# *Continental and global scale flood forecasting systems*

Overview

# Continental and global scale flood forecasting systems

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Floods are the most frequent of natural disasters, affecting millions of people across the globe every year. The anticipation and forecasting of floods at the global scale is crucial to preparing for severe events and providing early awareness where local flood models and warning services may not exist. As numerical weather prediction models continue to improve, operational centers are increasingly using their meteorological output to drive hydrological models, creating hydrometeorological systems capable of forecasting river flow and flood events at much longer lead times than has previously been possible. Furthermore, developments in, for example, modelling capabilities, data, and resources in recent years have made it possible to produce global scale flood forecasting systems. In this paper, the current state of operational large-scale flood forecasting is discussed, including probabilistic forecasting of floods using ensemble prediction systems. Six state-of-the-art operational large-scale flood forecasting systems are reviewed, describing similarities and differences in their approaches to forecasting floods at the global and continental scale. Operational systems currently have the capability to produce coarse-scale discharge forecasts in the medium-range and disseminate forecasts and, in some cases, early warning products in real time across the globe, in support of national forecasting capabilities. With improvements in seasonal weather forecasting, future advances may include more seamless hydrological forecasting at the global scale alongside a move towards multi-model forecasts and grand ensemble techniques, responding to the requirement of developing multi-hazard early warning systems for disaster risk reduction. © 2016 The Authors. *WIREs Water* published by Wiley Periodicals, Inc.

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## INTRODUCTION

Flooding has the highest frequency of occurrence of all types of natural disasters across the globe, accounting for 39% of all natural disasters since 2000, with >94 million people affected by floods each year worldwide[1] through displacement from homes, unsafe drinking water, destruction of infrastructure, injury, and loss of life. With an increasing population living in flood-prone areas, the forecasting of floods is key to managing and preparing for imminent disaster.

Investment in building resilience is prioritized in the Sendai Framework for Disaster Risk Reduction (DRR) 2015–2030,[2] with one component of this being the development and use of multi-hazard warning systems.[3] The World Meteorological Organization (WMO) states that economic losses due to severe hydrometeorological events have increased by nearly 50 times over the past 50 years. However, the global loss of life has decreased by a factor of 10[3]. This significant decrease in loss of life is attributed to improved monitoring and forecasting of hydrometeorological events alongside more effective preparation and planning. Four components are suggested by the WMO[3] for effective early warning systems: detection, monitoring, and forecasting hazards; analyses of risks involved; dissemination of timely warnings; and activation of emergency plans to prepare and respond.

The development of forecasting systems producing forecasts and warnings of severe hazards such as floods, droughts, storms, fires, and tropical cyclones on a global scale are critical for disaster risk reduction and further decreases in loss of life. The Sendai Framework for DRR 2015–2030[2] states that at global and regional levels, it is important to 'promote co-operation between academic, scientific and research entities and networks and the private sector to develop new products and services to help reduce disaster risk, in particular those that would assist developing countries and their specific challenges',[2] and forecasting systems such as those discussed here are essential in achieving this, particularly in providing forecasts for countries and regions where no other forecasts and early warnings are available.

The need for large-scale flood forecasting systems can be broken down into three key factors:

(i) to provide information on floodiness[4] across areas larger than a catchment, for example, to indicate where flooding during the rainy season will be worse than normal; information that is of high importance to humanitarian organizations[5];

(ii) to provide forecasts in basins across the globe where there are currently no forecasts available, which is not a massive scale-up of resources; large-scale forecasting is therefore cost-effective compared to focusing on developing and providing hydrometeorological forecasts for single catchments and greatly aids disaster risk reduction and flood early warning efforts globally;

(iii) to support existing capabilities, for example, by using ensemble forecasting techniques to enable probabilistic flood forecasts, or at longer lead times for earlier warnings; probabilistic and extended-range forecasting is computationally expensive, and in addition, many countries do not currently pay for access to these distributed meteorological forecast products and therefore are unable to produce any form of hydrometeorological forecast.

This review outlines the developments that have led to forecasting floods on the global scale, the current state-of-the-art technology in operational large-scale (continental and global) flood forecasting, and future developments in global-scale flood forecasting and early warning.

## ADVANCES IN THE SCIENCE AND TECHNIQUES OF GLOBAL FORECASTING

Producing forecasts at the global scale has only become possible in recent years due to the integration of meteorological and hydrological modeling capabilities, improvements in data, satellite observations and land-surface hydrology modeling, and increased resources and computer power.[6–10] While several meteorological and hydrological forecasting centers now run operational flood forecasting models, many of these are for specific locations, river basins, or countries.[8]

Global hydrological modeling is complex due to the geographical variation of rainfall-runoff processes and river regimes,[11] but large-scale flood forecasting systems are now emerging with recent scientific and technological advances and increasing integration of hydrological and meteorological communities, allowing for uncertainty to be cascaded from the meteorological input to the river flow forecasts.[12]

In this section, we analyze the key advances that have enabled the forecasting of floods at the global scale.

## The Increasing Skill of Precipitation Forecasts

The skill of precipitation forecasts in global numerical weather prediction (NWP) models has increased significantly in recent years[13–15] (e.g., gaining ~2 days precipitation skill since 2000[16]). With skilful medium-range quantitative precipitation forecasts (QPFs) being produced by NWP models across the globe, it has become possible to produce skilful forecasts of river flow and flooding at large scales for the purpose of early warning.[17] Table 1 outlines the resolutions and forecast ranges of some of the main QPF products used in operational large-scale flood forecasting systems.[8]

Precipitation is challenging to forecast due to the chaotic nature of the atmosphere,[18] where a small change in the initial conditions of the system can result in an unpredictable outcome. The underlying physical processes of precipitation generation are complex to model, and modeling deficiencies can lead to forecast inaccuracies, particularly at longer lead times.[19] In general, due to the lack of observations, precipitation predictions are less skilful in the southern hemisphere, although the difference in the skill of forecasts between the hemispheres has reduced significantly since the introduction of satellite observations and data assimilation.[19,20] Limited data are also an issue in much of the tropics alongside difficulties associated with the simulation of convective precipitation.[21] While QPF skill depends heavily on the region, season, intensity, and storm type,[19] precipitation skill is generally good for rainfall generated by synoptic-scale frontal weather systems.[22] The intensity of precipitation tends to be one of the major problems in QPFs, with convective[21] and orographic enhancement[23] processes tending to result in an under-prediction of intensity alongside the tendency of most global models to over-predict the intensity of light precipitation.[24] Many NWP models struggle with displacement;[19,25] while the areal extent, timing, and intensity of precipitation may be correct, precipitation displacement can be extremely detrimental to forecasts of river flow and flooding.

With ongoing improvements to NWP models[13,14,16,26] (resolution increases, new methods of simulating the physical processes, and increasing computer power), precipitation forecasts have become more useful to hydrological applications.

## Ensemble Flood Forecasting—Representing Uncertainty

Over the past 2 decades, NWP has moved from single-solution forecasts of the future state of the atmosphere to probabilistic forecasts using ensemble prediction systems (EPS).[27] Probabilistic forecasts allow the inherent uncertainties in NWP to be represented.[15,28] In hydrological modeling, the four main sources of uncertainty are input data, evaluation data, model structure, and model parameters.[29–32] The relative importance of these uncertainties tends to vary according to catchment characteristics, event magnitude, and lead time of the forecast,[12,27] but it is generally accepted that the greatest uncertainty in flood forecasting beyond 2–3 days lead time stems from the meteorological input.[27,29]

The standard approach in NWP is to produce a single (deterministic) forecast from the initial state, whereas EPS recognise and represent the uncertainty in the initial conditions by perturbing them to produce several initial states.[33,34] The forecast model is run from each of the perturbed initial states, producing many varying, but valid and equally probable, forecast scenarios. In addition to sampling the error in the initial state, many centers also incorporate stochastic physics, which involves applying random perturbations of the parameterized physical processes.[35]

**TABLE 1** | Technical details of quantitative precipitation forecasts used in large-scale flood forecasting[8]

| Product Type | Spatial Extent | Spatial Resolution | Temporal Resolution | Forecast Range | Uncertainty |
|---|---|---|---|---|---|
| Radar nowcasting | ~10,000–50,000km$^2$ | 1–4 km | 5–60 min | 1–6 h | Low |
| Ensemble radar nowcasting | ~10,000–50,000 km$^2$ | 1–4 km | 5–60 min | 1–6 h | ↓ |
| Radar-NWP blending | Regional | ~2 km | 15–60 min | ~6 h | |
| Limited-area NWP | Regional–Continental | 2–25 km | 1–6 h | 1–3 days | |
| Ensemble limited-area NWP | Regional–Continental | 2–25 km | 3–6 h | ~5–30 days | |
| Global NWP | Global | ~15–100 km | ~3–6 h | ~5–30 days | |
| Seasonal forecasts | Global | ~15–100 km | ~6–24 h | Months | High |

Predictions of river discharge are usually produced by providing the EPS as input to a hydrological model.[27,32,36,37] Prior to this, some pre-processing may be required[32,37]; scale corrections (downscaling or disaggregating) are made as the scale (temporal and spatial) does not usually correspond between the EPS and the hydrological model due to the irregular shape of catchments.[15] Bias or spread corrections may also need to be made.[27]

The use of EPS in flood forecasting allows probabilistic forecasts of flood events at much longer lead times than has previously been possible and is useful in producing forecasts in catchments where no other input data is available.[27] Cloke and Pappenberger[27] give a detailed review of the benefits of ensemble over deterministic flood forecasts, particularly looking at advantages for issuing flood alerts and warnings. Probabilistic forecasts of upcoming events have been shown to provide greater skill than deterministic forecasts[38] and provide key information about the possibility of occurrence of an extreme event.

## Operational Large-Scale Flood Forecasting

There exist various large-scale hydrological models run by communities around the globe; Bierkens et al.[39] give a detailed overview of the properties of 14 global scale and 4 continental scale models. Not all of these models are used operationally for the purpose of flood forecasting, and as such, a list of operational continental and global scale flood forecasting models, alongside key system information, is provided in Table 2.

Figure 1 shows a simplified conceptual model for a large-scale flood forecasting system, the components required and the output generated within each component. The operational systems outlined in Table 2 are the focus of this review, and each takes a different approach to the components of the conceptual model. In the following sections, we benchmark the state of current science and technology in undertaking operational continental- and global-scale flood forecasting and early warning.

# CONTINENTAL-SCALE FLOOD FORECASTING SYSTEMS

There are currently four operational continental-scale flood forecasting systems, two for Europe: the European Flood Awareness System (EFAS) of the European Commission (EC) and the European HYdrological Predictions for the Environment (E-HYPE) model of the Swedish Meteorological and Hydrological Institute (SMHI). The Bureau of Meteorology (BoM) runs the Flood Forecasting and Warning Service (FFWS) for Australia, and the U.S. National Weather Service (NWS) run a model covering the continental USA, the Hydrologic Ensemble Forecasting Service (HEFS). This section outlines the components of, and the forecast products produced by, each system.

## The European Flood Awareness System

EFAS is an EC initiative developed by the Joint Research Centre (JRC) to increase preparedness for riverine floods across Europe. It was in development from 2002, tested from 2005 to 2010, and has been operational since 2012. After devastating, widespread flooding on the Elbe and Danube rivers in 2002, the EC began development of EFAS, with the aim of providing transnational, harmonized early warnings of flood events and hydrological information to national agencies, complementing local services.[42] Various consortia execute different aspects (e.g., computation and dissemination) of the EFAS operational suite.[43]

### *Model Components*

Rather than using just one meteorological NWP forecast as input, EFAS uses four different forecasts, two ensemble forecasts and two deterministic. Figure 2 details the various components of the EFAS suite, including key information regarding the NWP models. The precipitation, temperature, and evaporation from each of the four forecasts are used as input to the Lisflood hydrological model, which is used as both the rainfall-runoff and the routing components shown in Figure 1 and simulates canopy, surface, and sub-surface processes such as snowmelt (including accounting for accelerated snowmelt during rainfall) and preferential (macropore) flow, soil, and groundwater processes.[42]

Simulated ensemble hydrographs are produced by Lisflood; however, these alone do not constitute a flood forecast. A decision-making element needs to be incorporated.[42] Due to the often limited number of discharge observations in many areas of the globe, these critical thresholds cannot be derived directly from observations. Meteorological data are run through Lisflood to calculate 22-year time series of discharge, to provide a reference threshold for minor or major flooding at each grid cell.

**TABLE 2** | Operational large-scale flood forecasting systems

| Forecasting System | EFAS (European Flood Awareness System) | E-HYPE (European Hydrological Predictions for the Environment) | FFWS (Flood Forecasting & Warning Service) | HEFS (Hydrologic Ensemble Forecast Service) | GloFAS (Global Flood Awareness System) | GLOFFIS (Global Flood Forecasting Information System) |
|---|---|---|---|---|---|---|
| Domain | Continental (Europe) | Continental (Europe) | Continental (Australia) | Continental (USA) | Global | Global |
| No. of ensemble members | 65 | 1 | ≤4 | 23 Short to medium range, 1 long range | 51 | 73 |
| Forecast range (days) | 15 | 10 | 10 | Sub-hourly to several years | 45 | 15 |
| Spatial resolution | 5 km, Regular grid | ~15 km, Irregular grid, varies by Basin | ~10 km | Varies by Basin | 10 km, Regular grid | 10 km, 50 km, Regular grid |
| Forecast frequency | 12-h | Daily | 6–12-h | Sub-daily to daily | Daily | 6-h |
| NWP input | ECMWF ENS, ECMWF deterministic, DWD Deterministic, COSMO-LEPS | ECMWF deterministic | BoM ACCESS global, regional, city-scale and relocatable deterministic forecasts | RFC deterministic, WPC deterministic, GEFS, CFS, historical observations | ECMWF ENS | ECMWF ENS, GEFS, GFS, historical forcing |
| Rainfall-runoff model | Lisflood Europe | HYPE | GR4J (daily), GR4H (hourly), URBS | Suite of models (see Figure 8) | HTESSEL (within ECMWF IFS) | PCR-GLOBWB, W3RA |
| Routing model | Lisflood Europe | HYPE | Muskingum channel routing | Suite of Models (see Figure 8) | Lisflood global | Deltares wflow |
| River Network | JRC Dataset | HydroSHEDS, HYDRO1K | CatchmentSIM | Suite of Models (see Figure 8) | HydroSHEDS, HYDRO1K | PCR-GLOBWB, SRTM90m, HydroSHEDS |
| Organization | JRC, ECMWF | SMHI | BoM | National Weather Service | JRC, ECMWF | Deltares |
| Website | www.efas.eu | e-hypeweb. smhi.se | www.bom.gov.au/ water/ floods | water.weather.gov/ ahps/ forecasts.php | www. globalfloods.eu | |
| Corresponding figure number | Figure 2 | Figure 5 | Figure 6 | Figure 8 | Figure 10 | Figure 12 |

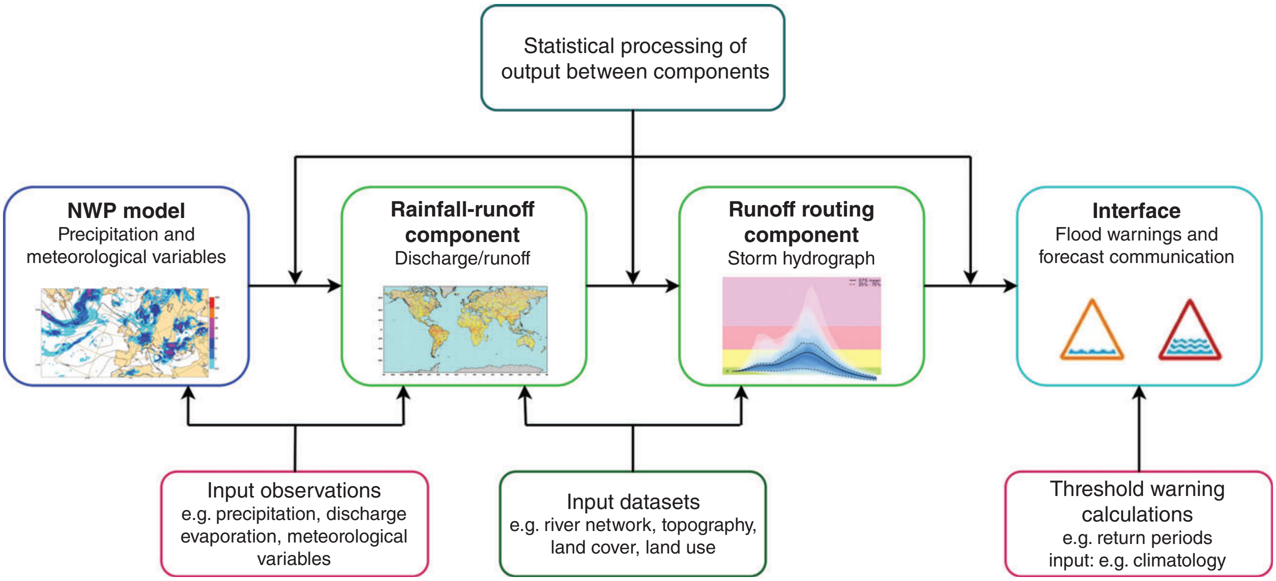


**FIGURE 1** | A conceptual large-scale hydrometeorological flood forecasting system.

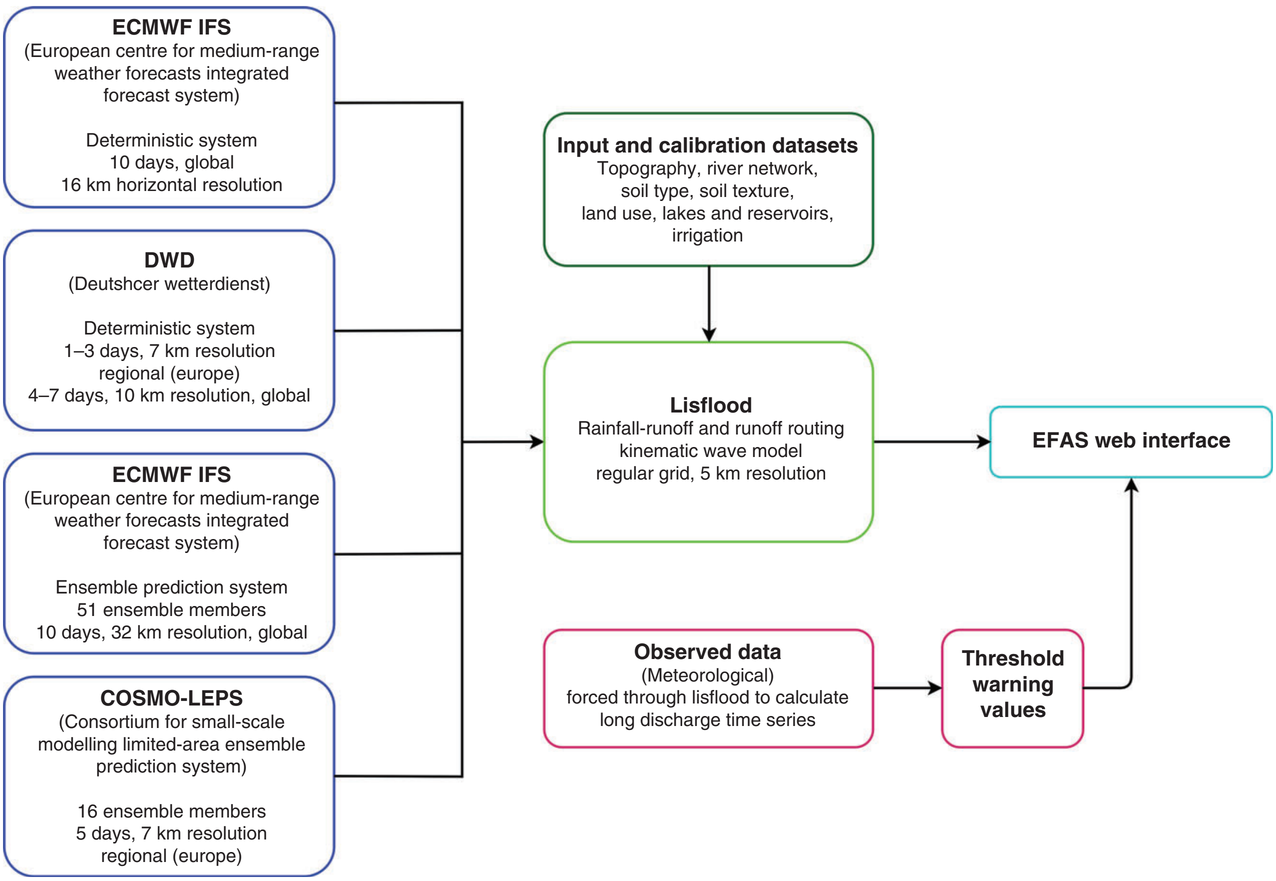


**FIGURE 2** | Components of the European Flood Awareness System (EFAS).

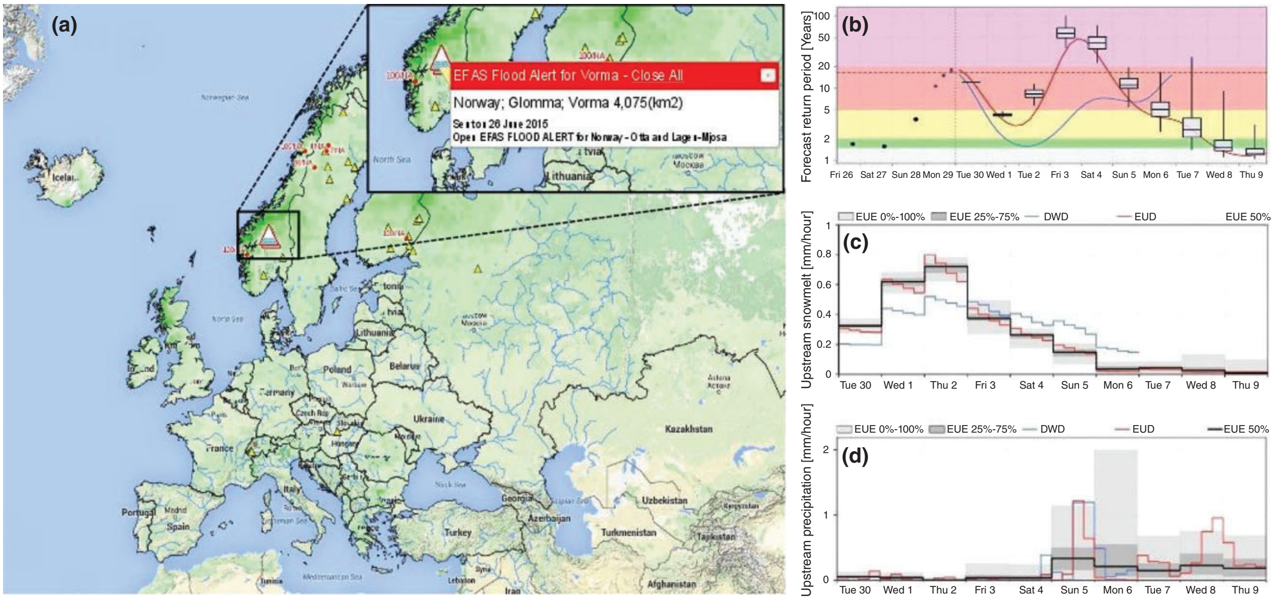


**FIGURE 3** | The European Flood Awareness System (EFAS) showing (a) the main interface with high (red) and medium (yellow) reporting points, flood alerts (warning triangles), and probability (% likelihood) of exceeding 50mm of precipitation (green shading) during the forecast period (10 days); (inset a) the flood alert displayed when the alert point is clicked on; (b) the return period hydrograph with return period thresholds (1.5 years green, 2 years yellow, 5 years red, 20 years purple); (c) upstream snow melt forecast; (d) upstream precipitation forecast.

### *Forecast Visualisation*

Alongside warnings for each forecast point, the EFAS interface (e.g. Figure 3) provides ensemble hydrographs, which allow the interpretation of the spread of the ensemble and the uncertainty in the forecast. Persistence diagrams showing information about the previous four forecasts also give the user additional information on the forecast uncertainty as NWP models should be able to pick up large-scale synoptic weather systems that typically produce severe events in advance, therefore showing a flood risk consistently in each forecast run.[42] The EFAS interface provides a map of Europe, with all points forecasting a flood event designated by a color responding to the warning threshold; this allows an overview of forecast flood events across the continent. The information and visualization within EFAS are designed to give clear, concise, and unambiguous early warning results.[42]

### *Warning Dissemination*

Copernicus is the European Emergency Management Service, and EFAS is the operational flood early warning system designed to disseminate warnings for Europe under the Copernicus initiative. According to the WMO Executive Council (EC-LVII-Annex VII),[43] National Meteorological and Hydrological Services (NMHS) constitute the single authoritative voice on weather warnings in their respective countries. Therefore, in order to respect the single voice principle with regard to floods, EFAS real-time information is provided only to hydro-meteorological authorities signing a 'Condition of Access' document. EFAS sends warning emails to these national authorities responsible for flood forecasting, designed to bring awareness of an upcoming flood event, with further details accessed through the interface. There are four types of warning emails provided. *Flood Alerts* are issued when a river basin has a probability of exceeding critical flood thresholds more than 2 days ahead; *Flood Watches* are issued when there is a probability of a river basin exceeding critical thresholds, but the event does not satisfy the conditions for a *Flood Alert* (such as river basin size or warning lead time); and *Flash Flood Watches* are issued when there is a >60% probability of exceeding the flash flood high alert threshold. An example of an EFAS *Flood Alert* is given in Box 1. The 2-day lead time criteria is specified as the forecasting systems used by the national authorities have usually issued a national warning with a lead time of up to 2 days. Additionally, daily overviews are sent to the Emergency Response Coordination Centre (ERCC) of the EC, containing information on ongoing floods in Europe, as reported by the national services and EFAS warnings.

BOX 1

EXAMPLE OF AN EFAS FLOOD ALERT, SENT TO EFAS PARTNERS AND NATIONAL AND REGIONAL SERVICES

EFAS FLOOD ALERT REPORT

Dear Partner,

EFAS predicts a high probability of flooding for Norway—Otta and Lagen-Mjosa tributaries (Glomma basin) from Monday June 29 onwards.

According to the latest forecasts (2015-06-25 12 UTC), up to 100% EPS (VAREPS) are exceeding the high threshold (>5 year simulated return period) and up to 86% EPS (VAREPS) exceeding the severe threshold (>20-year simulated return period).

Compared to the VAREPS mean, the ECMWF deterministic forecast is comparable and the DWD deterministic forecast is lower.

The earliest flood peak is expected for Saturday, July 4, 2015.

Please monitor the event on the EFAS-IS interface (http://www.efas.eu)

### *Forecast Verification*

EFAS also undergoes forecast verification, with two methods used for this system. First, the hits, false alarms, and misses are assessed for each flood event, with events evaluated through feedback reports and news media. Secondly, skill scores are calculated and reported regularly through EFAS bulletins, available via the website (see Table 2).

### *Operational Applications*

EFAS is integrated in the daily forecasting procedures of many national hydrological services across Europe, providing operational early warnings and additional information that is used for decision-making purposes at national and local scales. Additionally, EFAS is used by the ERCC to compile reports on the flood situation and outlook and for the coordination of emergency response at the continental scale.

## The European HYdrological Predictions for the Environment Model

E-HYPE is a multipurpose model based on open data (Table 3), which is used for various applications such as water management, research experiments, and flood forecasting.[45] The E-HYPE Water in Europe Today (WET) tool (Figure 4) compares the current hydrological situation with climatological data and past modeled events. The tool was originally designed to alert water managers to flow that is predicted to be outside the normal range (based on the 75th and 25th percentiles) and has evolved to provide information to many end users. Another setup of the HYPE model, EFAS-HYPE, uses further restricted datasets and is currently being tested as an additional model within EFAS. This section focuses on the river flow forecasts produced by the WET tool.

### *Model Components*

In contrast to other systems, E-HYPE currently uses only deterministic NWP input to drive the hydrological model component, although ensemble forecasting is intended for future system developments. The HYPE model[45,46] is a distributed rainfall-runoff model developed at SMHI, which divides catchments into sub-basins rather than a regular grid. Each sub-basin is further divided into classes based on land use, soil type, and elevation.[44] Alongside processes such as snow accumulation and melting, evapotranspiration, and groundwater recharge,[46] HYPE also takes into account anthropogenic influences including irrigation and hydropower.[44]

### *Forecast Visualization*

Within the WET tool, forecasts of river flow are compared to climatology based on the ECMWF ERA-Interim reanalysis and evaluation datasets (Figure 5) in order to produce an overview of river flow that is under or above the normal range. This information is displayed on a color-coded map of the sub-basins within the E-HYPE model (Figure 4).

### *Forecast Verification*

Through the E-HYPE and WET interface, various model performance statistics are available. The model is verified against observed discharge from river gauges and allows the user to quickly evaluate the performance of the model with regard to timing, variability, and volume error for the point of interest or across a larger region. The overall model performance in terms of mean annual discharge is also presented. Donnelly et al.[45] present a new method for evaluating the performance of a multi-basin model, and results from this evaluation of the historical model indicated that the model is suitable for predictions in ungauged basins as it captures the spatial variability of flow. While the model performs well in terms of long-term means and seasonality, the performance is less effective in terms of daily variability, particularly in

**TABLE 3** | Databases used within the flood forecasting systems. Due to the alternative set-up of the BoM FFWS, this information was not available

| | Data Source | | | | | |
|---|---|---|---|---|---|---|
| | | | | | GLOFFIS | |
| Data Type | EFAS | E-HYPE[44] | HEFS | GloFAS | PCRGLOB-WB | W3RA |
| Topography/ routing | SRTM/CCM2 | HydroSHEDS & HYDRO1K | NED & NHDPlus | HydroSHEDS & HYDRO1K | HydroSHEDS, HYDRO1K & NASA SRTM | HydroSHEDS, HYDRO1K & NASA SRTM |
| Land cover | CORINE | CORINE and Globcover 2000 | NLCD, MODIS, AVHRR | CORINE and Globcover 2000 | GLCC, MIRCA | MODIS |
| Urban areas | European Soil Data Centre (ESDAC) | Euroland SoilSealing 2009 | NA | Harmonized World Soil Database | GLCC | NA |
| Lake area and spatial distribution | GLWD (Global Lake and Wetland Database) | GLWD (Global Lake and Wetland Database) | NHDPlus | GLWD (Global Lake and Wetland Database) | GLWD, GRaND (Global Reservoir and Dams Database) | NA |
| Lakes and reservoirs | GLWD, GRaND (Global Reservoir and Dams Database) | GLWD, ERMOBST, FLAKE-Global, International Water Power & Dam, ILEC World Lake Database, LEGOS, SMHI | USGS & Federal state and local water management authorities (e.g. USACE, Reclamation) | GLWD, Global Reservoir and Dams Database GRAND | GLWD, FLAKE-Global, GRaND (Global Reservoir and Dams Database) | NA |
| Soil Type | European Soil Data Centre (ESDAC) | Based on Land Use and Elevation | SSURGO | Harmonized World Soil Database | FAO DSW | NA |
| Crop Types | NA | CAPRI, MIRCA-2000 | NA | NA | MIRCA | NA |
| Irrigation | EIM (European Irrigation Map), GMIA (Global Map of Irrigation Areas) | EIM (European Irrigation Map), GMIA (Global Map of Irrigation Areas) | NHDPlus, Local water authorities | GMIA (Global map of Irrigation Areas) | MIRCA | NA |

E-HYPE, European HYdrological Predictions for the Environment; GloFAS, Global Flood Awareness System; GLOFFIS, Global Flood Forecasting and Information System; HEFS, Hydrologic Ensemble Forecasting Service; NA, not applicable.

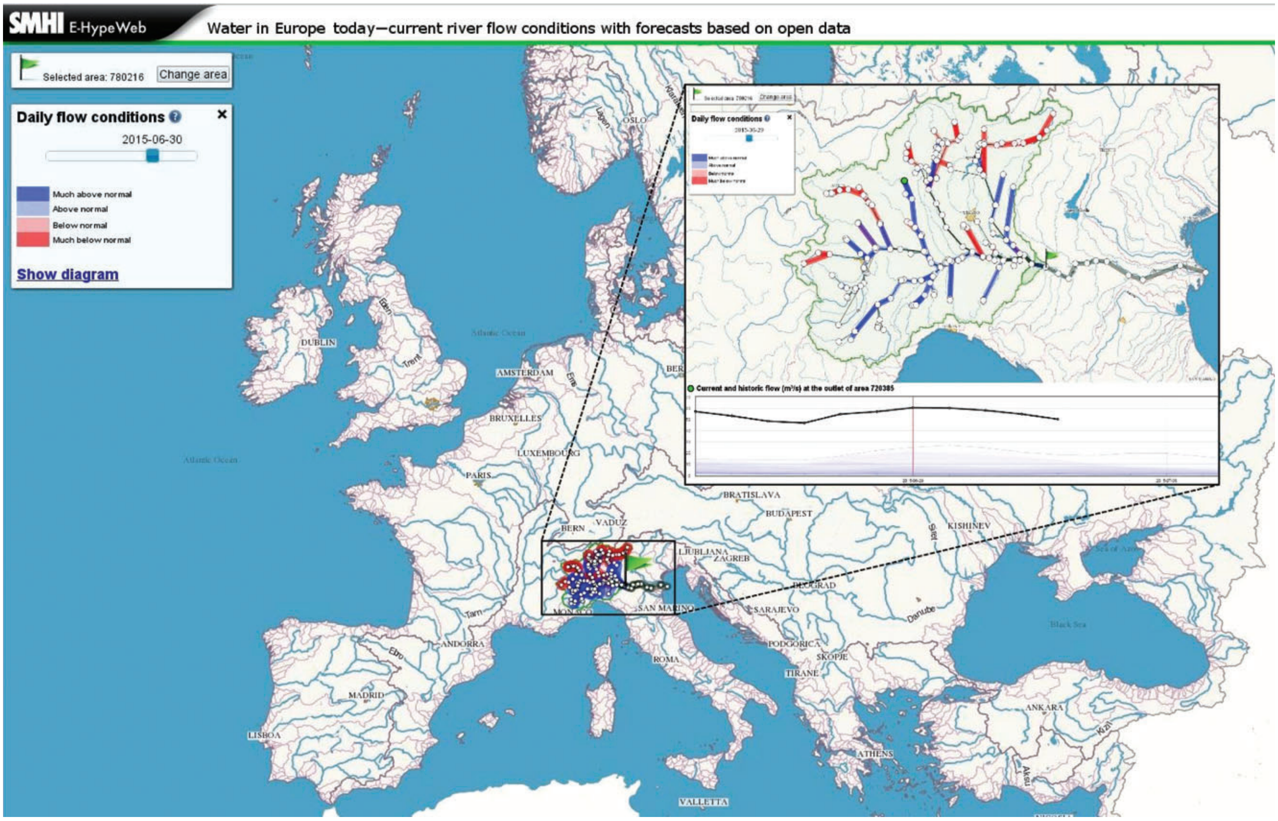


**FIGURE 4** | The Water in Europe Today (WET) tool interface with example forecast (inset) showing above-normal (blue shading) and below-normal (red shading) forecast river flow. The hydrograph shows current conditions and forecast river flow (black line) compared to climatology (blue shading). Forecasts are available at hypeweb.smhi.se/europehype/forecasts.

Mediterranean and mountainous areas, and in regions of the most anthropogenic influence.

### *Operational Applications*

E-HYPE is currently being used in several applications across Europe, such as seasonal flow forecasting for the EU European Provision Of Regional Impacts Assessments on Seasonal and Decadal Timescales (EUPORIAS) project, which aims to help societies deal with climate variability, and providing data for use in oceanography models and as part of the Sharing Water-related Information to Tackle Changes in the Hydrosphere - for Operational Needs (SWITCH-ON) EU project. The WET tool is also used by various other smaller companies around Europe to provide water forecasts, for example, soil-water forecasts for gardening companies.

## The Australian Flood Forecasting and Warning Service

The Australian BoM has been producing flood forecasts operationally for several decades, with the technology and systems used to produce these forecasts continually evolving. More recently, the BoM has introduced short-term (up to 7 days ahead) continuous streamflow forecasting using deterministic NWP models within the Hydrological Forecasting System (HyFS) production environment [based on the Deltares Flood Early Warning System (FEWS) forecasting framework] alongside event-based hydrological modeling and nowcasting using radar rainfall estimates. The BoM services also rely on forecasters for the dissemination and communication of flood warnings and local information regarding river conditions.

### *Model Components*

The NWP forecasts used to force the rainfall-runoff models are produced by the BoM's Australian Community Climate and Earth-System Simulator (ACCESS) NWP model. ACCESS has four components running at different spatial scales and resolutions (Figure 6). In addition to the NWP model output, forecasters and hydrologists at the BoM can produce 'What If' precipitation scenarios, which can force the hydrological models.

Alongside the semi-distributed GR (Ǵenie Rural á 4 Paramétres) hydrological models, event-based

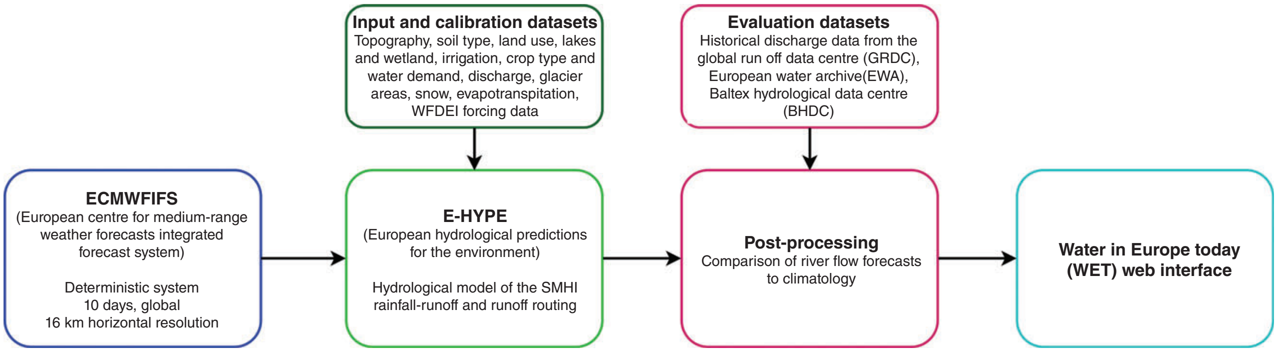


**FIGURE 5** | Components of the European Hydrological Predictions for the Environment (E-HYPE) Water in Europe Today (WET) tool.

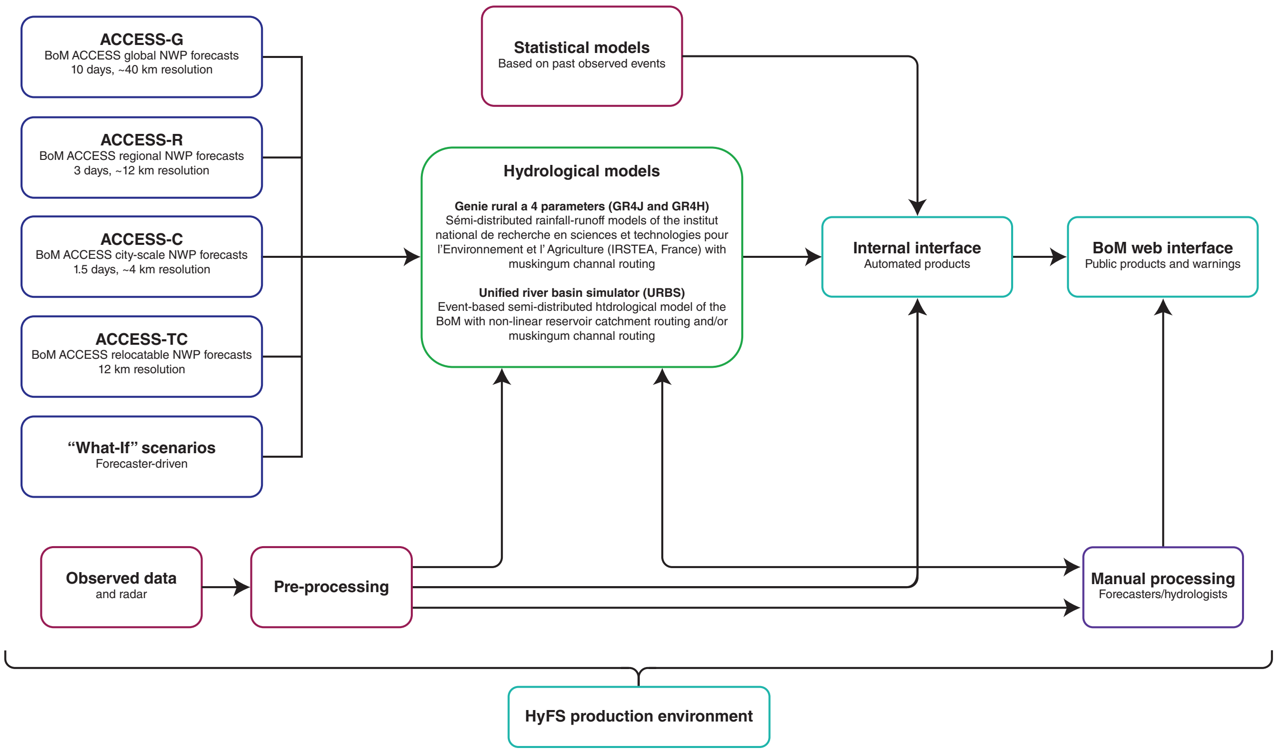


**FIGURE 6** | Components of the Australian Flood Forecasting and Warning Service (FFWS).

forecasting is used extensively; for this, local models are used in support of the continental scale system. The resulting river discharge estimations from both model versions are used, alongside observed data and statistical models, to produce automated graphical products such as maps, bulletins, warnings, and alerts.

### *Role of the Forecaster*

Whilst the other systems presented in this paper are almost entirely automated and model-based, the BoM system also relies on the input of expert meteorologists and hydrologists. In addition to producing 'What If' scenarios to feed into the hydrological models, the forecasters are able to manually post-process the forecasts and observed data to produce further products and visualizations and assess the quality of the data and forecasts in real time. The forecasters are also able to produce additional warnings on the fly, for example, if a reservoir is seen to fill or their experience alerts them to an alternative possible scenario to those produced by the hydrological models. The hydrologists at the BoM are also responsible for dissemination and communication of the forecasts and warnings.

A further reason for the input of forecasters is due to the challenges of producing operational flood forecasts for a large continent with an unevenly distributed population. Metropolitan areas have a dense observation network for both rainfall and river discharge; however, there are large areas of Australia that have no flowing rivers, such as in the Northern Territory where there is an average of one river gauge every 13,360 $km^2$.

### *Warning Dissemination*

The final products delivered to the end users include flood watches and warnings and information on current river levels and precipitation, which are disseminated to various users at specified stages in the evolution of a flood event through a dedicated web interface, email, fax, and telephone. These are usually text forecasts, an example of which is given in Box 2 for a minor flood event, written by the hydrologists based on the output of the HyFS but can also include automated alerts and bulletins for certain users. Figure 7 shows the corresponding publicly available graphics for this flood event, while the BoM hydrologists also have access to more sophisticated graphical products produced by the automated component of the HyFS, such as ensemble hydrographs.

### *Forecast Verification*

Currently, the BoM uses a manual verification approach, sampling 10% of the warnings issued, based on specifications set out for each forecast point such as a minimum lead time of 6 h or a peak forecast accuracy of $\pm 0.5$ m. With updates to the Flood Forecasting and Warning Service (FFWS), verification software will be introduced, which will automatically compute statistics analyzing the accuracy of the forecast river levels, peak, and timing based on a comparison with observed river levels. The lead time provided for warnings will also be analyzed and compared to the accuracy specifications, providing a measure of performance for a much greater sample of events, which will, in turn, drive further system improvement. Additionally, the HyFS continuous short-term forecasts are verified using a 15-day moving average climatology to calculate the mean absolute error skill score.

### *Operational Applications*

At the BoM, the continuous short-term streamflow forecasts are used across Australia to provide an early indication of an upcoming flood event in order to start making arrangements and decisions. These forecasts are then used as a 'heads-up' to start running event-based models at the local scale to provide official, public flood warnings. This is an excellent example of the use of large-scale flood forecasting systems to enhance and supplement existing, local-scale forecasting capabilities.

BOX 2

EXAMPLE OF A FLOOD WARNING WRITTEN BY HYDROLOGISTS AT THE BUREAU OF METEOROLOGY

MINOR FLOOD WARNING FOR THE SNOWY RIVER Issued at 9:58 am EST on Wednesday, July 15, 2015

River levels at Orbost are currently around the Minor Flood Level (4.2 m) and rising. A peak of around 4.3–4.4 m is expected during Wednesday afternoon [15/07/2015].

In the interests of community safety, the SES suggests the following precautions:
Don't walk, ride or drive through floodwater, Don't allow children to play in floodwater, Stay away from waterways and stormwater drains, and Keep well clear of fallen power lines

Current Emergency Information is available at http://www.ses.vic.gov.au For emergency assistance, call the SES on telephone number 132 500. For life threatening emergencies, call 000 immediately.

The SES advises that rainfall run-off into waterways in recent fire-affected areas may contain debris such as soil, ash, trees and rocks. People in fire-affected areas should be alert to the potential for landslide and debris on roads.

**Weather Forecast:**
For the latest weather forecast see www.bom.gov.au/nsw/forecasts/

**Next Issue:**
The next warning will be issued by 10:00 am Thursday [16/07/2015].

**Latest River Heights:**
Snowy R. at Basin Creek 4.33 m falling 09:16 AM WED 15/07/15 Buchan R. at Buchan 1.65m falling 08:45 AM WED 15/07/15 Snowy R. at Jarrahmond 4.35 m rising 09:00 AM WED 15/07/15 Snowy R. at Orbost 4.18 m rising 09:00 AM WED 15/07/15

For latest rainfall and river level information see www.bom/gov.au/nsw/flood/

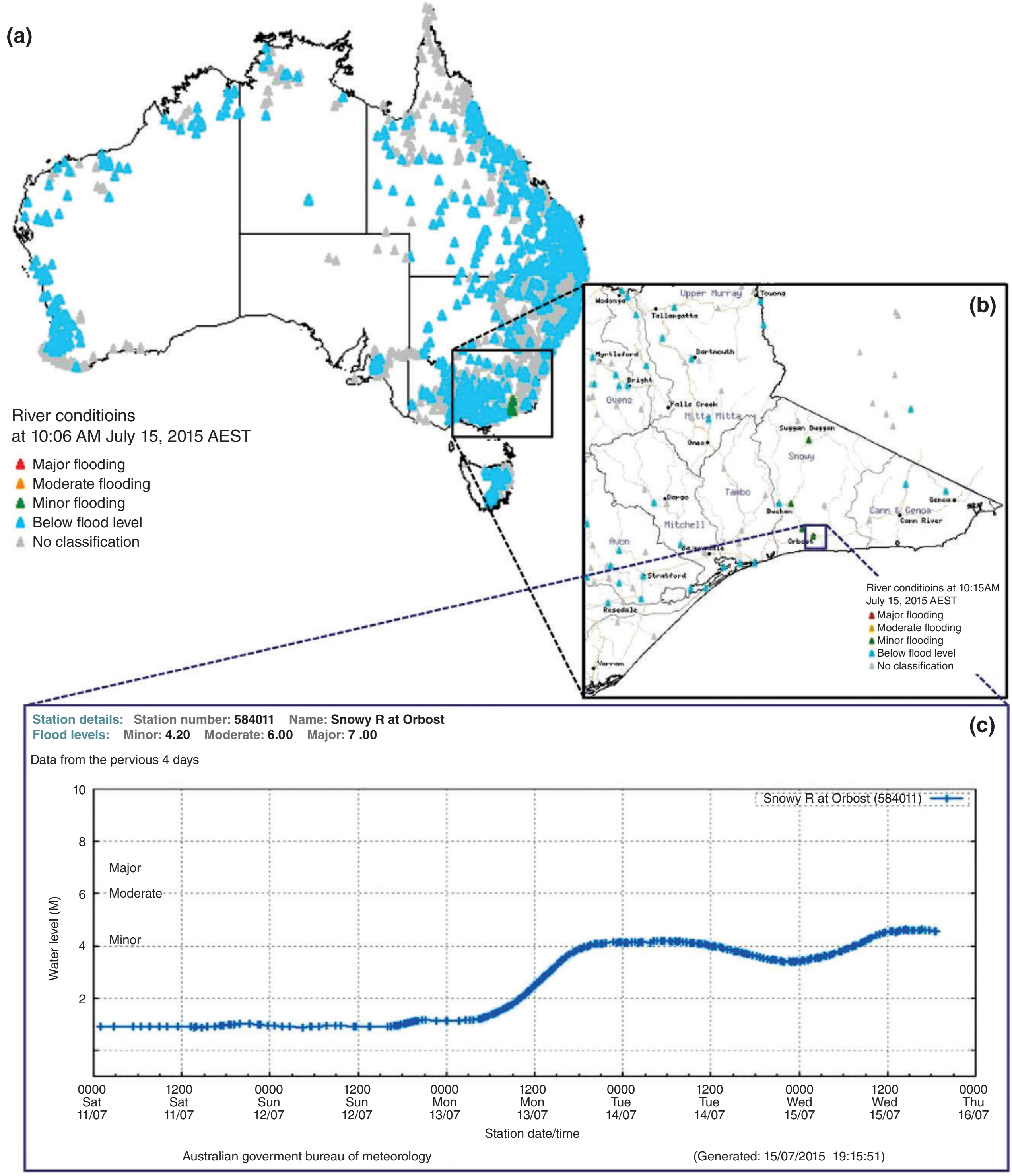


**FIGURE 7** | The BoM publicly available flood warnings showing (a) warnings and river conditions across Australia; (b) warnings and river conditions for a particular region; (c) current river levels at a specific warning point where flow is above the minor flood level.

## The U.S. Hydrologic Ensemble Forecast Service

The HEFS is run by the NWS and, for river basins across the U.S., provides 'uncertainty- quantified forecast and verification products'.[40] From the late 1990s, NWS service assessments, alongside feedback from end users and the US National Academies,[47] began to confirm the need for probabilistic river forecasts for flood forecasting and water resources. In 2012, the HEFS began to run experimentally at several regional River Forecast Centres (RFCs), each of which forecasts streamflow for hundreds of river locations, and is currently being rolled out operationally at all 13 RFCs. The HEFS aims to produce ensemble streamflow forecasts that seamlessly span lead times from less than 1 h up to several years and that are spatially and temporally consistent, calibrated (i.e., unbiased with an accurate spread), and verified.

### *Model Components*

The HEFS consists of five main components,[40] detailed in Figure 8, and has been implemented to run as part of each RFC's configuration of the Flood Early Warning System (FEWS)-based Community Hydrologic Prediction System (CHPS), which has been the software platform used to run the traditional deterministic flood forecasts and long-range ESP forecasts since 2010. The system is designed to be driven with four meteorological forecast inputs, two of which (GEFS and CFSv2) are the output of NWP models, while the RFC forecasts and climatologies are created by meteorologists for the spatial units of the RFCs' watershed models using predictions from the NCEP Weather Prediction Center (WPC), local NWS Weather Forecast Offices (WFOs), and other sources.[48]

Each RFC may use different combinations of the 19 components within the Hydrological Processor (HP) suite, but the majority of RFC operations center on a lumped implementation of the SAC-SMA[49] and SNOW-17[50] models. The pre-processing step within the HEFS (MEFP, Figure 8) creates an ensemble of seamless hours-to-seasons, calibrated weather and climate forcings, which are fed into the HP. Notably, through use of the MEFP and EnsPost pre- and post-processing components, both the uncertainties in the meteorological input and the hydrology are taken into account.

### *Forecast Visualization*

The graphics generator (Figure 8) uses the resulting ensemble hydrographs to produce visualizations of the forecasts that can be communicated to a range of end users for the purpose of decision making and warning dissemination. These final forecast products include spaghetti plots, exceedance probabilities in the form of bar graphs and probability distribution plots using comparisons with historical simulations (reanalysis datasets), and an expected value chart describing the ensemble distribution. Graphics from the HEFS are currently operational at only a handful of RFCs and are currently being rolled out at the remaining RFCs. An example of an HEFS hydrograph for one river location, alongside the public web interface, is shown in Figure 9. The forecast data associated with the graphical products are also typically available from the RFCs, and many users can access the data directly to drive local decision support models.

### *Warning Dissemination*

NWS product requirements are codified through NWS Directives,[41] and the RFCs generally issue

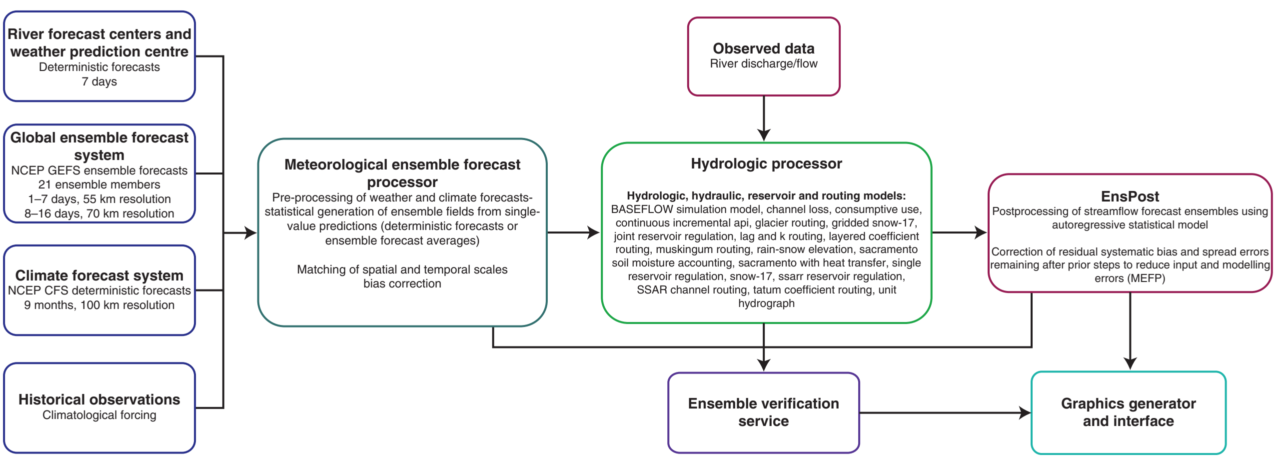


**FIGURE 8** | Components of the U.S. Hydrologic Ensemble Forecast System (HEFS).[40,41]

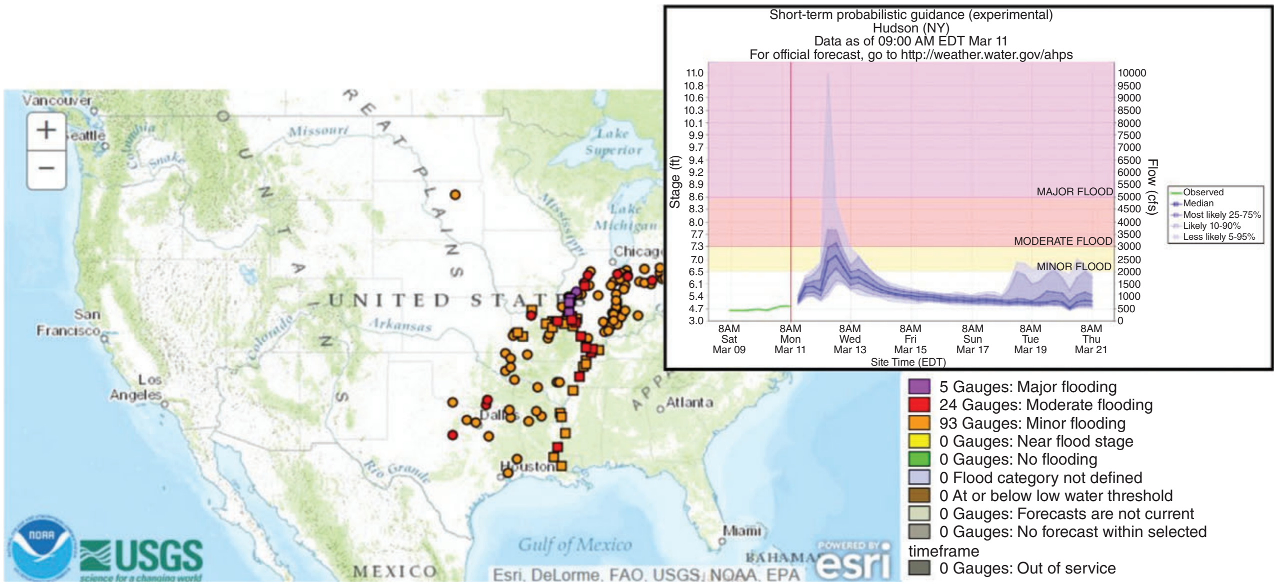


**FIGURE 9** | The U.S. Hydrologic Ensemble Forecast System (HEFS) overview map of locations forecasting floods, with color representing flood severity. An ensemble hydrograph is shown for a flood event at one river location, including observed stage and flow (green), forecast stage and flow (purple) in terms of probabilities, and colors indicating the forecast severity based on flood stage data (minor flood, yellow; moderate flood, red; major flood, pink). Forecasts are available at water.weather.gov/ahps/forecasts.php.

products based on hydrometeorological analyzes and long-range predictions that are not time critical and inform non-hazard-related user activities and decisions, such as the *Streamflow Guidance*. The NWS Weather Forecast Offices (WFOs), in contrast, issue the primary hazard-centered alerts related to flooding, including products such as a *Hydrologic Outlook* ('hydrometeorological conditions that could cause flooding or impact water supply'), *Flood Watch* (flooding is likely), or *Flood Warning* (flooding is imminent or occurring). The WFO hydrological products are based primarily on RFC analyzes and predictions; for instance, an RFC forecast exceeding a flood threshold triggers a recommendation to the WFO to release a flood warning that is reviewed by the WFO forecaster. Protocols for linking the newer HEFS ensemble forecasts to alerts are still in development.

### Forecast Verification

An additional component of the HEFS shown in Figure 8 is the Ensemble Verification System (EVS), which produces statistics such as the bias in the forecast probabilities, the skill relative to a 'baseline' forecasting system, and the ability to discriminate between events.[46] EVS runs within HEFS and is also freely available as a stand-alone application. The verification statistics are provided as graphical and textual products. They are used to guide research and development of the HEFS and to improve the configuration of the HEFS for operational forecasting. Studies by Brown et al.[51,52] found that the skill of the precipitation forecasts used for the HEFS are the greatest at lead times of up to 1 week for moderate precipitation and in the wet season (December to March), with limitations in the summer season due to difficulties in forecasting convection. The studies also showed that the skill of the streamflow forecasts, for both the HEFS and traditional RFC deterministic forecasts, is substantially increased through the use of the EnsPost component.

### Operational Applications

The HEFS is currently being implemented by all 13 NWS RFCs, with existing or proposed applications ranging from flood forecasting to river navigation, reservoir operation, and long-term planning and management of water resources. For example, reforecasts and operational forecasts from the HEFS are being used by the New York City Department of Environmental Protection (NYCDEP) to improve the management of water supply to NYC by optimizing the quantity and quality of water stored in the NYC reservoirs while avoiding unnecessary infrastructure costs.

## GLOBAL-SCALE FLOOD FORECASTING SYSTEMS

At present, there are just two flood forecasting systems that are operational at the global scale, the Global Flood Awareness System (GloFAS) of the ECMWF and EC and the Global Flood Forecasting and Information System (GLOFFIS) run by Deltares. There also exists a Global Flood Monitoring System[53,54] (GFMS) developed by the National Aeronautics and Space Administration (NASA) and the University of Maryland, which uses satellite precipitation as input to a hydrological model to produce real-time global maps of flood events. Global flood monitoring is an important aspect of disaster risk reduction and has many potential applications across the globe; however, the GFMS is not an operational hydrometeorological flood forecasting system and, as such, is not discussed in detail in this review. The reader is referred to the GFMS website[55] and publications[53,54] for further information on the GFMS. This section discusses the components of GloFAS and GLOFFIS along with the products and warnings provided to end users and verification techniques used to assess the performance of these systems.

### The Global Flood Awareness System

GloFAS has been producing probabilistic flood forecasts with up to 2 weeks lead time in a pre-operational environment since 2011[9]; this environment enables continuous research, development, and testing in order to produce an operational tool that is independent of administrative and political boundaries. GloFAS can provide downstream countries with early warnings and information on upstream river conditions alongside global overviews of upcoming flood events in large river basins for decision makers ranging from water authorities and hydropower companies to civil protection and international humanitarian aid organizations.

#### *Model Components*

In contrast to the other systems presented in this paper, GloFAS uses surface and sub-surface runoff forecasts produced by the NWP model rather than a separate rainfall-runoff component (Figure 1). The Hydrology Tiled ECMWF Scheme for Surface Exchange over Land (HTESSEL) is contained within the IFS and is used as forcing for the Lisflood river routing model. Figure 10 details the components of GloFAS. Although Lisflood global[55] is also a rainfall-runoff model, it is used here to simulate the routing processes and the groundwater processes after resampling the runoff forecasts from the IFS to the 0.1° resolution of Lisflood. Additionally, GloFAS contains a loss function to account for water loss within the channel reaches in arid areas, which also simulates the river–aquifer and river–floodplain interaction and the influence of evaporation from large rivers.

Runoff from the ECMWF ERA-Interim reanalysis archive has also been run through Lisflood offline, producing a deterministic climatology of river flow that is used to compute return periods for the global river network.

#### *Forecast Visualization*

Forecasts and warnings produced by GloFAS are provided through a password-protected interface (Figure 11) where users can register to see a global overview of warning points, forecast precipitation accumulations, ensemble hydrographs including

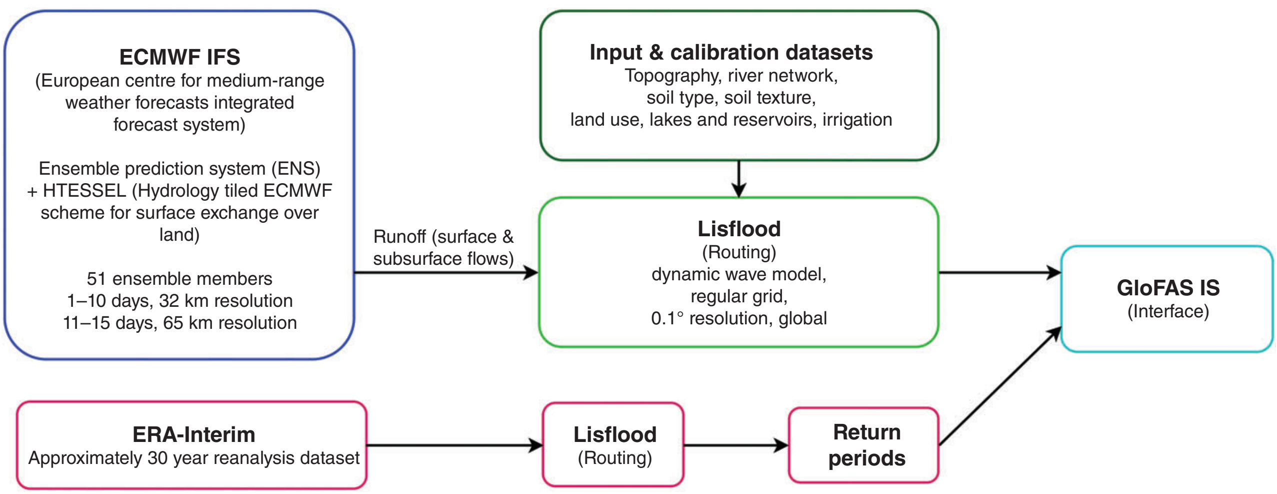


**FIGURE 10** | Components of the Global Flood Awareness System (GloFAS).

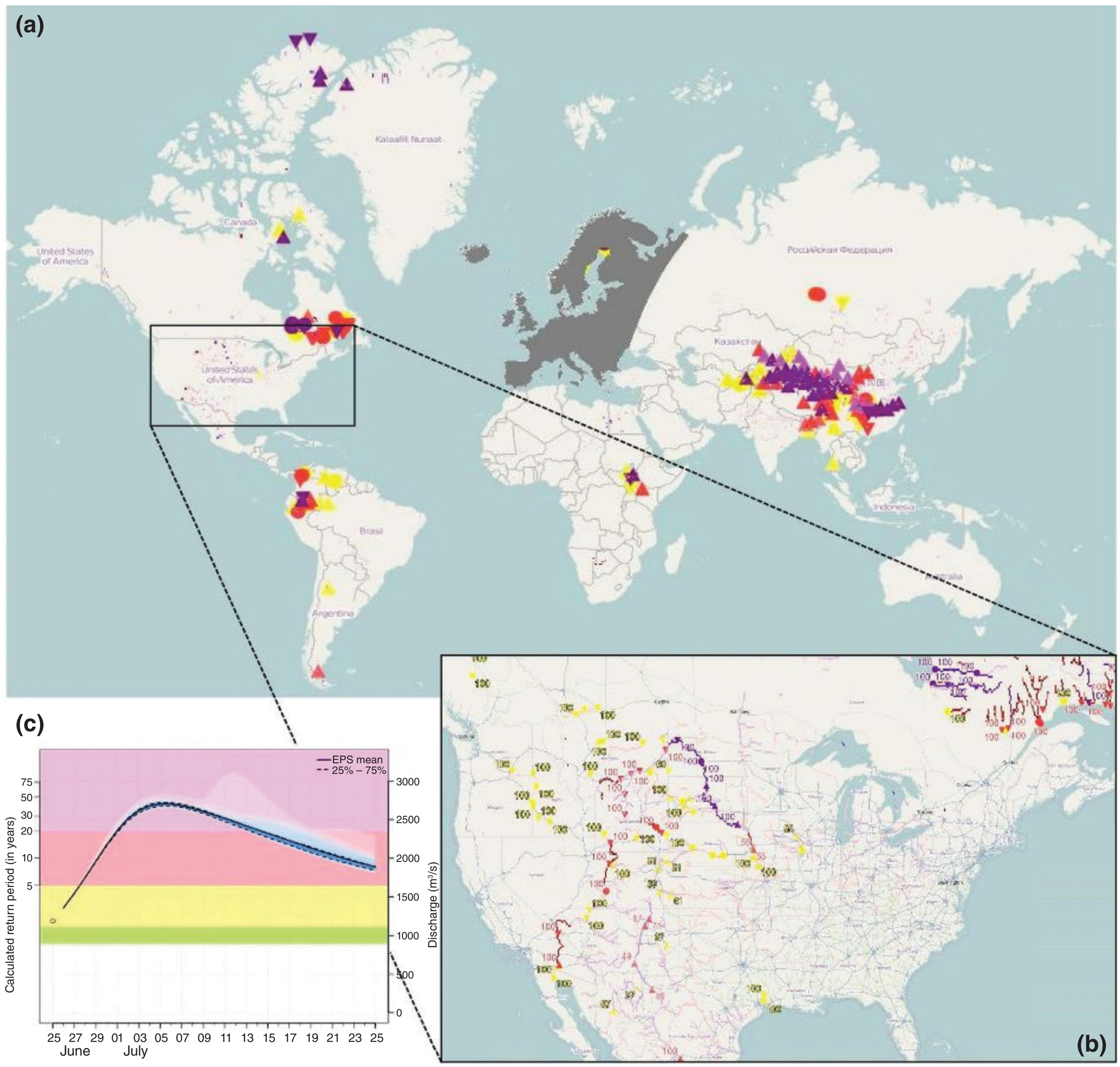


**FIGURE 11** | The Global Flood Awareness System (GloFAS) interface showing (a) a global overview of severe (purple), high (red), and medium (yellow) reporting points; (b) a more detailed view of warning points in the U.S.A.; (c) the return period hydrograph with return period thresholds (1.5, green; 2, yellow; 5, red; and 20 years, purple) for one point in the U.S.A. Forecasts are available at www.globalfloods.eu.

return period threshold exceedances and warnings, and persistence diagrams. The ECMWF and JRC do not directly disseminate flood warnings as each country has national procedures to follow, but anyone is able to access and analyze the forecasts for decision-making purposes and research. It is noted that due to the forecast and warning responsibilities within Europe, all countries for which EFAS produces forecasts are removed from the GloFAS interface as these are not publicly available.

### *Forecast Verification*

Alfieri et al.[9] analyzed the performance of GloFAS and found that forecasts were skilful at 58% of stations, which increased to 71% when model bias was removed. Evaluation of the early warning system[9] found that the longest lead times, exceeding 25 days in some regions, are found in large river basins in South America, Africa, and South Asia, while smaller basins have a maximum lead time of 20 days and, in some cases, 10 days. The least skilful forecasts were for stations in arid and semi-arid regions, such as Australia, Mexico, and the Sahel. Other discrepancies were found in relation to the modeling of snow accumulation and melting processes in HTESSEL and therefore the timing of the peak discharge during spring in snowmelt regions. Evaluation of GloFAS is updated regularly to reflect its continued and ongoing development.

### *Operational Applications*

As of the September 14, 2015, GloFAS has 177 registered users from governmental or other public authorities (~28%), non-governmental organizations (NGOs, ~7%), the private sector (~10%), and from academic/training and/or research institutions (~55%). As with EFAS, GloFAS is used by national services to provide additional early flood information and is used by, for example, civil protection and humanitarian aid organizations who benefit from a global overview of flood events and may have no other source of information for the region of interest. GloFAS is also used by the ERCC for the purpose of compiling reports on natural hazards and flood risk across the globe.

## The Global Flood Forecasting Information System

The Global Flood Forecasting Information System (GLOFFIS) is a research-oriented operational system based on Delft-FEWS.[56] GLOFFIS is one of three global systems run by Deltares in the Netherlands; also operational are a storm surge model, GLOSSIS,[57] and a water scarcity system, GLOWASIS. These three systems belong to an open, experimental information and communications technology facility, IdLab, and are being used to test new ideas around interoperability, hydrological predictability, big data, and visualization.

### *Model Components*

Similar to the approaches taken by many of the continental-scale flood forecasting systems, GLOFFIS uses several meteorological inputs to drive the hydrological component of the system. The idea behind this is to validate, verify, and inter-compare real-time rainfall (alongside temperature and potential evaporation) products as they become available. The initial conditions are derived from historical forcings based on both the GFS and the ECMWF control forecast (also extracted from the TIGGE archives) and a

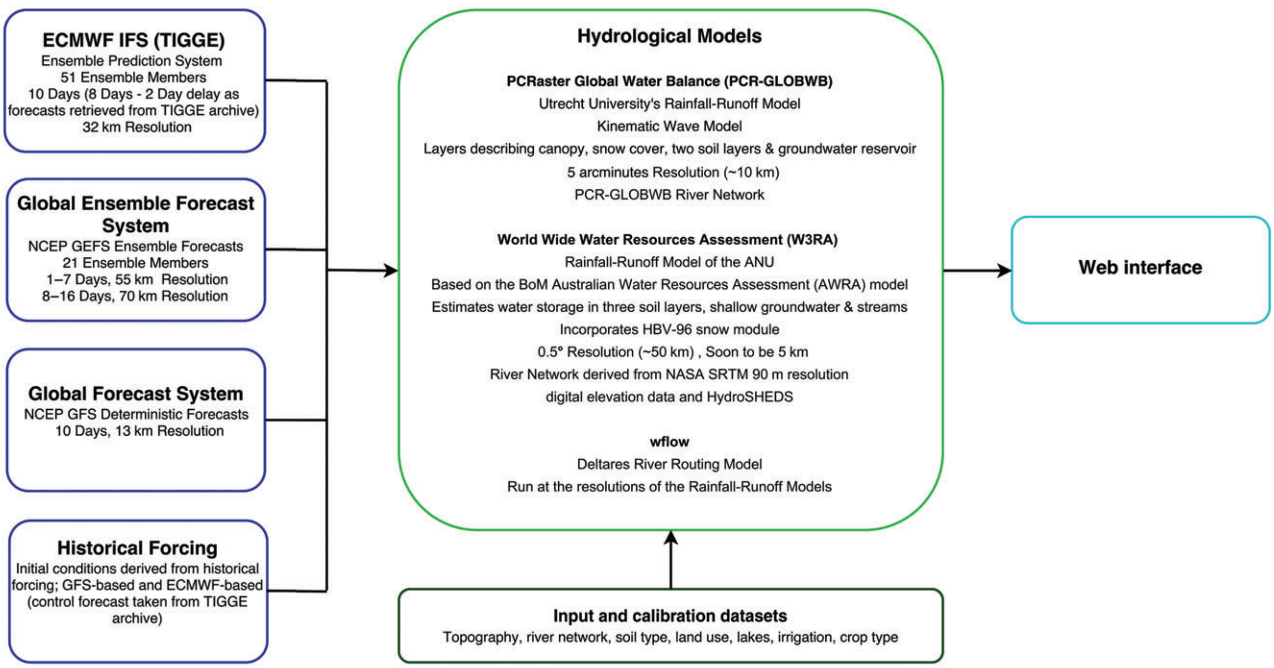


**FIGURE 12** | Components of the Global Flood Forecasting Information System (GLOFFIS).

combination of FEWSNET (Africa) and Climate Prediction Center (CPC) Unified Gauge-Based Analysis of Global Daily Precipitation, complimented by GFS temperature and potential evaporation. Each of the NWP inputs are fed into two hydrological models (with multiple initial conditions), PCR-GLOBWB and W3RA, which also incorporate the HBV-96 snow module,[58] to account for snow processes.

The current components and resolution of GLOFFIS are detailed in Figure 12, with plans to update the resolution of the W3RA component to 0.05° (~5km) and implement an improved river network. In the future, the Japan Aerospace Exploration Agency (JAXA) Global Satellite Mapping of Precipitation (GSMaP) and the Global Precipitation Measurement (GPM) Integrated Multi-satellitE Retrievals for GPM (IMERG) products will also be added as additional datasets from which to derive initial conditions.

### *Forecast Visualization*

As the GLOFFIS and interoperability experiment is a very recent development, many aspects have yet to be implemented. The IdLab is also intended to investigate visualization and data exchange, and for GLOFFIS, multiple visualization and data access and exchange methods will be tested/validated. An example of the Delft-FEWS interface for GLOFFIS is shown in Figure 13. The two forthcoming visualization platforms for GLOFFIS are not yet available, but there is a plan to offer access via a platform similar to the system developed for Guanabara bay[59] and via the Deltares adaguc portal,[60] originally developed by KNMI.[61]

### *Forecast Verification*

Thorough statistical verification of GLOFFIS is underway using available open discharge and meteorological forecast data alongside (real-time) eyeball verification. Real-time discharge data is being collected and can be accessed and compared with the simulated discharge within the Delft-FEWS GLOFFIS platform and reports generated by the system. The verification threshold levels are derived from long historical discharge records and historical simulations, similar to the methods used in other continental- and global-scale forecasting systems.[9]

### *Operational Applications*

Although GLOFFIS is not yet fully implemented, it is being used internally at Deltares and by their customers, with discussions already underway between Deltares and other potential end users of the system. GLOFFIS is intended to be a research tool on predictability and interoperability first and foremost but will be suitable for a variety of applications once fully operational.

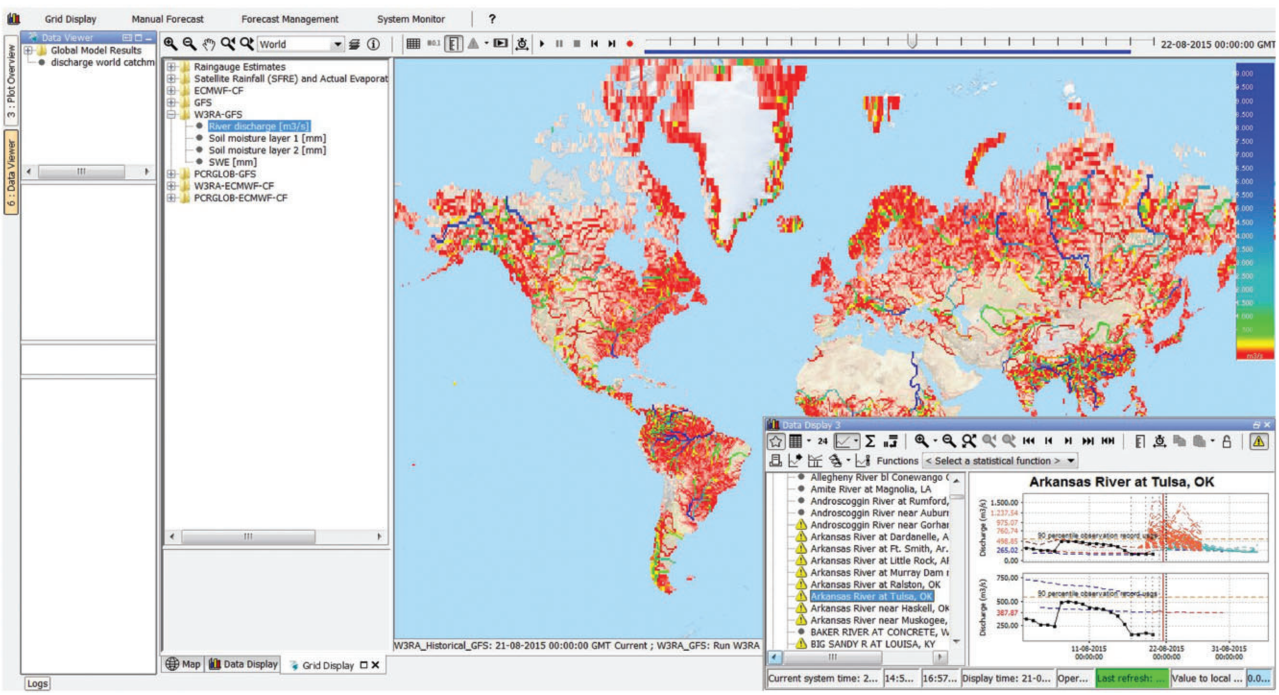


**FIGURE 13** | Runoff output of the Global Flood Forecasting Information System (GLOFFIS) W3RA model in the Delft-FEWS forecast platform interface.

## THE GRAND CHALLENGES OF GLOBAL-SCALE FLOOD FORECASTING

There are many challenges associated with global-scale flood forecasting. These range from insufficient data and difficulties combining models and computer resource requirements to the cost of running these models and methods of communicating forecasts efficiently. The challenges faced in operational flood forecasting are discussed in detail by Cloke and Pappenberger,[27] Hannah et al.,[62] Wood et al.,[63] Liu et al.,[64] Pappenberger et al.,[65,66] Kauffeldt,[29] Pagano et al.[67] and Bierkens[10]; this section focuses on the current capabilities of the systems reviewed here and discusses some of the grand challenges of global-scale flood forecasting based on the current system's limitations alongside experiences and lessons learned from the development of these systems.

### Current Capabilities

Large-scale flood forecasting has only become possible in recent years, and systems such as those outlined in this review are able to produce coarse-scale discharge forecasts at spatial scales covering entire continents or the globe using NWP products and other expertise, comparing these to observed and modeled historic events in order to produce forecasts of flood events in the medium range, typically 7–15 days. Results from EFAS suggest that river flow and flood forecasts driven by meteorological forecasts are able to provide significant added value to the monitoring of European rivers,[68] whilst for GloFAS, results show that the maximum added value is shown '(i) in medium-size river basins, (ii) in those with relatively fast response and (iii) in basins with no definite trend in the seasonal runoff',[9] with lead times of up to 1 month possible in some large river basins.[9] These systems are also capable of producing and disseminating basic forecast, and in some cases, early warning, products in real time and are key in supplementing national and local flood forecasting capabilities while supporting global-scale activities.

A recent study by Pappenberger et al.[66] provides evidence of the economic benefits of large-scale flood early warning systems in addition to the clear benefits of forecasts and early warnings to populations at risk of flooding. The study demonstrates that the monetary benefit of EFAS is ~€400 for every €1 invested, indicating that large-scale flood forecasting systems not only have the capability to provide early awareness of potential severe events but also provide economic benefits through potential avoidance of flood damages.

### Improving Data Availability

Grand Challenge: to access data of sufficient quality and length, assimilate new types of observations, and meaningfully incorporate data of inhomogeneous quality.

One of the major challenges in large-scale forecasting lies in the availability of input data of the quality that is required,[62] such as data required for estimation of the initial hydrological state, geographical boundaries of river basins, and large-/global-scale datasets of land use, soil data etc. For example, smaller-scale national flood forecasting systems are often able to assimilate or update discharge information in real time, while continental- and global-scale models are limited by the lack of availability of real-time, open data for this purpose.

Along with the technical challenges associated with accessing and assimilating the data, non-technical data challenges also exist. For example, there are difficulties with retrieving, quality controlling, formatting, archiving, and redistributing the data collected[67] at centers across the globe. This often requires specialized training and staff, for example, at the U.-S. National Weather Service, much of the hydrologists' time is spent processing data and maintaining the infrastructure used to archive and distribute the data, and the stream measurements used in the BoM system are collected by several hundred entities and must be collated before processing.[67]

More international and interdisciplinary data sharing,[62] through institutions such as the Global Runoff Data Centre (GRDC), and cooperation is essential in moving forward with global-scale forecasting efforts and would greatly increase the data available to forecasting centers not just for use in forcing these models but for verification of the forecasts and continuous improvement of forecast accuracy. In order to work towards overcoming this challenge, it is important to contribute to open data policies and ensure that data availability is at the core of all related activities.

### Model Parameterization

Grand Challenge: to find regionalization methods and ways to represent sub-grid scale uncertainty on the global scale.

Alongside the problems associated with the data required for forecasting flood events, there are further challenges involved in the parameterization of models and the use of a single model for all catchments across a continent or the globe. Wood et al.[63]

discuss the possibility that much higher resolution forecasting systems will soon be feasible, which would further provide detailed information regarding the storage, movement, and quality of water. In order to implement models of higher resolutions, there are other challenges that must also be addressed; these challenges lie in the parameterization of processes at both current and future spatial resolutions and the 'lack of knowledge involved in evaluating and constraining the uncertainty in those parameters given current and future data availability'.[69]

This challenge could be addressed, for example, by developing scaling theories to represent effective parameterization and associated uncertainties relevant to a global forecasting chain and methods that can incorporate largely varying data and information availability.

## Improving Precipitation and Evaporation Forecasts

Grand Challenge: to translate improved precipitation and evaporation forecasts into improved discharge forecasts.

There have been many improvements in NWP and precipitation forecasting thus far, which have enabled global flood forecasting, as discussed earlier in this review. Despite these improvements, there are still limitations in the NWP forecasts that affect the discharge and therefore flood forecasts. Some of these have been discussed, such as difficulties predicting convection[21] and orographic enhancement processes.[23] It is not only precipitation forecasts that need to be further improved but other NWP variables used in hydrometeorological forecasting systems, such as evaporation. The challenge then lies in translating the continuous improvements made to the NWP forecasts into improved discharge forecasts.

Moving forward, it will be important to develop tools and methods, such as satellite measurements, to measure potential evaporation and precipitation on a global level with acceptable accuracy.

## Incorporating Anthropogenic Influences

Grand Challenge: to understand which of the anthropogenic influences have a significant impact on hydrological forecasting and therefore need to be included in global forecasting models.

The lack of knowledge of anthropogenic influences on runoff is a major challenge for large-scale flood forecasting.[70] These influences, for which there is currently no global database, include dams and their regulation, reservoirs, weirs, water extraction, irrigation, and river re-routing; some of this activity also goes unreported and unregulated, creating additional barriers to incorporating information on water management. One of the specific challenges noted by SMHI for Europe is the changes in processes modeled within these systems due to depleted aquifers.

It is also important for these systems to incorporate aspects of anthropogenic influence such as land use and urban areas. Many of the users of these systems require information on potential impacts of the forecast flood events, for example, the number of people likely to be affected and how much agricultural land is threatened. The inclusion of more impact information is one of the current limitations and focuses for the development of EFAS and GloFAS. A further challenge exists in terms of the unevenly distributed global population, which results in sparse data networks in large, unpopulated regions and difficulties in the dissemination and communication of forecasts and warnings; this challenge is specifically mentioned by the BoM for Australia but also exists at the global scale.

In order to account for anthropogenic influences in global flood forecasting systems, one solution would be to map all of these influences and perform a sensitivity analysis to determine which are impacting the forecasts, so that the key anthropogenic influences can be incorporated into the models.

## Resources and Costs

Grand Challenge: to quantify, understand, and communicate the values and benefits derived from a global forecast whilst establishing a cost-effective execution of these forecasts.

Thus far, the spatial resolution of global-scale land surface models has largely been constrained by the computational resources required to run global weather models, currently, at best, ~20 km. The monetary costs of producing forecasts using large-scale prediction systems must also be taken into account. While the costs of running these systems are not generally published, the aforementioned study by Pappenberger et al.[66] states that the estimated cost of EFAS (across the four EFAS operational centres, see section The European Flood Awareness System) is €1.8 million per year, with an estimated €20 million in development costs over 10 years. In addition, with each improvement and update to a forecasting system, it also becomes necessary to re-run model climatologies, re-calculate thresholds, and revise decision-making criteria, all of which can be technologically challenging and require significant computational time and resources.[11,20]

As these systems develop, the resources required to run global flood forecasting systems will be reduced, whilst the technology used continues to improve. This will enable more centers to run global models at lower costs and with fewer time constraints in the future.

### Effective Communication of Forecasts

Grand Challenge: to communicate uncertainties to a large range of user groups in countries across the globe, some of whom will not be known, and to embed these systems into national warning chains, whilst respecting sensitivities associated with the single voice principle.[43]

A key challenge associated with global-scale flood forecasting stems from the understanding and communication of flood forecasts. For instance, with the move towards ensemble flood forecasting, there is also a need for improved understanding of probabilistic forecasts. Ensemble forecasts produce large amounts of information, and it is vital that the most important information is conveyed appropriately for ease of use and correct interpretation of the forecasts, allowing for well-informed decisions and promoting a common understanding between end users.

One of the current key challenges for EFAS is ensuring that the flood forecast and warning information is easily accessible to a broad range of users from countries across Europe, who interpret the forecasts very differently. This challenge is amplified further when producing forecasts, as with GloFAS and GLOFFIS, for the entire globe and a spectrum of users ranging from experts in the fields of hydrology and meteorology to those with no experience in using these types of products. GloFAS already has a range of partners and end users, from those who are interested in discharge forecasts for specific stations to those who are interested purely in the impact of the floods. An additional consideration is that of the single voice[43] principle, which states that national services constitute the single authoritative voice on weather warnings in their respective countries. As more systems are introduced with the capability of producing forecasts and warnings, the more difficult this principle becomes; in future, it may be that many institutions are able to disseminate warnings and benefit from the wealth of available forecasts and information, and a new challenge of the systems will be to become the trusted source of information.

In order to effectively communicate forecasts and warnings, it is important to co-develop the forecast visualizations and warnings with a large range of users and enable some flexibility for users to customize the interface. International and interdisciplinary cooperation is also key in moving forward with this challenge as issuing forecasts and warnings can be challenging without the existence of a political agreement between upstream and downstream countries for the sharing of information related to floods.[71]

### Forecast Evaluation and Intercomparison

Grand Challenge: to find new and novel methods to verify extremes, which are suitable for hydrological forecasting.

Many forecasting systems, including large-scale flood forecasting systems, are moving towards ensemble forecasting methods. While there are many benefits to using a probabilistic approach, a key challenge associated with ensemble flood forecasting is the evaluation of flood forecasts due to the low frequency of occurrence of extreme floods alongside the lack of data from different flood events.[27] The analysis of an ensemble's ability to fully represent the uncertainty is also complex and uncertain in itself.

This relates to a further grand challenge, that of implementing a Flood Forecasting Intercomparison Project to compare various aspects of these large-scale operational flood forecasting systems. This will be a valuable and important project moving forward as these systems become more advanced and widely used for many applications but is currently not undertaken due to the difficulties involved in comparing models of a variety of different scales, with varying system set-ups and interfaces and different objectives and end users. The computational resources required for such a project are also extensive.

To have effective forecast evaluation measures in place, it is important for institutions running these systems to facilitate access to the forecasts so that the forecasts can be evaluated by an unbiased, external entity.

## THE FUTURE OF GLOBAL-SCALE FLOOD FORECASTING

Flood forecasting at the large (continental and global) scale is key to providing overviews and early warnings of flood events across the globe, including regions where no alternative local-scale flood forecasts are available. This section outlines aspects of the future of global-scale flood forecasting as we continue to work towards overcoming the grand challenges and move towards ever more valuable multi-hazard forecast and early warning systems.

## Adaptive Modeling Strategies

Adaptive modeling strategies involve the idea of adjusting model predictions in real time if discrepancies are observed between the forecast and observations, where discharge measurements are available in real time. This allows the uncertainty in the forecasts to be further constrained. In meteorological applications, this is referred to as data assimilation and is used routinely in weather forecasts and NWP; however, it is often referred to as updating in hydrology and is not widely used at present in applications such as those discussed here.[30] Simple applications of updating require starting new forecasts using available observations (sequential data assimilation[72]), whereas more complex updating involves the adjustment of current predictions to the observations when discrepancies occur, assimilating the new observed data into the model in real time (variational data assimilation[72]). While data assimilation is not used extensively in flood forecasting systems to incorporate observations into the forecasts, this is likely to be increasingly incorporated in future to further improve the accuracy and lead time of large-scale flood forecasts.[63]

An area of research that will be important in moving towards the incorporation of adaptive modeling strategies is the development of data assimilation toolboxes, allowing institutions to use and benefit from data assimilation tools that are otherwise incredibly complex. One example of this is OpenDA, 'an open interface standard for a set of tools to quickly implement data assimilation and calibration for arbitrary numerical models'.[73]

## Extended-Range Forecasting

Future advances in global-scale operational flood forecasting are likely to include more long- range forecasting. There already exists an element of river-specific predictability in some large rivers where the movement of a flood wave downstream can take days or weeks, and a flood event is a relatively certain outcome once large amounts of precipitation are recorded upstream. Realistic initial conditions can be beneficial to seasonal prediction; for example, relatively large soil storage capacity leads to long memory of soil moisture, and the accuracy of soil moisture initial conditions may be key in long-range forecasting.[74] The same is true of snow cover and snow pack, particularly in climate zones where snow is the major water resource.[75]

Seasonal forecasts are currently used across a wide range of weather-sensitive sectors, with many operational weather forecasting centers producing seasonal forecasts, which provide 'seasonal-mean estimates' of weather, such as whether the coming season will be wetter or drier than usual.[76] Such forecasts have the potential to aid the forecasting of floods on seasonal time scales, providing crucial information for flood preparedness and mitigation.[77] Seasonal hydrological forecasting has begun to emerge across the globe over the past decade due to the ongoing development of coupled atmosphere–ocean–land general circulation models,[77] while the seasonal water supply forecasts have been used in the U.S. since the 1930s based on snow survey measurements and, later, precipitation data. [78] Yuan et al.[77] highlight several questions related to the future of seasonal hydrological forecasting, from how to combine weather and climate models toward seamless hydrological forecasting to how to improve the prediction of inter-annual variability of variables relevant to hydrological forecasting applications. There also exists the challenge of the effective communication of seasonal flood forecasts and transfer of these forecasts into warnings and actions.[77] The WMO S2S (Sub-seasonal to Seasonal) prediction project[79] aims to improve the understanding and forecast skill of the sub-seasonal and seasonal time scales, with a focus on extreme weather including floods, and will be key in moving towards extended-range flood forecasts.

## Flash Flood Forecasting

Flash floods are associated with spatially and/or temporally intense precipitation and can have high societal impacts. For example, 105 out of 139 countries list flash floods as being in the top two of their most important hazards.[80] Despite this, there is currently no global flash flood forecasting system, but continental systems exist in Europe (as part of EFAS),[42,81] northern America,[82] southern Africa,[83] and Australia alongside other national- and basin-scale systems around the globe.[84] These systems often take the form of one or a combination of empirical correlations, unit hydrographs, and hydrological modeling driven by limited area models.[85]

The challenge of creating a global flash flood forecasting system is that global NWP systems typically have a limited resolution of many of the fine spatial scale processes, such as convection, which are responsible for intense precipitation. Increasing the spatial resolution of global NWP systems may reduce this issue and allow for the implementation of a methodology such as that of,[86] which utilizes the surface runoff estimated from HTESSEL to forecast extreme runoff risk. An alternative could be to use forecasts of parameters that can be used to estimate the likelihood of intense sub-grid scale precipitation arising. For example, the ECMWF NWP model forecasts the convective available potential energy (CAPE) and CAPE-SHEAR parameters that show the atmospheric instability and the ability of supercell formation in the event of deep moisture convection, respectively[87].

With continuous improvements to NWP systems, new continental and global flash flood routines will be developed based on global NWP models.[88] In addition to flash floods, future applications of global flood forecasting and multi-hazard early warning systems will begin to include other types of flooding, for example, coastal storm surges.

### Grand Ensemble Techniques

Recent advances in meteorological forecasting and NWP have moved toward multi-model forecasts and grand ensemble techniques. Programs such as TIGGE[89] [The Observing System Research and Predictability EXperiment (THORPEX) Interactive Grand Global Ensemble] have led to advances in ensemble forecasting, predictability, and development of severe weather prediction products in meteorology. In hydrology, combining models for flood forecasting presents an additional challenge (e.g., due to different river networks and climatologies), but despite this, future applications of flood forecasting should move toward the establishment of grand ensemble techniques.[90] In the future, increased access to monthly and sub-seasonal (for example, through the S2S project[79]) forecasts from multiple centers will enable us to push the limits of predictability through use of these grand ensemble techniques.[90]

### New Data Possibilities

Alongside the recent and future advances in forecasting systems, other technologies are constantly advancing and will have beneficial impacts on flood forecasting across the globe. For example, new satellites and earth observation technologies for flood observation are being adopted in hydrology to improve flood forecasts.[91,92] García-Pintado et al.[92] discuss several earth observation techniques that have the potential to improve flood detection and forecasting. Improved data from satellites may be able to provide more accurate topographical, land cover, land use, river network and river width information[93]; these are some of the most important data regarding river basin characteristics, and their accuracy is key to flood forecasting systems. Real-time satellite observations of river width during flooding would also serve to improve both forecasts and warnings in real time and verification of the forecasting systems post-event.

Alongside improved databases describing basin and river characteristics, observations of the data used as input to flood forecasting systems and in data assimilation techniques[63] could include snowpack extent, water levels (from altimetry), river discharge, river width, snow, and soil moisture. Continental- and global-scale observations of many of these variables are not currently available, but global coverage from satellites could prove extremely beneficial in large-scale flood forecasting applications, particularly in regions of poor data availability.[69]

## CONCLUSIONS

Here, two global- and four continental-scale operational flood forecasting systems have been reviewed, outlining the current state-of-the-art technology in operational large-scale flood forecasting. Producing forecasts at the global scale has only become possible in recent years, with scientific and technological advances and the increasing integration of hydrological and meteorological communities. Due to these recent advances, large-scale flood forecasting systems are able to produce coarse-scale discharge forecasts at spatial scales covering entire continents or the globe using NWP products and other expertise, comparing these to observed and modeled historic events in order to produce medium-range forecasts of flood events.

Many countries are required to prepare for floods that originate outside of their borders. International and interdisciplinary collaboration is necessary in order to overcome many of the challenges involved in transboundary flood forecasting; large-scale forecasting systems have the potential to provide valuable added information about imminent flooding. So far, results from large-scale flood forecasting systems suggest that river flow and flood forecasts are able to provide significant added value to the monitoring of rivers across the globe.[9,67] Many challenges remain for global-scale flood forecasting, from lack of available data of the quality and scale required to the effective communication of forecasts and warnings to varying end users and communities across the globe. Ongoing research aims to overcome these challenges to further improve the accuracy and applicability of large-scale flood forecasting. The systems outlined in this paper are continuously evolving and are already proving to be key in supplementing national and local forecasting capabilities while supporting global-scale activities.

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