



Technical Review and Perspective

GLOBAL FLOOD AWARENESS SYSTEM (GLOFAS): FROM GLOBAL HYDROLOGICAL FORECASTING TO OPERATIONAL FLOOD-RISK EARLY WARNING

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ABSTRACT

Flood forecasting and early-warning systems have become essential components of disaster-risk reduction, particularly in regions where hydrometeorological monitoring networks remain sparse and where rapid urbanization, land-use change, and climate variability are increasing exposure to extreme hydrological events. The Global Flood Awareness System (GloFAS) represents a major advance in operational large-scale hydrology by providing spatially consistent and probabilistic river-flow forecasts across national and transboundary river basins. Nevertheless, the effective translation of global hydrological forecasts into locally actionable flood warnings remains challenging because of uncertainties in meteorological forcing, hydrological model structure, observational constraints, spatial resolution, flood-threshold estimation, and the representation of local hydraulic processes. This paper provides a technical and geographical assessment of GloFAS within the broader framework of contemporary flood forecasting and early warning. Particular emphasis is placed on the integration of hydrological modelling, Geographic Information Systems (GIS), remote sensing and Earth observation, probabilistic forecasting, flood-frequency analysis, and high-resolution hydraulic modelling. The specific challenges associated with ungauged and poorly gauged basins, urban flooding, and hydroclimatic non-stationarity are critically examined. Recent developments in artificial intelligence and machine learning are further discussed as complementary tools for bias correction, parameter regionalization, model post-processing, multisource data fusion, and uncertainty reduction. On this basis, a global-to-local flood-warning framework is proposed in which global hydrological forecasting serves as an initial layer of risk detection and is progressively complemented by regional observations, catchment-scale hydrological models, local hydraulic simulations, Earth-observation products, and exposure and vulnerability information. The

analysis highlights that the greatest operational value of GloFAS does not lie in replacing national or local forecasting systems, but in providing an open, coherent, transboundary, and anticipatory hydrological information layer capable of strengthening them. Such an integrated approach is particularly relevant to data-scarce and developing regions, where global forecasting systems may substantially improve flood preparedness, provided that their outputs are locally validated, uncertainty-aware, and effectively incorporated into impact-based early-warning and decision-support frameworks.

Keywords: Global Flood Awareness System (GloFAS); flood forecasting; early-warning systems; flood risk; hydrological modelling; GIS; remote sensing; Earth observation; artificial intelligence; climate change; ungauged basins; global-to-local forecasting.

INTRODUCTION

Floods are among the most recurrent, spatially extensive and socio-economically disruptive natural hazards worldwide. Their occurrence reflects the complex interaction of atmospheric forcing, catchment hydrology, channel hydraulics, geomorphology, land-surface characteristics and human activity. The transformation of intense or prolonged precipitation into damaging flood conditions is controlled by rainfall magnitude and temporal distribution, antecedent soil moisture, infiltration capacity, catchment morphology, drainage density, land use and land cover, river-network conveyance and the spatial organization of exposed communities and infrastructure. Consequently, flood risk cannot be understood solely as a meteorological phenomenon; rather, it represents the outcome of a coupled hydroclimatic and territorial system (Rao and Hamed, 2001; Hachemi and Benkhalel, 2016; Dottori et al., 2016; Derdour et al., 2017; Abd Rahman et al., 2023; Hafnaoui et al., 2023; Ezz, 2025).

The consequences of flooding have been further intensified by rapid urbanization, expansion into flood-prone areas, increasing soil sealing, modification of natural drainage pathways and inadequate stormwater infrastructure. Numerous case studies have demonstrated that the severity of flood impacts is often strongly conditioned by anthropogenic transformation of the catchment rather than by precipitation alone. Research conducted in Skikda, Medjez El Bab, Béchar, Cotonou, Béjaïa and El Bayadh illustrates the extent to which urban development, river-corridor occupation, drainage deficiencies and inappropriate land management may amplify flood exposure and vulnerability (Boulghobra, 2013; Ayari et al., 2016; Bekhira et al., 2019; Hountondji et al., 2019; Benslimane et al., 2020; Hafnaoui et al., 2022; Ben Said et al., 2024). These conditions have contributed to a progressive transition in flood-risk management from post-disaster response toward anticipatory strategies based on monitoring, forecasting, early warning and preparedness.

Reliable flood forecasting requires an accurate representation of the relationship between atmospheric forcing and catchment response. Rainfall-runoff modelling therefore remains one of the principal foundations of operational hydrology. However, rainfall-runoff relationships are highly nonlinear and depend on catchment storage, antecedent wetness, soil characteristics, evapotranspiration, topography and river-network structure.

A wide range of modelling studies has consequently been devoted to representing these processes under contrasting climatic and physiographic conditions (Abdi and Meddi, 2015; Djellouli et al., 2015; Faregh and Benkhaled, 2016; Fernando et al., 2021; Atallah et al., 2024; Mehta and Yadav, 2024). These studies consistently show that predictive performance depends not only on model structure but also on the quality, spatial representativeness and temporal continuity of the input data.

Precipitation uncertainty constitutes one of the principal sources of uncertainty in flood forecasting. The hydrological significance of a storm depends not simply on accumulated rainfall, but on its intensity, duration, frequency, spatial organisation and timing relative to catchment conditions. Statistical and stochastic analyses of precipitation have therefore long played a central role in hydrological design and forecasting. Investigations of rainfall variability, extreme precipitation and precipitation-frequency characteristics have demonstrated the importance of understanding both temporal persistence and spatial heterogeneity when interpreting flood-generating events (Lazri et al., 2007; Houichi, 2017; Benkaci et al., 2020; Zeggane et al., 2021; Bong et al., 2023).

The limitations of conventional flood forecasting become particularly evident in ungauged and poorly gauged river basins. Many regions of the world continue to lack sufficiently dense and reliable hydrometeorological observation networks, while existing records may be discontinuous, inaccessible or too short for robust calibration of flood models. This observational deficit represents a major constraint in low- and middle-income countries, where populations may simultaneously experience high flood exposure and limited institutional capacity for hydrological monitoring. The increasing availability of satellite precipitation estimates, global digital elevation models, land-cover products, remotely sensed soil and surface-water information and global meteorological reanalyses has therefore created new opportunities for large-scale hydrological forecasting.

Geospatial technologies have become integral to this evolution. Geographic Information Systems facilitate the integration of topography, hydrography, rainfall, soils, land cover and infrastructure within a coherent spatial framework, while remote sensing enables repeated observation of large and inaccessible areas. The value of these approaches has been demonstrated through GIS-based rainfall characterization, remote monitoring of hydrological surface conditions and spatial assessment of water-related processes (Hamimed et al., 2017; Adja et al., 2021; Jaiswal et al., 2023; Deb, 2024). The combination of Earth observation with numerical hydrological models has therefore substantially expanded the possibility of generating flood information in regions where conventional observations remain limited.

Against this background, the Global Flood Awareness System (GloFAS) has emerged as a major international platform for global-scale hydrological forecasting. Developed within the European flood-forecasting framework and currently operated through the Copernicus Emergency Management Service, GloFAS provides spatially consistent probabilistic river-flow forecasts across the global river network. The system is particularly relevant for large transboundary basins and data-scarce regions, where flood evolution may extend across administrative boundaries and where no single national monitoring system provides sufficient spatial coverage.

The fundamental scientific contribution of GloFAS lies not simply in the production of global streamflow forecasts, but in the establishment of a coherent hydrometeorological modelling framework capable of comparing forecast flows against model-consistent climatological thresholds. In this context, flood forecasting becomes a problem of probabilistic threshold exceedance rather than deterministic discharge estimation alone. Flood-frequency analysis is therefore essential because a forecast discharge must be interpreted relative to the expected hydrological regime of the river system (Rao and Hamed, 2001; Hachemi and Benkhalel, 2016). Regional investigations of flood characteristics further demonstrate that the hydrological significance of a given discharge varies substantially among basins and climatic environments (Meigh et al., 1997; Abd Rahman et al., 2023; Hafnaoui et al., 2023).

Nevertheless, forecasting high river discharge and forecasting flood inundation are not equivalent tasks. A model may successfully predict an extreme discharge while providing little direct information on the spatial extent, depth or velocity of subsequent flooding. Hydraulic modelling and detailed topographic representation are generally required to transform river discharge into spatially explicit inundation characteristics. Flood-risk mapping and hydraulic applications conducted in Medjez El Bab, Béjaïa, arid Algerian catchments and Mersa Matruh illustrate the importance of combining hydrological prediction with hydraulic simulation and geospatial analysis (Ayari et al., 2016; Benslimane et al., 2020; Athmani et al., 2025; Ezz, 2025).

This issue becomes even more critical in urban environments. Urban flood dynamics may be governed by local-scale processes, including sewer-network capacity, road geometry, imperviousness, drainage obstruction, culvert performance, retention facilities and microtopographic controls. Models such as SWMM have therefore become indispensable for representing urban stormwater processes at spatial scales that cannot be resolved adequately by continental or global hydrological models. Applications reported by Baudhanwala et al. (2023) and Bentalha (2023), together with urban flood simulations undertaken by Benslimane et al. (2020), reinforce the need for a hierarchical modelling strategy in which global forecasts are supplemented by high-resolution local analysis.

At the same time, data-driven methods are reshaping the field of flood forecasting. Artificial neural networks have been applied successfully to daily and instantaneous flood prediction (Cherki, 2019), while gene-expression programming has demonstrated potential for estimating hydraulic parameters such as Manning's roughness coefficient (Chaplot, 2021; Chaplot et al., 2021). Broader applications of machine-learning, artificial neural network and neuro-fuzzy methods in water engineering further indicate their capacity to represent nonlinear hydrological relationships and complement conventional models (Bougamouza et al., 2022; Bouriche et al., 2023; Ansari et al., 2024; Belouz et al., 2025). Rather than replacing physical hydrology, these approaches are increasingly expected to support hybrid modelling architectures combining process-based knowledge with data-driven correction, parameter estimation, bias reduction and uncertainty quantification.

Another major scientific challenge concerns the assumption of hydrological stationarity. Flood-warning thresholds and recurrence intervals are commonly derived from historical

climatology under the implicit assumption that the statistical behavior of hydrological extremes remains stable (UNDRR, 2015; RIMES, 2020). Climate change, urbanization, deforestation and other forms of land-surface modification increasingly challenge this assumption. Studies examining hydroclimatic variability and projected climate impacts demonstrate that both river-flow regimes and extreme-event characteristics may evolve over time (Assemian et al., 2021; Chadee et al., 2023; Pang and Tan, 2023; Mah et al., 2024; Lalwani et al., 2026; Patil et al., 2026). Consequently, future flood-awareness systems may need to incorporate non-stationary or adaptive thresholds capable of responding to changing hydrological baselines.

The principal scientific question is therefore no longer simply whether a global system can forecast an anomalously high discharge (WHO, 2022). The more consequential issue is under what conditions a global hydrological forecast becomes sufficiently accurate, spatially relevant and operationally interpretable to support an effective early-warning decision. Addressing this question requires simultaneous consideration of meteorological uncertainty, hydrological model performance, observation density, basin characteristics, forecast lead time, spatial resolution, threshold definition, inundation representation, exposure, vulnerability and institutional capacity for warning dissemination.

Accordingly, this study develops a technical and geographical assessment of GloFAS from a multi-scale and decision-oriented perspective (EC, 2017). The specific objectives are to: (i) examine the hydrometeorological and geospatial architecture underpinning global flood forecasting; (ii) assess the principal sources of uncertainty and limitations, particularly in ungauged and data-scarce basins; (iii) position GloFAS within the wider hierarchy of hydrological, hydraulic and urban flood-modelling tools; and (iv) propose an enhanced global-to-local framework integrating probabilistic forecasting, Earth observation, local hydraulic modelling, artificial intelligence and impact-oriented decision support. Particular attention is given to developing and data-scarce regions, where globally available flood-information systems may substantially reduce disparities in access to hydrological intelligence, provided that global forecasts are appropriately validated, interpreted and adapted to local conditions.

Scientific positioning of GloFAS

Floods rank among the most destructive and spatially pervasive hydro-meteorological hazards worldwide. Their occurrence and severity result from the interaction of multiple processes, including precipitation intensity and duration, antecedent soil-moisture conditions, catchment morphology, river-network connectivity, land-cover characteristics, hydraulic conveyance capacity, and the degree of human occupation of flood-prone areas. Consequently, reliable flood forecasting cannot be reduced to meteorological prediction alone; rather, it requires an integrated modelling chain capable of transforming atmospheric forcing into hydrological response, evaluating the likelihood of threshold exceedance, and ultimately translating hydrological anomalies into actionable information for disaster-risk management.

Within this framework, the Global Flood Awareness System (GloFAS) represents a major development in large-scale operational hydrology. Designed to provide spatially consistent flood-forecast information across national and transboundary river basins, GloFAS addresses one of the most persistent limitations in global flood-risk management: the uneven availability of hydrological observations. Its importance is particularly pronounced in regions where stream-gauging networks are sparse, fragmented, inaccessible, or insufficient for the development of robust national forecasting systems.

GloFAS should not, however, be regarded as a universal substitute for national or local flood-forecasting services. Its principal scientific and operational value lies in its capacity to provide globally consistent, probabilistic and transboundary hydrological information, thereby complementing local observation networks and supporting anticipatory decision-making where conventional monitoring systems remain limited.

Functional architecture of a global flood-forecasting system

At the conceptual level, the GloFAS forecasting chain may be expressed as:

Meteorological forcing → hydrological initial conditions → distributed hydrological modelling → streamflow forecasting → threshold exceedance analysis → probabilistic flood signal → hazard/impact interpretation → early-warning information.

The reliability of the final warning therefore depends on the quality and consistency of each component of this modelling chain.

Meteorological forcing

Precipitation is the dominant atmospheric driver of most flood events, yet rainfall alone does not determine flood magnitude. Catchment response is strongly conditioned by antecedent wetness, infiltration capacity, evapotranspiration, storage deficits, terrain characteristics, and drainage-network organization. Consequently, accurate representation of rainfall magnitude, duration, frequency and spatial distribution is fundamental to hydrological forecasting.

A broad body of hydrological literature has demonstrated that the statistical and temporal structure of precipitation exerts a decisive influence on runoff generation and flood occurrence. Studies addressing precipitation variability, rainfall frequency, extreme rainfall and spatio-temporal hydroclimatic behaviour provide an important methodological basis for the interpretation of flood-producing precipitation (Lazri et al., 2007; Houichi, 2017; Benkaci et al., 2020; Zeggane et al., 2021; Bong et al., 2023).

Rainfall-runoff transformation

The next stage consists of transforming atmospheric forcing into hydrological response. This process requires an adequate representation of interception, infiltration, soil-water storage, evapotranspiration, surface runoff, subsurface flow, groundwater contribution, flow concentration and channel routing.

At catchment scale, numerous modelling strategies have been developed, ranging from conceptual rainfall–runoff models to semi-distributed and fully distributed approaches. Applications reported by Abdi and Meddi (2015), Djellouli et al. (2015), Faregh and Benkhalel (2016), Fernando et al. (2021), Atallah et al. (2024), and Mehta and Yadav (2024) demonstrate both the value and the sensitivity of rainfall–runoff modelling to input-data quality, parameter estimation, model structure and basin characteristics.

For a global forecasting system, this challenge becomes considerably more demanding because one modelling framework must operate across hydroclimatic environments ranging from humid tropical basins to arid and semi-arid catchments, snow-dominated systems, heavily regulated rivers and highly modified landscapes.

Probabilistic forecasting and uncertainty

A major strength of modern large-scale forecasting systems lies in their explicit treatment of uncertainty. A flood forecast should not be interpreted merely as a single future discharge value; it represents a range of plausible hydrological trajectories arising from uncertainties in atmospheric forcing, model initial conditions, parameterization and hydrological-process representation.

The operational quantity of interest can therefore be expressed conceptually as follows:

$$P\left[Q(t) > Q^T\right] \quad (1)$$

where $Q(t)$ denotes forecast discharge at time t , while Q^T represents a discharge threshold associated with a given return period or hydrological severity class.

This probabilistic formulation is particularly relevant for risk-based decision-making because it permits authorities to evaluate not only the expected magnitude of an event but also the confidence associated with its occurrence.

Flood thresholds and hydrological rarity

A forecast discharge becomes meaningful only when interpreted against the historical or modelled hydro-climatology of the river system. Flood-frequency analysis is therefore central to the conversion of streamflow forecasts into flood-warning information.

Classical flood-frequency methods provide a statistical basis for estimating discharge thresholds associated with given recurrence intervals (Rao and Hamed, 2001). Related studies in semi-arid and Mediterranean environments further demonstrate the importance of regional hydrological variability and the difficulty of transferring frequency relationships between catchments with contrasting climatic and geomorphological characteristics (Hachemi and Benkhalel, 2016; Houichi, 2017; Hafnaoui et al., 2023).

Threshold-based warning is especially effective when the thresholds themselves are representative of local hydrological behavior. However, caution is required when model-

derived thresholds are applied to strongly regulated rivers, rapidly urbanizing basins, data-scarce catchments or systems undergoing major land-use transformation.

The critical challenge of ungauged and poorly gauged basins

One of the strongest scientific justifications for GloFAS is its relevance to basins for which hydrological observations are sparse or unavailable.

In such environments, flood forecasting increasingly relies on:

- globally available meteorological forcing;
- digital elevation models;
- remotely sensed land-surface information;
- soil and land-cover databases;
- parameter regionalization;
- satellite observations;
- hydrological similarity between gauged and ungauged basins.

This capability is of considerable importance for Africa, South Asia, parts of Latin America and numerous transboundary river basins. Nevertheless, data scarcity cannot be interpreted as uncertainty elimination. On the contrary, the lower the observational constraint on the hydrological model, the greater the need for an explicit evaluation and communication of forecasting uncertainty.

GIS, remote sensing and Earth observation

The geographic dimension is fundamental to flood forecasting. Geographic Information Systems provide the spatial framework required to integrate topographic, hydrological, climatic, soil and land-cover information, while remote sensing offers a means of observing regions where conventional field monitoring remains inadequate.

Several recent contributions illustrate the increasing role of geospatial methods in hydrological analysis. Adja et al. (2021) demonstrated the value of GIS for analyzing spatio-temporal rainfall variability, while Hamimed et al. (2017) used remote-sensing data to monitor evapotranspiration and land-surface water status. GIS-based hydro-geographical approaches have also been employed by Jaiswal et al. (2023) and Deb (2024).

The scientific value of global flood forecasting is therefore enhanced when modelled hydrological signals are combined with independent Earth-observation information, particularly satellite-based flood mapping.

From discharge forecasting to inundation forecasting

A crucial conceptual distinction must be made between four successive levels of flood information:

1. forecasting unusually high river discharge;
2. determining whether bankfull or critical hydraulic thresholds may be exceeded;
3. identifying the spatial extent, depth and velocity of inundation;
4. estimating potential human, infrastructural and economic consequences.

These stages should not be conflated.

A forecast of extreme streamflow does not automatically provide the geographic extent of inundation. Converting discharge into flood depth and floodplain extent generally requires detailed hydraulic modelling combined with sufficiently accurate topographic information.

Studies conducted by Ayari et al. (2016), Benslimane et al. (2020), Athmani et al. (2025) and Ezz (2025) demonstrate the importance of hydraulic and spatial modelling for representing flood propagation and identifying exposed zones.

The most scientifically defensible operational framework is therefore a multi-scale forecasting architecture:

Global forecast → basin-scale warning → regional/local hydrological modelling → hydraulic inundation modelling → exposure analysis → impact-informed decision.

Urban flooding as a structural limitation of global models

Urban flooding represents a particularly demanding forecasting problem. Flood generation within cities may depend on processes occurring at spatial scales of only a few meters or tens of meters, including road microtopography, sewer-network capacity, blocked drains, impervious surfaces, culverts, storage facilities and interactions between river systems and drainage networks.

Such processes cannot be fully reproduced by a global hydrological model, irrespective of major improvements in grid resolution.

Applications of SWMM and related urban hydrological models reported by Baudhanwala et al. (2023) and Bentalha (2023), together with numerical urban flood studies such as Benslimane et al. (2020), demonstrate why high-resolution local modelling remains indispensable. Comparable flood-management studies in Béchar, Cotonou and other rapidly urbanising environments further highlight the importance of local infrastructure and land-use conditions (Bekhira et al., 2019; Hountondji et al., 2019).

Accordingly, GloFAS should primarily be regarded as a large-scale riverine flood-awareness and forecasting system rather than as a direct substitute for detailed urban drainage models.

Artificial intelligence and hybrid flood forecasting

Artificial intelligence provides an increasingly important complement to physically based hydrological modelling.

Cherki (2019) demonstrated the applicability of artificial neural networks to both daily and instantaneous flood forecasting. Chaplot et al. (2021) applied gene-expression programming to the estimation of Manning's roughness coefficient, illustrating the potential of data-driven techniques for hydraulic parameter estimation. Machine-learning and neuro-fuzzy approaches have also been successfully employed in related hydraulic and hydrological applications (Bouriche et al., 2023; Ansari et al., 2024; Belouz et al., 2025).

Nevertheless, the most promising direction for operational flood forecasting is unlikely to involve the wholesale replacement of physical models by artificial intelligence. A more robust paradigm consists of developing **hybrid physics–data-driven systems** integrating:

hydrological observations + physically based modelling + remote sensing + data assimilation + machine learning + uncertainty quantification.

Machine-learning techniques may contribute to precipitation-bias correction, model post-processing, parameter regionalization, anomaly detection, flood classification, streamflow correction and multisource data fusion.

Climate change and hydrological non-stationarity

A further challenge concerns the assumption of stationarity underlying many flood-frequency analyses and operational thresholds. Historically derived return periods implicitly assume that the statistical distribution of hydrological extremes remains stable through time.

Such an assumption is increasingly difficult to defend under climate change, rapid urbanization, deforestation, land-cover conversion and river regulation.

Studies addressing hydroclimatic variability and future climate conditions highlight the need to consider non-stationary processes in contemporary water-resources and flood-risk assessment (Assemian et al., 2021; Chadee et al., 2023; Pang and Tan, 2023; Mah et al., 2024; Lalwani et al., 2026; Patil et al., 2026).

Future global flood-warning systems may therefore need to move progressively from static climatological thresholds toward adaptive or non-stationary warning criteria that account for evolving hydroclimatic conditions.

Toward a global-to-local flood-warning architecture

A major conceptual improvement proposed here is to treat GloFAS not as an isolated forecasting platform, but as the first layer of an integrated global-to-local flood-risk information chain.

Level 1 - Global monitoring:

GloFAS identifies emerging large-scale hydrological anomalies and potential flood conditions.

Level 2 - Regional downscaling:

Regional meteorological, hydrological and remote-sensing observations refine the global signal.

Level 3 - Local modelling:

Catchment and urban models such as HEC-HMS, HEC-RAS, SWMM or equivalent tools reproduce hydrological and hydraulic processes at higher spatial resolution.

Level 4 - Dynamic observation:

Stream gauges, weather radar, satellite SAR, IoT sensors and crowdsourced observations update the evolving hydrological situation.

Level 5 - Impact analysis:

Hazard information is intersected with exposure and vulnerability datasets.

Level 6 – Decision support:

Probabilistic hydrological information is converted into anticipatory actions, emergency mobilization and risk communication.

This approach represents a shift from the conventional question:

“What will the river discharge be?”

toward a decision-oriented framework asking:

“Where will flooding occur, when is it likely to occur, with what probability and severity, who or what may be affected, and what action should be taken?”

CONCLUSION

The increasing frequency, complexity, and societal consequences of flood disasters have reinforced the need to move beyond conventional event-response approaches toward integrated systems capable of anticipating hazardous hydrological conditions before their most damaging consequences occur. Within this evolving paradigm, the Global Flood Awareness System (GloFAS) represents an important development in operational hydrology because it provides a spatially coherent framework for monitoring and forecasting river-flow anomalies across national boundaries and over regions characterized by highly heterogeneous levels of hydrometeorological observation.

The analysis developed in this study shows that the principal strength of GloFAS lies in its global coverage, probabilistic forecasting capability, transboundary perspective, and capacity to provide hydrological information in poorly gauged or data-scarce regions. These characteristics are particularly important in developing countries and large

international river basins, where conventional forecasting systems may be constrained by insufficient streamflow observations, fragmented monitoring networks, limited data exchange, or institutional and technical limitations. In such contexts, global forecasting can provide an essential first indication of potentially hazardous hydrological conditions and thereby extend the lead time available for preparedness and anticipatory action.

However, global coverage inevitably involves a compromise between spatial consistency and local hydrological detail. The reliability of a flood forecast remains dependent on the quality of meteorological forcing, representation of antecedent catchment conditions, hydrological model structure and parameterization, accuracy of flood thresholds, and availability of observations for model evaluation. These limitations become particularly significant in small, rapidly responding, highly regulated, mountainous, arid, semi-arid, and strongly urbanized catchments. Consequently, the presence of a significant modelled discharge anomaly should not automatically be interpreted as an accurate representation of the magnitude and spatial consequences of local flooding.

A fundamental distinction must therefore be maintained between streamflow forecasting, flood-threshold exceedance, inundation forecasting, and flood-impact assessment. These represent successive but scientifically distinct levels of information. Although global hydrological modelling can identify the probability of unusually high river discharge, detailed prediction of flood extent, water depth, flow velocity, and infrastructure exposure generally requires higher-resolution topographic information and local hydraulic modelling. This distinction is particularly critical in urban environments, where flood dynamics are influenced by drainage-network capacity, impervious surfaces, culverts, retention structures, road geometry, and microtopography. The successful application of models such as SWMM, HEC-HMS, and HEC-RAS reported in the literature therefore supports a complementary rather than competitive relationship between global and local modelling approaches. The relevance of such local modelling approaches is well represented in the literature, including applications of SWMM to urban flood forecasting and HEC-HMS to rainfall-runoff modelling.

Accordingly, this study advocates a global-to-local forecasting architecture in which GloFAS constitutes the first level of a progressively refined flood-information chain. Global forecasts may first identify basins where anomalous hydrological conditions are developing. Regional meteorological and hydrological observations can subsequently refine this information, while catchment-scale rainfall-runoff models can reproduce local hydrological responses. Hydraulic models can then translate forecast discharge into spatially distributed inundation characteristics, and GIS and Earth-observation data can support the identification and monitoring of affected areas. Finally, the integration of hazard, exposure, and vulnerability information can transform hydrological forecasts into impact-oriented warnings suitable for emergency management and anticipatory action.

Remote sensing and GIS are particularly important within this framework because they provide the spatial continuity required to bridge the gap between global forecasts and local observations. Satellite precipitation, land-cover information, digital elevation models, soil-moisture observations, and remotely sensed surface-water products can supplement conventional monitoring, especially in inaccessible and poorly instrumented

regions. The literature considered in this study confirms the increasing contribution of GIS and remote sensing to hydrological characterization and water-resources assessment.

Artificial intelligence provides an additional opportunity to strengthen this modelling chain. Neural networks, machine-learning algorithms, neuro-fuzzy systems, and related data-driven techniques should not necessarily be viewed as alternatives to process-based hydrological modelling, but rather as complementary instruments within hybrid physics–data-driven forecasting systems. Potential applications include correction of meteorological biases, streamflow post-processing, parameter regionalization in ungauged basins, anomaly detection, multisource data assimilation, and estimation of forecast uncertainty. The application of artificial neural networks to daily and instantaneous flood forecasting already reported in the literature illustrates the potential of this direction.

Climate change introduces a further challenge by questioning the stationarity assumptions underlying conventional flood-frequency analysis and warning thresholds. Changes in extreme precipitation, land-cover conditions, runoff generation, and catchment response may progressively reduce the representativeness of thresholds derived exclusively from historical hydro-climatology. The growing body of work addressing climate variability and climate-change impacts on hydrological systems indicates that future flood-warning frameworks should increasingly consider adaptive and non-stationary approaches. The literature assembled for this study includes applications based on IPCC climate scenarios as well as broader assessments of climate-change impacts on river hydrology.

The future development of flood early-warning systems should therefore be directed not merely toward producing more forecasts, but toward producing more interpretable, locally relevant, uncertainty-aware, and impact-oriented information. Forecast quality must ultimately be assessed in relation to its capacity to support decisions. A technically accurate hydrological prediction has limited societal value if it cannot be translated into a clear understanding of where flooding may occur, how severe it may become, which populations and infrastructures may be affected, and what preventive action should be undertaken.

From this perspective, the most appropriate role of GloFAS is not to replace national hydrological services, local observation networks, or detailed hydraulic models. Rather, its strategic value lies in providing a global hydrological intelligence layer capable of complementing these systems, extending flood awareness beyond administrative boundaries, and providing early indications of potentially severe events. This complementary function is particularly valuable for countries with limited monitoring capacity and for transboundary basins where coordinated forecasting remains difficult.

Ultimately, an effective flood early-warning system should evolve from a predominantly hazard-centered approach toward an integrated chain linking observation, prediction, uncertainty, inundation, exposure, vulnerability, communication, and anticipatory action. The transition from “How high will the river flow?” to “Where and when will flooding occur, how likely and severe will it be, who or what will be affected, and what action should be taken?” represents the central scientific and operational challenge for the next

generation of flood-warning systems. Within such a framework, GloFAS can play a pivotal role, provided that global forecasts are systematically connected to local knowledge, high-resolution modelling, Earth observation, emerging artificial-intelligence techniques, and decision-making mechanisms. This integration offers a promising pathway toward more robust, equitable, and climate-resilient flood-risk management, particularly in data-scarce regions where the benefits of improved anticipatory information may be greatest.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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