipitation patterns and intensifying extreme weather events (Ward et al. 2014; Alfieri et al. 2018; Fowler, Lenderink, et al. 2021). Much of the discussion of research needs in this area is captured by Fowler, Ali, et al. (2021). For more frequent, long-duration precipitation extremes, changes to atmospheric dynamics can act to both increase and decrease the intensity and frequency of precipitation extremes depending on the region (Pfahl et al. 2017). However, for rarer events at longer durations, changes converge regionally to produce increases (Wasko et al. 2023). Short duration extremes are expected to intensify even more than long duration extremes, causing them to become more peaked temporally with warming (Villalobos-Herrera et al. 2023; Visser et al. 2023), and changing the spatial extent of storms (Zhong et al. 2024). Understanding these changes and their interactions with the catchment response remains complex (Peleg et al. 2018) but recent advances in computing power are pointing toward new ways of overcoming these challenges.

The development of large ensembles of climate models allows for a deeper understanding of low-frequency variability (both natural and anthropogenic) in atmospheric circulation patterns, storm types, and storm sequences that influence when and where floods are likely to occur, while high-resolution "convection-permitting" weather and climate simulations can translate this variability into critical storm-level precipitation dynamics, including interactions with terrain features. However, short-duration, high-intensity storms pose challenges to standard numerical prediction models as their land surface components fail to route intense rainfall-runoff processes precisely (Guido et al. 2023). Alternative approaches such as hydrodynamic modeling can simulate these dynamic processes, even simulating flood waves, but cannot be applied over the largest catchments yet (Glenis et al. 2018).

Due to the limited mechanistic processes in many modeling frameworks, it is still a challenge to model the complexities and nonlinear nature of the hydrological response, particularly at different spatiotemporal scales and for nonstationary drivers. For instance, the Framework for Understanding Structural Errors (FUSE) proposed by Clark et al. (2008) simulates different parameterizations to model the fluxes of surface runoff, vertical percolation, evaporation, and baseflow by hypothesizing a limited soil store sub-model (two-layer). The Joint UK Land Environment Simulator (JULES; Best et al. 2011) and the community Noah land surface model with multi-parameterization options (Noah-MP; Niu et al. 2011) were designed to model the land-surface and climate procedures over a (limited) range of hydrologic processes. The WRF-Hydro model (Gochis et al. 2020), which is used as the US National Water Model for flood forecasting, has limitations in considering sub-grid variability of ponded water on the routing grid, which can be sensitive to parameters and internal time steps. Moreover, these models are restricted to a small model ensemble (e.g., Vano et al. 2012; Hooker et al. 2023) while floods occur over different spatial scales, thus requiring many physical processes and model structures/configurations to deal with their complex nature and drivers.

Hydrologic modeling efforts and data-driven approaches go hand in aiding our understanding of the heterogeneity of flood generation processes, with data required to parametrize the modeling efforts described above. Many areas are ungauged, necessitating regionalization of parameter estimates (Wasko et al. 2024) and statistical approaches to regionalize flood statistics. Errors in these datasets propagate to the parameter estimates and model results, and often parameters, rather than being used to represent a physical process, are simply used to tune the model response to match observations. While much research investigates the quantification of this uncertainty, and the advent of new datasets (e.g., remote sensing) are often touted to provide an avenue for reducing uncertainty in hydrologic modeling, uncertainties will remain as these data are often calibrated to a sparse observational network. Hydrodynamic models can offer improved representations of overland flow but still require parameterization and are intensive to run. Methods that blend models and data through artificial intelligence attempt to bridge these gaps.

Recent advancements in deep learning models can provide accurate and responsive flood forecasting systems (Samadi 2022). Specifically, physics-informed deep learning models can be developed to emulate complex physical processes in flood generation and routing (e.g., Saberian et al. 2024), although discovering the fundamental runoff generation mechanisms to infuse implicit watershed physical parameters into deep learning algorithms can be challenging. Furthermore, spatiotemporal variability in data (Seibert and McDonnell 2002; Zhou et al. 2023) and uncertainty associated with data-driven modeling and decision making can hinder prediction accuracy (Sadeghi Tabas and Samadi 2022). Uncertainty arising from noise in data and deep learning modeling structures, parameters, and hypotheses must also be considered (Der Kiureghian and Ditlevsen 2009). Limited data availability and resource constraints can also significantly affect data-driven predictions, impacting model training, deployment, and overall prediction accuracy.

A key challenge in moving forward is how to integrate the strengths of physical and deterministic models with data-driven approaches to improve the representation of flood processes. Continued research and developments in data monitoring and sensing, data-driven methods, coupled hydrological and atmospheric modeling, and traditional and data-driven inundation mapping are critical for enhancing our understanding, reconstruction, and prediction of the spatiotemporal variability of flooding. These challenges underscore the need for ongoing advancements in data integration techniques, sensor technology, and interdisciplinary collaboration to improve our ability to predict and respond to evolving flood risks.

2.3 | Interplay With Climate and Land Use Change

Land use changes have been as significant in impacting the generation of flood risk as changes in climate (Wheater and Evans 2009; Jha et al. 2011). Changes in land use can impact hazard generation through the influence of their greenhouse gas emissions affecting global climate, by creating local meso- and micro-climate effects, by altering flood pathways, and by increasing catchment susceptibility to flooding. Risk management strategies, such as channelization, can create feedback mechanisms leading to further changes in land use that may contribute to a vicious circle of accelerating risk. The dynamics of flooding are affected through urbanization and engineered water management such as dam and levee construction, but understanding the complex interplay between climate, land use and land management, water management systems, and risk remains an emerging area of research. Key research questions to address relate to the methods needed for projections of future physical changes in catchments driven by human activities, such as reservoir management, urbanization, and changes in agriculture; identifying feedback mechanisms to meso- and micro-hydrology; the potential for land use policy to mitigate risk by including the impact of policy on behaviors; and improved understanding of the sensitivity of different flood models to future land use scenarios.

2.3.1 | Catchment Hydrology Using Land Use Projections

Land cover plays a vital role in flood generation as it defines the roughness of the land surface in catchment models (Dwarakish et al. 2015). So far, most studies assessing the impacts of climate change on flooding primarily consider changes in meteorological variables under different emission scenarios (e.g., Wedajo et al. 2022), often neglecting land use changes and assuming they remain static. This is despite the fact that a significant portion of the land surface has been altered by human activities (Iacob et al. 2017). Future studies on catchment hydrology must assess the surface-subsurface response of catchments under the combined effects of changing meteorological variables and land use. Understanding the interplay between these factors is essential for managing flood risks and ensuring the ecological health of catchments. Land-use projections require consideration of human/landscape interactions, development scenarios, and specific flood and water management strategies.

2.3.2 | Impact of Water Management

Besides climate and land use change, floods are also shaped by water regulation practices, including dam and reservoir regulation, groundwater abstraction, and/or water diversions (Wada et al. 2017). Such regulation can alleviate or aggravate flood peaks and volumes as well as their impacts on society (Brunner 2021; Kreibich et al. 2022). Specifically, flow regulation through dams has been shown to affect flood peaks and volumes (Brunner 2021), especially immediately downstream of the dams and in case of large storage availability (Volpi et al. 2018; Xiong et al. 2019). Besides local flood characteristics, flow regulation through dams can also change the spatial properties of floods, that is, increase or decrease their spatial extent (Brunner 2021). While ordinary extreme events can often be alleviated by targeted water regulation, regulation fails in reducing the impacts of unprecedented events (Wang et al. 2017; Kreibich et al. 2022). However, our understanding of the effects of regulation on floods at a global scale is hampered by the very limited availability of global regulation data at sufficient spatial and temporal resolution (Brunner et al. 2021) and by the rather simplistic representation of regulation in global-scale hydrological models (Hanasaki et al. 2006).

2.3.3 | Evolving Landscapes Through Urban and Micro-Scale Interactions

Uncertainty and variability are created through the design and management of land with respect to surface water management and drainage systems. Recent developments in Natural Flood Management through Blue-Green Cities and other nature-based approaches (see Guido et al. 2023) seek to maintain the natural water cycle in developed catchments through a combination of large- and small-scale sustainable drainage systems (Lamond 2016). Within urban development, the potential for such systems to alleviate flooding has been well researched at smaller scales; however, questions remain on the extent to which multiple benefits of these systems can affect wider ecosystems and feedback into meso- and micro-climates. Importantly, these approaches require wider stakeholder engagement, beyond those traditionally associated with flood risk management, including the communities and urban designers that create and manage such spaces (Krivtsov et al. 2021). As these spaces are part of the fabric of the wider urban system, often unmanaged or managed for multiple objectives, the behaviors and preferences of urban communities should inform scenarios.

2.3.4 | Sensitivity of Flooding at Different Spatial Scales and Types and Uncertainty of Future Scenarios for Land Use Changes

Flood sensitivity varies across spatial and temporal scales and flood types. Small watersheds respond quickly to intense rainfall, leading to flash floods, while large river basins experience gradual flooding from prolonged rainfall or snowmelt. Urban areas, with extensive impervious surfaces, face heightened risks of pluvial and riverine flooding. Climate change alters precipitation patterns, adding uncertainty. Future flood scenarios are also uncertain due to land use changes. All these factors need to be considered in unison if we are to understand, model, predict, and project floods for an uncertain future. For example, increased urbanization increases impervious surfaces, exacerbating runoff. Deforestation reduces water absorption, heightening flood risks (Guido et al. 2023). Infrastructure development modifies water flow, influencing flood dynamics, while socioeconomic factors further contribute to uncertainty, vulnerability, and risk in our flood response by directly and indirectly affecting flood drivers (Khajehei et al. 2020; Yarveysi et al. 2023).

3 | Next Steps

Our call for increased understanding of flood processes, potential impacts, and agility of flood models contributes to the debate on the "correct" conceptualization of flood generation mechanisms and the representation of complex processes using new data and models that might support new hypotheses. Finding a good synergy and balance between dominant catchment parameters and model-/data-based interfaces requires revisiting or perhaps modifying the representations of spatial variability and hydrologic connectivity, process representations, numerical schemes, and couplings with other model components such as the atmosphere. When viewed from this perspective, we can ensure that flood generation processes and mechanisms, the spatial resolution used to simulate these mechanisms, and the methods used to estimate model parameter values are represented explicitly.

In our opinion, improving flood process understanding across scales and regions, increasing monitoring and collection of high-resolution data efforts, and refining both model structures (e.g., refining model equations and state) and parameterizations are key to advancing the hydrologic theory of runoff generation mechanisms. This involves both (i) improving the hydrodynamic scheme and physical realism of traditional flood models and reducing the reliance on deterministic methods that are plagued by systematic errors and unrealistic runoff generation mechanisms, and (ii) increasing the agility of physically motivated modeling systems and integrating data-driven approaches in traditional flood models to better understand landscape complexities, the uncertainties, and non-stationarities. Furthermore, improving mechanistic flood understanding is encouraged by explicitly considering the dominant biophysical and hydrological processes by focusing on spatial variability, hydrologic response connectivity, and scale-dependent flow parameterizations under changing hydroclimatic and land use conditions. Implementing this vision requires the integration of our understanding of environmental physics with high-resolution data across different regions to both refine the structure of current flood models and to incorporate more robust physically based scaling theories that can explain the heterogeneity of biophysical and hydrological connectivity and reduce the uncertainties throughout the entire model chain. Such understanding will accelerate progress on flood prediction methods and help society to develop appropriate solutions to manage flood consequences at regional and global scales.

4 | The Importance of Global Dialogue

The grand challenge of understanding different flood drivers and mechanisms is not confined to a single region of the world—it is a global challenge. Thus, as we seek to understand flood risks and impacts, a diverse range of perspectives is imperative. For many decades, academics and policymakers across the world have fruitfully collaborated on the mechanistic understanding and mitigation of weather hazards, and these global partnerships have facilitated meaningful intellectual exchanges and practical implementations of approaches to assist with societal response and recovery following major flooding events (e.g., Fowler, Wasko, et al. 2021). For example, HEPEX, formed to develop and demonstrate new hydrologic forecasting technologies and to facilitate the

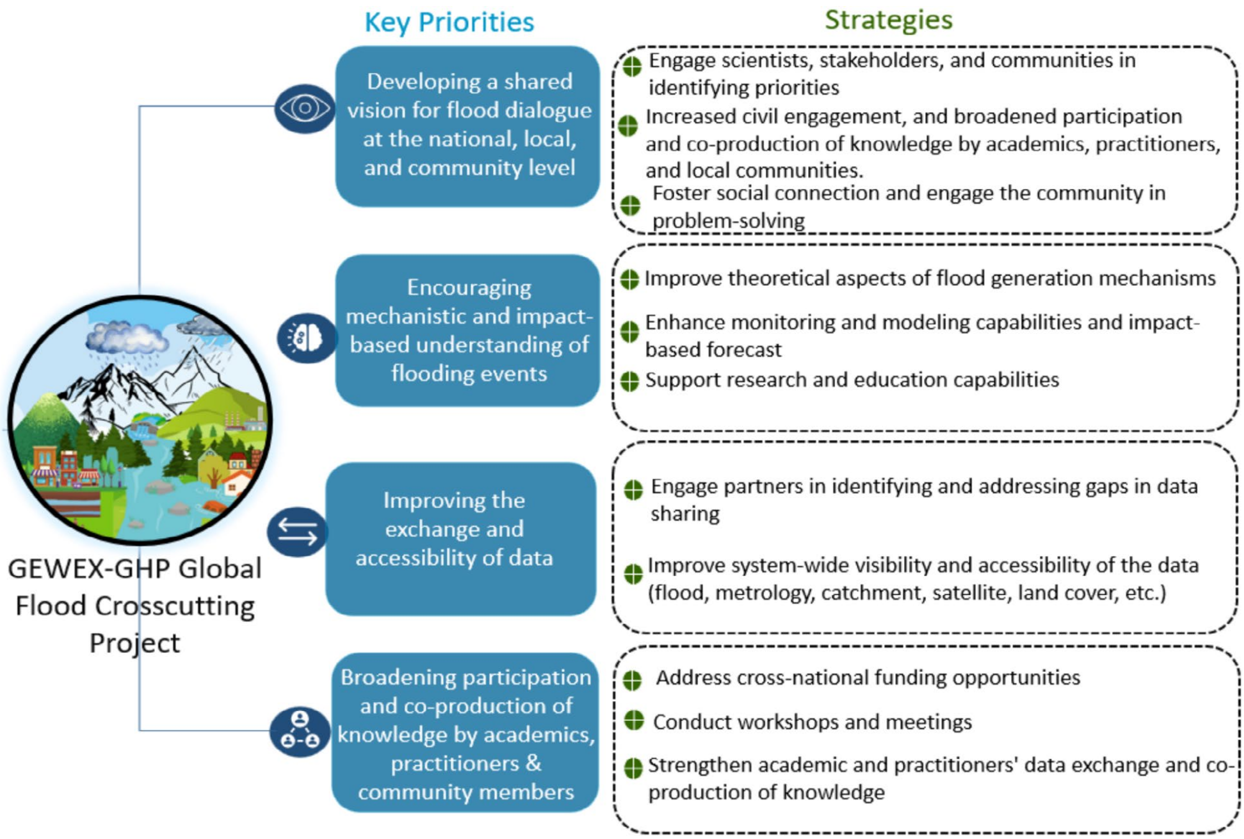

FIGURE 3 | A global vision for flood research coordination and exchange of knowledge.

implementation of beneficial technologies into the operational environment (Schaake et al. 2006), has existed for over 20 years. Similarly, the Global Flood Partnership (GFP) was established in 2014 with a vision to synthesize the research results (including data processing algorithms, new observational methods, etc.) into the technical know-how needed for operational flood forecasting implementation across the globe.

As researchers from across the world come together, they produce a valuable combination of knowledge and experience in science, engineering, and technology with perspectives from distinct cultural backgrounds and histories. This transdisciplinary blend of similarities and differences can create a common perspective for community understanding of flood risks and challenges, as well as a platform for collaboration on the development of novel solutions. As we consider this holistic new framework for global flood dialogue that is, at its heart, science-driven, then combining ideas from across the world promotes its global relevance. Furthermore, we believe that establishing a Global Flood Cross-Cutting initiative requires cross-national, transdisciplinary collaboration, with a shared vision and a comprehensive theoretical foundation used to define and develop strategies for understanding flood impacts and developing solutions for different regions. In this spirit, this paper summarizes our common vision, identifying knowledge gaps and strategies to address these grand challenges in flood research and setting our findings into the context framed in Figure 3. As shown, we believe that key priorities should focus on improved mechanistic and impact-based understanding of flooding, improved data accessibility, increased civil engagement, and broadening participation and co-production of knowledge by academics, policymakers, and local communities. Engaging local, regional, and national policymakers to ensure that flood research and outcomes inform policy decisions and resource allocation can benefit flood risk management by developing comprehensive perspectives, promoting effective communication, and fostering collaborative decision-making. An example of this is the UK's Flood Hydrology Roadmap (Lamb et al. 2022) which sets out a vision for flood hydrology in the United Kingdom for the next 25 years. This is accompanied by an action plan that details how that vision will be achieved; covering England, Wales, Scotland, and Northern Ireland from 2021 to 2046, it considers all sources of inland flooding and ranges from operational practice to scientific research to policy making and regulation.

5 | Concluding Remarks

Flooding is becoming increasingly complex and volatile across the globe. Flood generation mechanisms are shaped by local to global factors that must be considered in the discourse on long-term disaster preparedness and planning. One fundamental way to advance our understanding of flood generation mechanisms and impacts is by developing a more holistic research agenda and strategies designed to capture changes from hydroclimate variables to land surface mechanisms across a range of spatio-temporal scales, to refine and adjust the portrayal of physical processes by hydrologic models, and to manage flood risks under non-stationarity, socially complex, and compound stressors. Such strategies should consider the importance of flood risk reduction measures to enable a better response to flood impacts when they do occur, for example through an improved impact-based flood early warning system and emergency management planning scenarios, as well as for longer-term climate adaptation planning. Impact-based flood forecasts can provide early intelligence to local authorities for better-informed decisions and tailored emergency actions. Although the challenges remain when the uncertainties propagate throughout the entire forecast model chain that require quantification. In addition, addressing the scarcity of flood monitoring and remote sensing data should be prioritized moving forward. Terrain characteristics, such as slope, drainage density, and elevation can serve as a proxy for flood susceptibility analysis when hydrological data is scarce and limited (Basso et al. 2023). Furthermore, remote sensing data offers a cost-effective and scalable solution for monitoring large areas, including those with limited or no ground-based infrastructure.

Moving forward, we assert that improving flood research across the global community must address the above challenges by integrating our collective knowledge and understanding with the strengths of new theories and modeling philosophies, considering that "cookie-cutter" solutions often do not yield the desired results and outcomes. For research to be relevant in addressing those challenges, community members' knowledge should be incorporated into flood research and risk assessment. Co-production of knowledge by academics, policymakers, and community members is vital in achieving research goals, particularly for improved transboundary collaboration before and after flood events, and civic engagement in flood risk governance.

We have laid out a vision for addressing flood research challenges which presents a shift in how we approach the problem of flooding, offering a holistic, transdisciplinary way of thinking about water, its impacts, and risks. We hope that our common vision will help to coordinate global interdisciplinary efforts and more effectively leverage regional capacities to enable improved understanding and quantification of flood consequences and impacts, and the coordination of cross-national efforts in developing improved early warning systems and information for climate adaptation. To action this vision, we must establish an international program to improve understanding toward averting flood catastrophes. This must start by addressing the specific science questions we have raised above, and by identifying opportunities where global transdisciplinary collaborations can uniquely advance flood research into policy and practice. This is a vision that we hope to achieve in the GEWEX Global Flood Crosscutting initiative.

Author Contributions

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Related WIREs Articles

Causative classification of river flood events

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