TECHNICAL MEMORANDUM

778

On the operational implementation of the European Flood Awareness System (EFAS)

Paul Smith, Florian Pappenberger, Fredrik Wetterhall, Jutta Thielen[1], Blazej Krzeminski, Peter Salamon[1], Davide Muraro[1], Milan Kalas[1] and Calum Baugh

Forecast Department

[1]European Commission Joint Research Centre, Institute for Environment and Sustainability, Ispra,Italy

Submitted to “Flood Forecasting: A Global Perspective” (Eds. Thomas E Adams & Thomas C. Pagano)

April 2016

European Centre for Medium-Range Weather Forecasts
Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen terme

Series: ECMWF Technical Memoranda

A full list of ECMWF Publications can be found on our web site under:
http://www.ecmwf.int/en/research/publications

Contact: library@ecmwf.int

Abstract

Within Europe the most severe flood events are often cross border and may need to be managed by several responsible authorities in different countries and administrative districts. In these situations flood risk management becomes challenging as inconsistent or erroneous information may arise, for example, from lacking or incomplete communication between authorities or differing forecasts resulting in divergent assessments of the ongoing and forecasted flood event. This could lead to incoherent decision making and actions across the chain of responsibilities which could be counterproductive to taking the optimal measures for reducing the impacts of the flood event. Key requirements in avoiding discrepancies in information content are: clear communication channels, agreed protocols for exchange of data and information and a reference information set. This paper discusses the European Flood Awareness System (EFAS) which operates on a pan-European scale to provide coherent medium range flood forecasts and related information and which serves as an independent reference information set for most of the hydrological services responsible for flood forecasting in Europe as well as the European Civil Protection. Here, alongside an overview of the managerial and technical aspects of EFAS case studies are used to illustrate the effectiveness of the system in providing early warning of the potential for flooding to the different services. These case studies focus on the central European floods of 2013 and Balkan floods of 2014.

1 Introduction

In Europe more than 40 rivers cross at least one border with the most transnational river in Europe being the Danube which is shared by 18 countries. In case of flooding, this means that different authorities involved in water resource management, civil protection and the organisation of aid must communicate, share data and information and, ideally, take concerted actions to reduce the impact of the flooding along the course of the river. In these situations flood risk management becomes challenging as inconsistent information, which may be arising from incomplete communication between authorities, differing results from different forecasting models and subsequent assessment of the ongoing and forecasted flood event, or simply misunderstandings due to language barriers, can introduce uncertainties and errors in the assessment of the ongoing and upcoming situation. These errors could lead to incoherent and uncoordinated decision making and actions across the chain of responsibilities, becoming counterproductive to reducing the impacts of the flood event (Demeritt et al., 2007).

In order to avoid discrepancies in information content, clear communication channels, agreed protocols for exchange of data and information are necessary and many countries have agreed bi-lateral protocols accordingly. However, except for few examples such as the river Rhine, which needs to be managed across six different country borders and for which a single model is set-up and information made available to all authorities concerned (Renner et al., 2009), different models and forecasting systems exist for the different countries or even administrative units. This lack of reference information, which is consistent for all parties involved, can make an evaluation and assessment of the information complicated and difficult, in particular for those not covered by bi-lateral agreements with upstream countries or those responsible for the management of European aid.

Significant flooding across Europe at the start of the century highlighted the need for improvements in flood risk and crisis management. Post event analysis lead the European Commission (EC) to initiate, amongst other important initiatives, the development of the European Flood Awareness System[1] (EFAS, Bartholmes et al., 2009; Burek et al., 2011; European Commission, 2002; Thielen et al., 2009a) based on initial research activities (Gouweleeuw et al., 2005; Pappenberger et al., 2005; de Roo et al., 2003). The objectives of EFAS are to provide pan-European medium-range streamflow forecasts and early warning

[1] Previously the European Flood Alert System

information in particular for large transnational river basins, in direct support to the national forecasting services, as well as harmonized information on possible high-impact flooding to the Emergency Response Coordination Centre[2] (ERCC) of the European Commission. In the case of major flood events, EFAS contributes to the better protection of the European Citizen, the environment, property and cultural heritage.

From 2003 to 2012, EFAS was developed and tested at the Joint Research Centre (JRC), the EC's in house science service, in close collaboration with various national hydrological and meteorological services across Europe, European Civil Protection through the ERCC and other research institutes (Buizza et al., 2009; Cloke et al., 2009; Kalas et al., 2008; Pappenberger et al., 2008a, 2012b, 2011c; Ramos et al., 2007; Raynaud et al., 2014; Younis et al., 2008b). The European Commission's Communication "Towards Stronger European Union Disaster Response" adopted and endorsed by the Council in 2010 (European Commission, 2010) underpins the importance of strengthening concerted actions for natural disasters including floods, which are amongst the costliest natural disasters in the EU. Partially in response to this, EFAS became part of the Copernicus Emergency Management Service (EMS) in 2011 and in 2012 it was transferred from research to operational service.

The importance of pan-European early warning systems in complementing national information systems was further highlighted in 2013 with the decision on a Union Civil Protection Mechanism, where it is stated that the European Commission "shall contribute to the development and better integration of transnational detection and early warning and alert systems of European interest in order to enable a rapid response, and to promote the inter-linkage between national early warning and alert systems and their linkage to the ERCC and the CECIS" (European Union, 2013). The Copernicus Emergency Management Service including early warning systems for better emergency management was finally endorsed in Regulation (European Union, 2014) As a result, over the past 10 years EFAS has become increasingly integrated into national and European flood risk management.

Currently more than 48 hydrological and civil protection services in Europe are part of the EFAS network. At this time EFAS provides pan-European (Figure 1) overview maps of riverine flooding hazards up to 10 days in advance as well as post-processed forecasts at river gauging stations where the national services provide real time data. In order ensure that EFAS does not interfere in the one voice warning mandate postulated by the World Meteorological Organisation, EFAS forecast products are not publicly available in real-time. Instead, national and EU authorities mandated to inform or act on ongoing or upcoming flood situations, can get access to EFAS after having signed Condition of access which regulates the dissemination of EFAS information for the EFAS operational centres and the partner organisations. As a continental scale trans-boundary forecasting system EFAS offers forecast products that are complimentary to national or region systems (see Alfieri et al., 2012a, for an overview) but does not attempt to resolve local scale events for catchments below 2000 km^2, urban flooding or flashflood and debris flows like platforms such as FKIS-Hydro (Romang et al., 2010). In contrast to global flood forecasting initetives such as GloFAS (Alfieri et al., 2013; Pappenberger et al., 2012a) the significantly higher spatial resolution of EFAS allows for a more refined resolution of the hydrological processes. The wide range of products aiming to satisfy flood forecasters as well as civil protection and aid managers along with the dissemination activities mean that EFAS is more than a software tool for lining data and models in real time and producing forecast products such as Delft-FEWS (Werner et al., 2013).

In this work the status of the operational EFAS system as of March 2015 is outlined. The background history and development of EFAS is not covered in detail. Readers are referred to Thielen et al. (2009a) and the citations in this work. The description starts with an organisational overview (Section 2) before proceeding to outlines the data acquisition (Section 3); the model components of the forecasting chain

[2]Previously the Monitoring Information Centre (MIC)

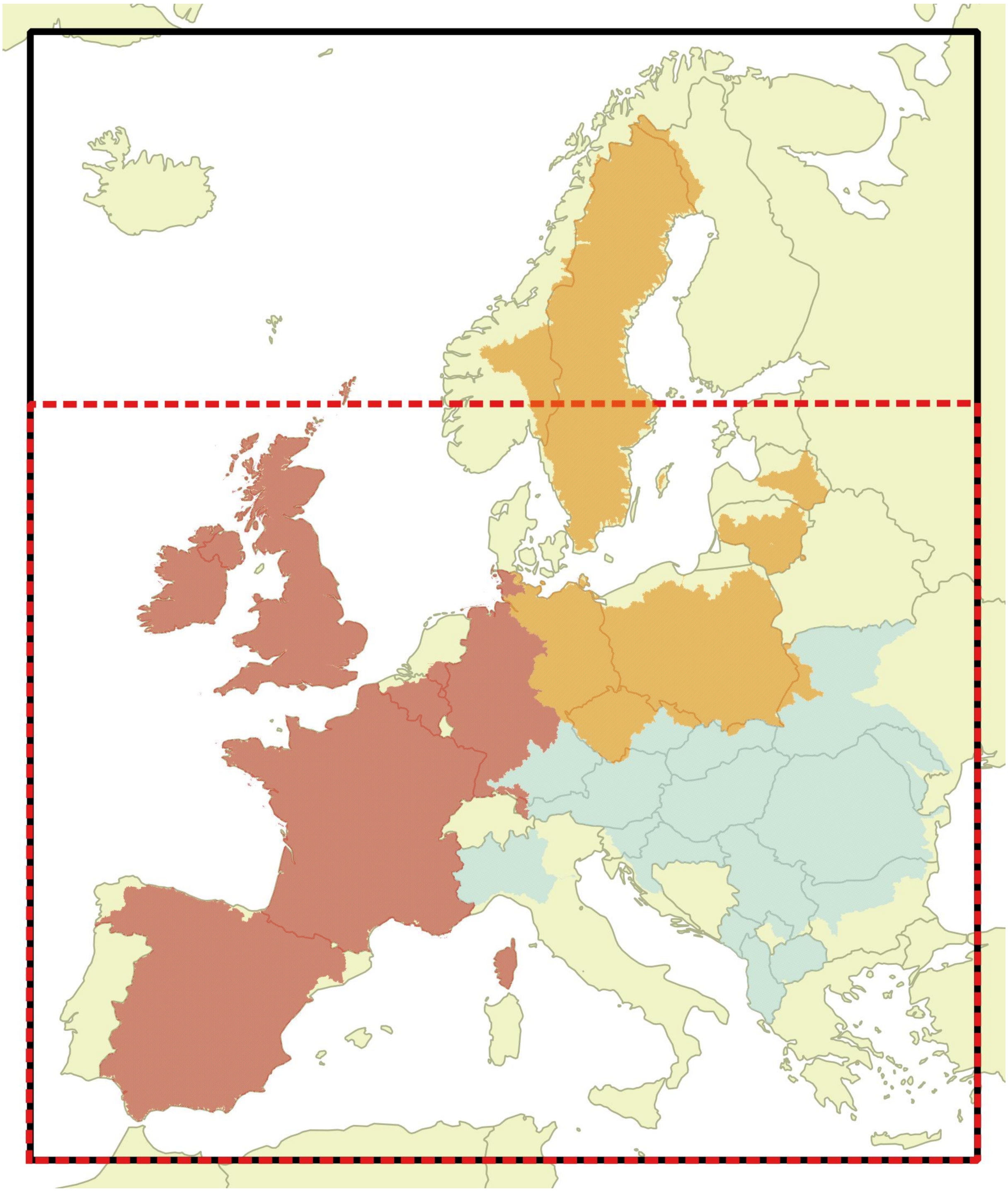

Figure 1: Map showing EFAS (black line) and COSMO-LEPS (red line) domains. Shaded areas represent the river basins covered by partner authorities with the colour indicating the corresponding dissemination centre: Swedish Meteorological and Hydrological Institute (orange), the Slovak Hydrometeorological Institute (Blue) or Rijkswaterstaat Waterdienst (red).

(Section 4) and the infrastructure utilised for generating forecasts (Section 5). Following this the forecast products are described (Section 6) along with their dissemination (Section 7). The monitoring and operational performance of EFAS infrastructure is discussed in Section 8. Before concluding (Section 10) Section 9 reviews the quality of the forecast and presents two case studies to illustrate the value of EFAS before conclusions are drawn.

2 EFAS structure

EFAS follows many operational hydro-meteorological systems in generating forecast products based on the output of a hydrological model forced by numerical weather predictions. For each forecast the initial conditions of the hydrological model are derived using observed meteorological data. The forecast products are placed on a web platform available to the EFAS partners. These products are then analysed and if necessary the awareness of responsible authorities to the potential for upcoming flood events raised.

After the development phase, the operational EFAS has been outsourced to four centres while the overall management is continued by the European Commission. Following an open tendering process for contracts from 20012-2016, the following aspects of the system operations have been issued:

1. **Hydrological data collection centre**: a consortium of the Andalusian Environmental Information Network (REDIAM) and the Spanish ELIMCO Sistemas collects historic and real-time river discharge and water level data.
2. **Meteorological data collection centre**: is runs onsite at the JRC. It collects historic and real-time observed meteorological data.
3. **Computational centre**: the European Centre for Medium-Range Weather Forecasts (ECMWF) collates numerical weather predictions; generates the forecast products and operates the EFAS Information System web platform.
4. **Dissemination centre**: a consortium between the Swedish Meteorological and Hydrological Institute (SMHI), the Slovak Hydrometeorological Institute (SHMU) and the Rijkswaterstaat Waterdienst (RWS, the Netherlands) analyses the results on a daily basis, assesses the situation, and disseminate information to the EFAS partners and to the European Commission.

The tendering for the next phase of EFAS operations was launched in December 2014 for a duration of a further 6 years.

The division of work between four centres was designed to harvest the diverse skills within the European meteorological and hydrological communities by allowing institutions to focus on their areas of expertise. Under the current contracts the dissemination of EFAS results is performed by a consortium of national hydro-meteorological services, ensuring that the distribution of EFAS information is executed by authorities which are experts in the field of flood forecasting as well as mandated to communicate with civil protection. This ensures the necessary competence to understand the complexity of legal issues associated with flood forecasting and civil protection within the countries. This is also necessary to build the trust between the different partners that the EU system at no point interferes with the National single voice warning principle..

The communication between the centres is ensured through a variety of standard means including a dedicated communication platform within which video conferencing, electronic chat, document sharing and issue tracking are implemented. Partner organisations can raise issues by contacting the centres or putting it on the agenda of the annual meeting.

3 Data Acquisition

EFAS requires hydrological and meteorological data from in situ observations to calculate the initial hydro-meteorological conditions and forecasting data to drive the flood forecasting system. Various meteorological and hydrological national services or river basin authorities provide realtime and historic data to EFAS. A complete list of data providers are listed on https://www.efas.eu/about-efas.html

For EFAS, the meteorological and hydrological data collection centres are in charge of managing the existing network of providers of observed data. The centres can also contact potential providers and negotiate standard data license agreements between the provider and the COPERNICUS services. Data are collected on a 24/7 basis.

Hydrological data collection provides real-time and historic in situ hydrological observed data. Real-time data are used in the generation of post-processed forecast products while the historic data is also used in model calibration. Currently data are collected for over 800 sites shown in Figure 2. The meteorological data collection centre collates several variables from gauges including precipitation, temperature and wind speed, though not all variables are collected from all stations. Figure 3 indicates the coverage gauges returning real-time precipitation data.

Alongside the in situ observations H SAF (http://hsaf.meteoam.it/) satellite derived soil moisture and snow coverage products are also collated for visualisation purposes. Where the flood alerts issued by the National agencies are available these are displayed in a common framework. For example, EFAS-IS shows the warnings issued by the Swedish Hydrological Service to the public in the same way as it illustrates the warnings by the Bavarian water services. This provides a feedback loop from the officially issued warnings to the EFAS system.

4 Model Components

Within EFAS hydrological forecasts are generated by cascading an ensemble of meteorological forecasts through a deterministic hydrological model. This section briefly outlines both the models that provide meteorological forcing and the hydrological model LISFLOOD.

4.1 Meteorological Models

In order to capture some of the uncertainty in the weather predictions, EFAS has been designed to operate with several numerical weather prediction (NWP) systems capable of providing the required forcings for the LISFLOOD hydrological model (see Section 4.2). Currently EFAS makes use of four products (Table 1). Two are based on the European Centre for Medium Range Weather Forecasts (ECMWF) Integrated forecasting System of which the latest cycle 41r1 became operational on the 12th May 2015. Details of older cycles can be found at http://www.ecmwf.int. The ECMWF-HRES is a deterministic high resolution run while the ECMWF-ENS is an ensemble forecast of lower resolution (Table 1).

The German Weather Service provides a further deterministic forecast based on combining their Global

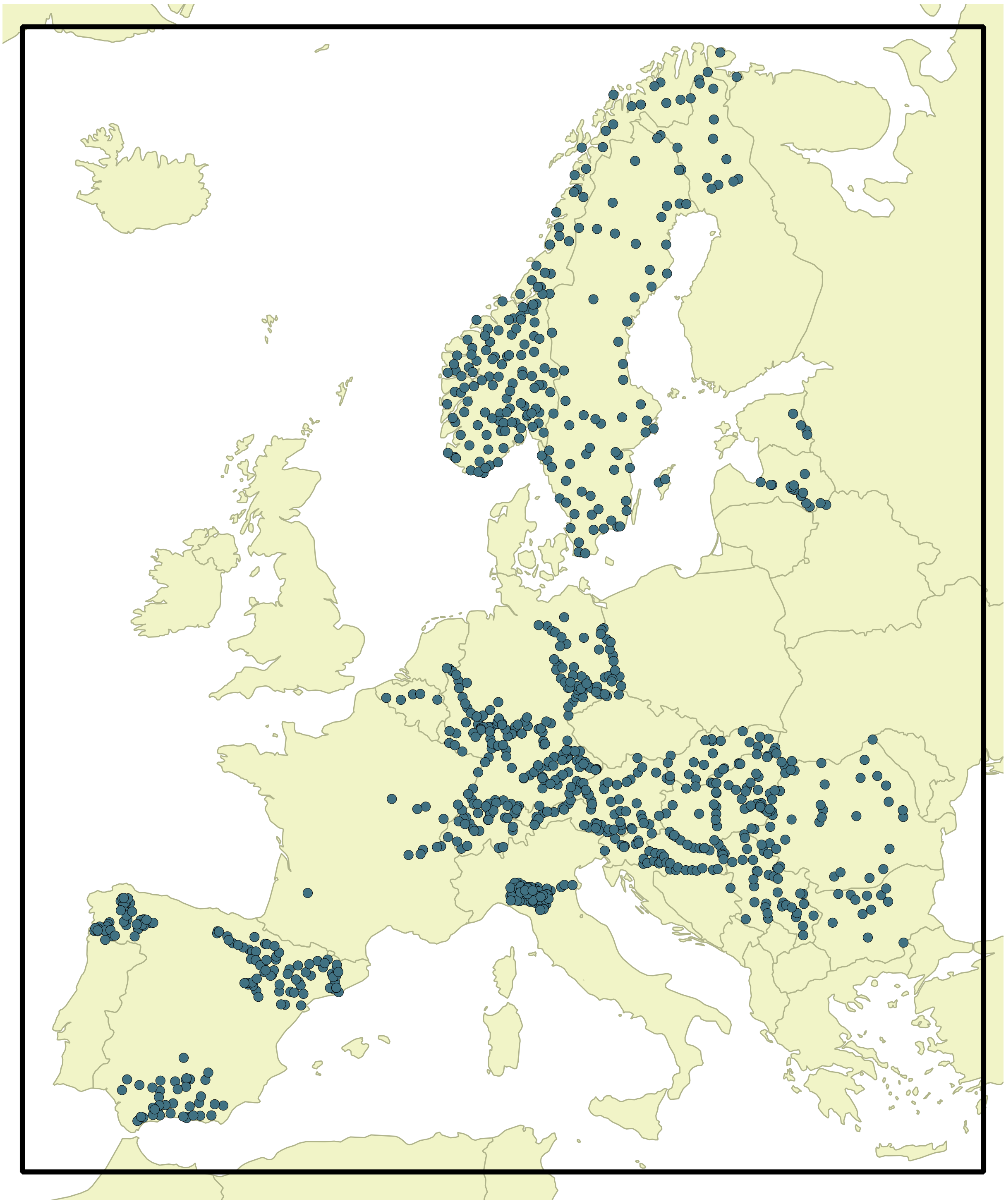

Figure 2: Coverage of EFAS real-time gauging stations

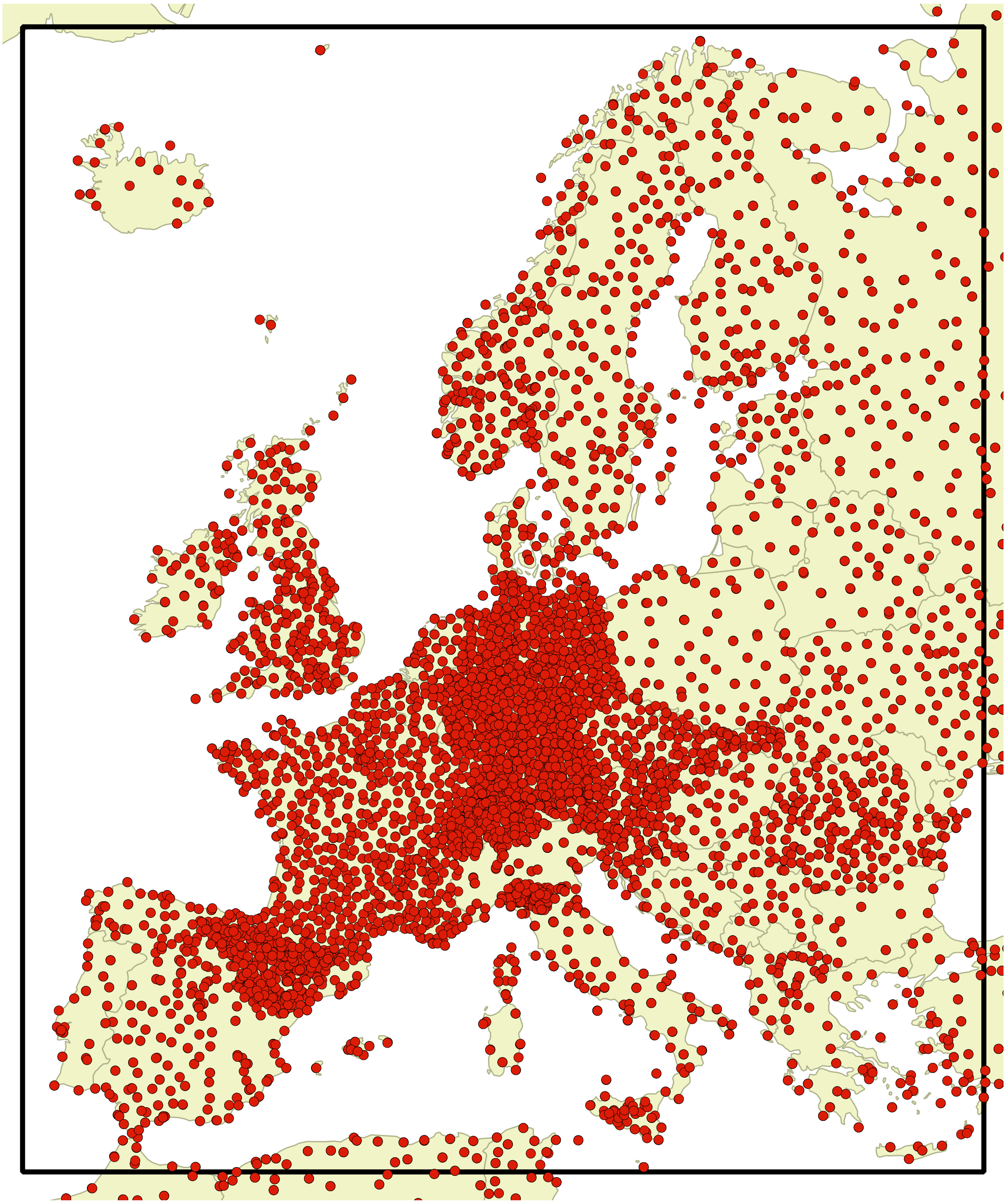

Figure 3: Coverage of EFAS real-time precipitation stations

Product	Spatial Resolution [km]	Vertical layers	Maximum lead time [days]	Number of members
ECMWF-HRES	T1279/16 km	137	10	1
ECMWF-ENS	T639/32 km for lead time 1-10 days, T319/64 km for lead time 11-15 days	91	15	51
German Weather Service	7km up to day 3 then ˜30km	40	7	1
COSMO-LEPS	7km	40	5.5	16

Table 1: Summary details of the meteorological models used in generating EFAS forecasts

and limited area models, essentially using the smaller scale forecasts as a dynamical downscaling of the coarser, global model forecast (Schulz, 2005). The final meteorological product is the Limited-area Ensemble Prediction System (LEPS, version 5.1) of the Consortium for Small-scale Modelling (COSMO) (Montani et al., 2011). This model, though of higher resolution only covers the part of the domain (Figure 1) with boundary conditions provided by ECMWF-HRES. All of the four models generate forecasts at 00:00 and 12:00 UTC.

4.2 LISFLOOD

LISFLOOD is a Geographic Information System (GIS) based spatially-distributed hydrological rainfall-runoff model developed at the JRC (Bartholmes et al., 2008; Knijff et al., 2010). This model was developed at the Joint Research Centre (JRC, European Commission) for operational flood forecasting (Thielen et al., 2009a) at pan-European scale. Driven by meteorological forcing data (precipitation, temperature, potential evapotranspiration, and evaporation rates for open water and bare soil surfaces), LISFLOOD calculates a complete water balance at a 6-hourly or daily time step and for every grid-cell. Processes simulated for each grid cell include snowmelt, soil freezing, surface runoff, infiltration into the soil, preferential flow, redistribution of soil moisture within the soil profile, drainage of water to the groundwater system, groundwater storage, and groundwater base flow (see Figure 4). Runoff produced for every grid cell is routed through the river network using a kinematic wave approach. The pan-European setup of LISFLOOD uses a 5 km grid on a Lambert Azimuthal Equal Area projection. Spatial data are obtained from various European databases with emphasis on having a homogeneous base for all over Europe. Data on soil properties are derived from the European Soil Geographical Database (King et al., 1994). Vegetative properties (Leaf Area Index - LAI) were obtained from the GLOBCARBON project, based on monthly, 1km resolution LAI data for the period of 1998 – 2007 (available at the SPOTIMAGE/VITO distribution site). The land cover dataset was created using the European Corine land cover 2000 (EEA, 2000, CLC2000; 100 m - version 12/2009). The Global Land Cover 2000 (GLC2000) database has been used for the missing areas of the European land cover database. Elevation data are obtained from the Shuttle Radar Topography Mission (SRTM) (Farr et al., 2007) and river properties were obtained from the Catchment Information System (Hiederer and de Roo, 2003). The meteorological data are extracted from the JRC MARS and the EU-FLOOD-GIS databases, which contain various data providers such as national institutions and continental scale data providers, and are interpolated to the model grid using an inverse distance scheme (Ntegeka et al., 2013). All meteorological variables are interpolated on a 5 x 5 km grid using inverse distance weighting. Temperature variables are first corrected using the elevation. Observed river flow data at gauging stations from Europe taken from the Global Runoff Data Centre (http://www.bafg.de/GRDC/EN/Home/homepage_node.html) as well as

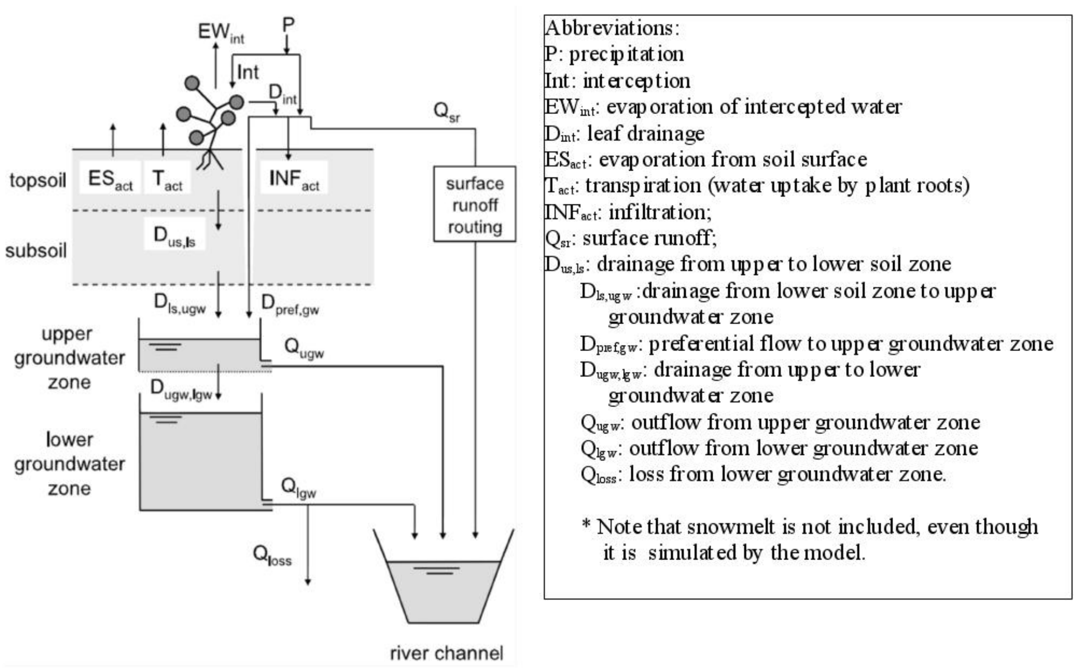

Figure 4: Schematic description of the LISFLOOD model

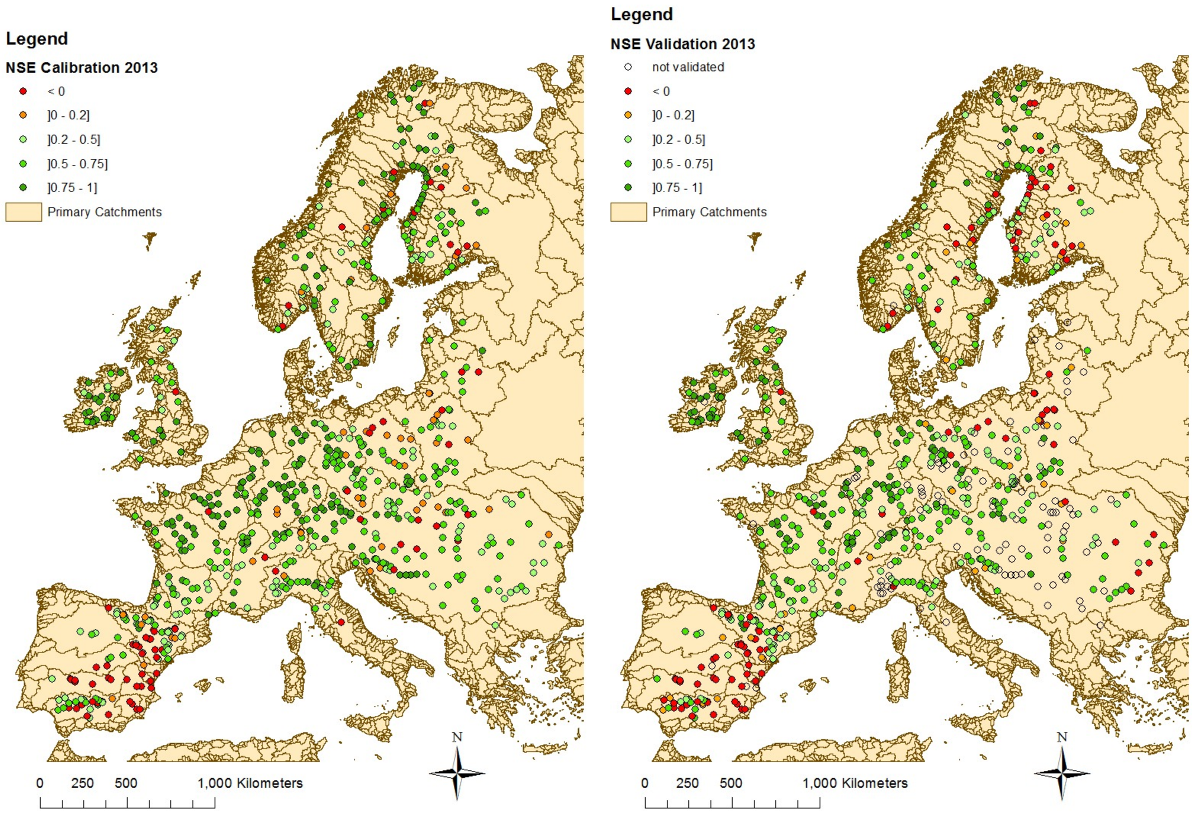

Figure 5: The Nash-Suttcliffe efficiency of LISFLOOD at the 693 sites for the calibration (left) and validation (right) periods.

national/regional data providers were used during calibration.

A calibration exercise completed in 2013 (Zajac et al., 2013) produced Europe wide parameter maps based on the estimation of parameter values for 693 catchments. Estimation was carried out using the Standard Particle Swarm 2011 (SPSO-2011) algorithm (Zambrano-Bigiarini and Rojas, 2013) and a root mean squared error criteria. For 659 of these a set of 9 parameters that control snowmelt, infiltration, preferential bypass flow through the soil matrix, percolation to the lower ground water zone, percolation to deeper groundwater zones, residence times in the soil and subsurface reservoirs and river routing, were estimated by calibrating the model against historical records of river discharge. For the remaining 34 catchments the option to represent reservoirs was used requiring the calibration of four additional parameters related to reservoir operation; though neglecting the calibration of the deepest groundwater store resulted in 12 calibration parameters for these catchments. Figure 5 shows Nash-Sutcliffe efficiency (NSE) of the calibrated LISFLOOD model for the calibration (01-Jan-1994 to 31-Dec-2002) and validation (01-Jan-2003 to 31-Dec-2012) time periods. In calibration LISFLOOD is shown to have explanatory power for 90% of the catchments. For 32% of the catchments LISFLOOD explains over three quarters of the variance of the observed series. Visual and numeric comparison of the calibration and validation periods show a broadly similar performance.

Notwithstanding the overall good agreement between the observed and simulated flow statistics, large discrepancies do occur at a small number of stations, particularly in the Iberian Peninsular and on the Baltic coasts. Deviations from the observation-based statistics may be attributed to errors in meteorological forcing, the spatial interpolation of meteorological data, as well as to shortcomings in the hydrological model, its static input and the calibration of its parameters. Some of the differences may also be due to those man made modifications of flow regimes present in many catchments, but which are not fully accounted for in the hydrological model.

5 Generating Forecasts

The generation of forecasts is the responsibility of the computational centre. The task can subdivided into three main components: (i) Collating all the necessary forcing and input data; (ii) running LISFLOOD and (iii) preparing results for visualisation. Details of the scheduling and execution of these tasks is given Section 5.2. Section 8 outlines the steps undertaken to monitor forecast generation. To give context to the later discussion Section 5.1 provides an outline of the hardware used.

5.1 Infrastructure

The generation of the EFAS forecasts is executed on a dedicated 'production' Linux cluster. The development and testing of the EFAS system is carried out on a separate general purpose cluster with hardware specifications similar to the production cluster.

The production cluster comprises of 8 nodes, each with two quad-core Xeon Intel processors and 128 GB of memory. The nodes run the same image of the operating system (SUSE Linux Enterprise server 13.1) but are configured differently such that one is an interactive node and the remaining 7 are batch (or compute) nodes. A separate Management Workstation is used to provision, configure and monitor the whole cluster. Portable Batch System (PBS) software is used to schedule and distribute and manage jobs across the cluster. The cluster makes use of two storage units, each consisting of an I/O node (eight cores and 64 GB of memory) connected to via a double 8GB/s Fibre Channel link to the IBM System Storage populated with an array of 300 GB SAS disks. All the hardware has redundant components in order to eliminate every single point of failure.

The production cluster and its storage have been installed in 2 racks, at different locations in the ECMWF computer hall. All areas of the computer hall are equipped with an inert gas fire suppression system. The ECMWF site is fed through two separate redundant power cables. The internal power distribution infrastructure is also redundant with Diesel rotary UPS units (located in a separate building) providing emergency power.

5.2 Scheduling and Execution

EFAS forecasts are run through the Supervisor Monitoring Scheduler (SMS) software, a multi-threaded workflow package that enables users to run a large number of jobs (around 1100 in case of EFAS) with dependencies on each other and on time in a controlled environment. It provides for a reasonable tolerance to hardware and software failures, combined with good restart capabilities. It is used at ECMWF to run most of the operational suites across a range of platforms. The scheduling of tasks takes into account the dependencies between them as well as date and time dependencies. This makes SMS particularly suited for use in EFAS where tasks require sequential evaluation yet must be performed simultaneously to ensure timely delivery of the forecasts; for example running LISFLOOD to generate forecasts must

Forecast variation	NWP forcing	12 Cycle		00 Cycle		Max. number of simultaneous tasks
		Start	End	Start	End	
dwd	German met. service	17:50	18:00	06:20	06:30	2
eud	ECMWF-HRES	19:00	19:10	07:00	07:10	2
eue	ECVMWF-ENS	20:30	21:00	08:30	09:00	51
cos	COSMO-LEPS	21:15	21:25	09:15	09:25	16

Table 2: Summary of hydrological forecast variations with approximate UTC run times

occur after the initial conditions are determined but each set of meteorological forecasts can be evaluated simultaneously.

The EFAS SMS suite is divided into 'modules'. A module is a collection of tasks sharing a common purpose and often the same work directory. Each module is further divided into a critical and non-critical stage. The critical stage performs operations which, if delayed, may result in a failure to generate some or all of the forecast products on time. The critical stage tasks are therefore closely monitored and supported on a 24/7 basis. Examples of critical stage tasks include preparing input data, running hydrological simulations, post-processing the results of these simulations, generating plots and tabular data, and publishing these products on the EFAS web interface. The non-critical stage includes storing of EFAS output in a tape archive and removing old output from work directories. Any delays or failures of these tasks require an investigation but are not critical to the delivery of forecasts.

The remainder of this section describes the scheduling of the modules in EFAS which control the evaluation of LISFLOOD to generate an ensemble of hydrological forecasts. Other modules are evaluated after each forecast perform produce additional analysis for the forecast products outlined in Section 6.

EFAS hydrological forecasts are produced twice a day as part of the 00 and 12 cycles. The cycle names relate to the nominal time the meteorological forecasts used as forcings. Each cycle runs four variations of hydrological forecasts. The variations arise due to forcing each one with a different meteorological forecast which improves forecast performance (Pappenberger et al., 2008a; Ye et al., 2013). In the case of the ensemble meteorological forecasts each ensemble is evaluated separately. Details of these variation and there evaluation are given in Table 2 Alongside the two forecast cycles a water balance module is evaluated. This is a simulation run of LISFLOOD driven by inputs based on meteorological observations. On a given day the model evaluates the 24 hours up to 06:00 UTC, starting at -42 hours and ending at -18 hours, relative to the nominal time of the subsequent '00' hydrological forecasts . As the final state of this simulation is valid at 18 hours prior to the start of the 00 hydrological forecast simulations, it cannot be used directly as initial conditions for these simulations. To fill this gap, a short 18-hour LISFLOOD simulation is run, driven by either DWD or ECMWF deterministic forecasts (depending on the variation of the subsequent hydrological forecast). Similarly, 30-hour long “fill-up” simulation is performed to create initial conditions for the 12 hydrological forecast run.

6 Forecast Products

From the ensemble of hydrological forecasts a number of forecast products are derived. The form of these products are one of the most dynamic parts of the system with their evolution being driven by user

EFAS threshold	Description	Impact
Severe	Alert level corresponds to a simulated flood event with a return period of >20 yr	Potentially severe flooding expected.
High	Alert level corresponds to a simulated flood event with a return period >5 yr and <20 yr	Significant flooding is expected
Medium	Alert level corresponds to a simulated flood event with a return period >2 yr and <5 yr.	Bankfull conditions or slightly higher expected. If flooding occurs no significant damages are expected.
Low	Alert level corresponds to a simulated flood event with a return period >1.5 yr and <2 yr.	Water levels higher than normal or up to bankfull conditions but no flooding is expected.

Table 3: EFAS thresholds and return periods

requests and comments (Pappenberger et al., 2012b; Ramos et al., 2009; de Roo et al., 2011; Wetterhall et al., 2013). In this section four of the key EFAS products are outlined.

6.1 Flood Alerts

EFAS only provides information to the national hydrological services when there is a danger that critical flood levels might be exceeded. In EFAS, the critical thresholds are needed at every grid point and therefore cannot be derived from observations. Instead, based on observed meteorological data, long term discharge time series are calculated at each grid with the same LISFLOOD model parametrisation that is set up in the forecasting system. From these long-term simulations return periods are estimated – the 1, 2, 5 and 20-year return periods. All flood forecasts are compared against these thresholds – at every pixel – and the threshold exceedance calculated. Only when critical thresholds are exceeded persistently over several forecasts, is information at these locations is produced, e.g. in the form of colour-coded overview maps or time series information at control points. The persistence criteria; currently 3 consecutive forecasts with greater than a 30% probability of exceeding a threshold based on the forecasts derived from the ECMWF ENS forcing; has been introduced to reduce the number of false alerts and focus on large fluvial floods caused mainly by either widespread severe precipitation, combined rainfall and snow-melt or prolonged rainfalls of medium intensity.

6.1.1 EFAS thresholds and return periods

The EFAS thresholds are based on a 22 year model run using observed meteorological data as input. producing a surface re-analysis (Balsamo et al., 2015, similar to). A Gumbel distribution; fitted using the L-moments procedure; is applied to each pixel in the LISFLOOD discharge output maps to obtain return periods. The return periods are then associated to EFAS alert levels as described in Table 3.

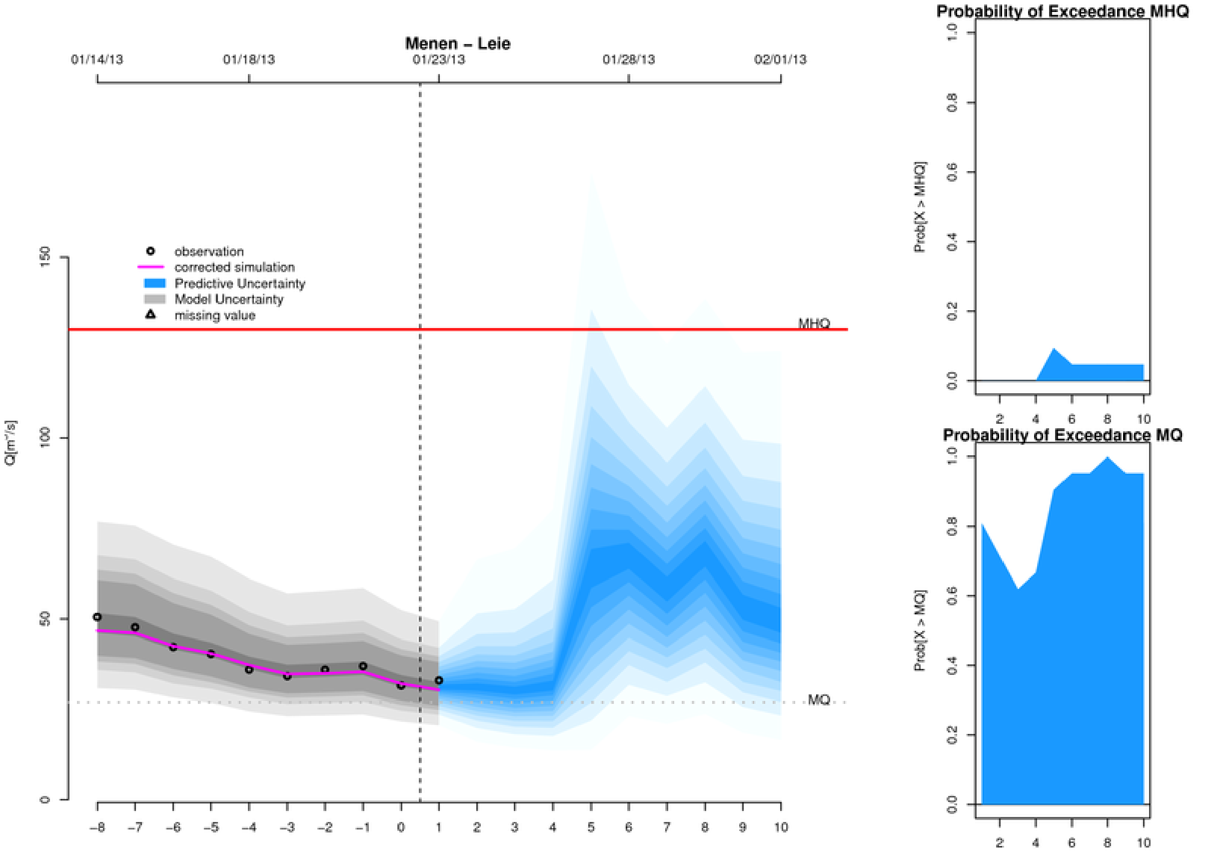

Figure 6: Post processed 10-day discharge forecast at Menen on the River Leie showing summaries of the post-processed forecast along with the probability of exceeding the daily mean (MQ) and mean annual maxima (MHQ) observed discharges.

6.2 Post-processed forecasts

At a given location the forecasts can be post-processed both to minimise errors in the timing, volume and the magnitude of the peak when compared to the observed but also to derive more accurate calibrated probabilistic forecasts (Bogner and Kalas, 2008; Bogner et al., 2014; Bogner and Pappenberger, 2011; Bogner et al., 2012). The approach used is a two step process and is applicable at points along the river network where both historic and real-time observations of discharge are available.

The first step of the process is correction of each member of the ensemble of forecasts using the approach outlined in Bogner and Pappenberger (2011). The second step combines the forecast up to ten days lead time using Bayesian Model Averaging (BMA, Raftery et al., 2005) the parameters of which are estimated for each lead time using a moving window of past forecasts. An example output is shown in Figure 6. Both the forecast hydro-graph and the probability of crossing thresholds derived from the historical observed data are shown.

6.3 Flash Flood alerts

Although designed for larger, riverine floods, the concepts and methodologies of EFAS have been shown to be also applicable for the detection of flash floods (Alfieri et al., 2011a,b; Younis et al., 2008a).

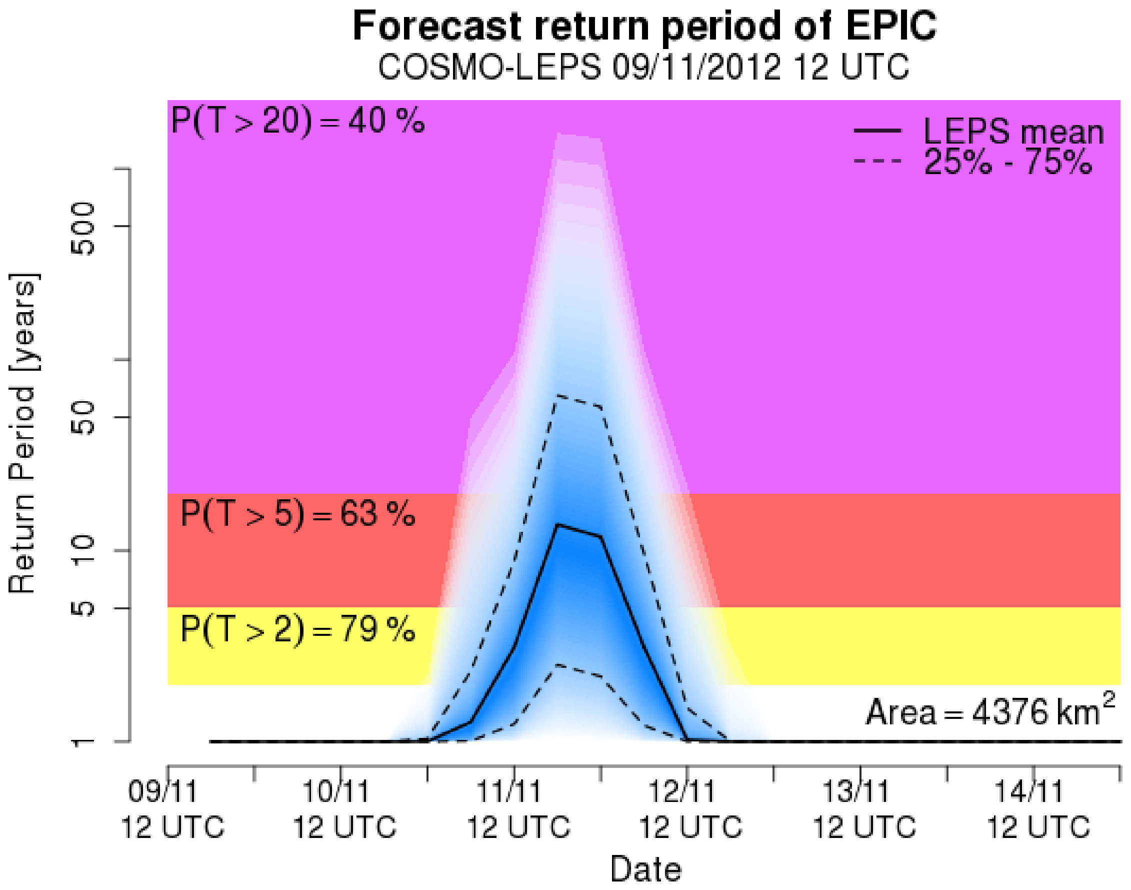

Figure 7: Return period plot of probabilistic EPIC forecast for 9/11/2012 12 UTC. Reporting point for the Piave river at the outlet, NE Italy.

The EFAS user community welcomed the inclusion of a flash flood indicator as novel product. For EFAS, flash flood early warning is performed through the detection of rain-storms with extreme rainfall accumulations over short durations (6, 12 & 24 hours) and within small-size catchments (<5,000 km^2) prone to flash flooding. The European Precipitation Index based on simulated Climatology (EPIC, Alfieri and Thielen, 2012) is used as an indicator of upcoming hazardous events. System results only depend on the Quantitative Precipitation Forecast (QPF) and on the modelled river network. EPIC is calculated twice per day with a probabilistic approach, using COSMO-LEPS forecasts and a grid resolution of 1 km. At those locations with significant probabilities of exceeding reference warning thresholds (i.e., return periods of 2, 5, and 20 years), reporting points are created and geo-located in the web interface. For each point, a return period plot is produced, showing the uncertainty range of EPIC return periods over the 132-hour forecast horizon, as described by Alfieri and Thielen (2012). An example plot is also shown in Figure 7. An analysis of daily EPIC forecasts over 22 months ending in September 2011 denoted a probability of detection of rain-storm events and flash floods of 90%, corresponding to 45 events correctly predicted, with average lead time of 32 hours (Alfieri et al., 2012b). A future development to this system will replace the EPIC method with the European Runoff Index based on Climatology (ERIC Raynaud et al., 2014). This works in the same way as EPIC but is based on the surface runoff values calculated by the LISFLOOD hydrological model. Therefore it has a better representation antecedent catchment conditions which may exacerbate the flash flood severity. It will become operational within the summer of 2015.

6.4 Rainfall animation

The rainfall animation based on the COSMO-LEPS ensemble and ECMWF deterministic models are available. Images can be shown for different time-steps as well as the continuous animation of the sequence over the forecast range. For the deterministic model the visualization routine uses a standard approach, where rainfall rates are binned into 16 classes of variable size and shown with a rainbow-like colour palette. For COSMO-LEPS ensemble forecast product, a novel visualization technique is implemented. The ensemble mean of rainfall rates is linked to a colour palette, following the same approach as of the deterministic forecast. In addition, the ensemble spread is classified into three classes, according to the coefficient of variation (CV) of forecast values against the ensemble mean. Each class is then shown with different level of transparency, which increases with the CV. Figure 8 shows an example of this type of image.

6.5 Soil moisture and Snow anomaly maps

EFAS also displays some of the initial conditions of the hydrological model such as the soil moisture and the snow water equivalent. However, as in flood forecasting it is often more important how different the soil moisture and snow conditions are in comparison to the "normal" situation so anomalies are also displayed. The anomalies are calculated by scaling the value using the mean and stand deviation of the values taken on that year day in the LISFLOOD long term model run used to derive the warning thresholds.

In the case of the snow water equivalent the simulated variable corresponds to a 10-day average. Therefore also the long-term average and the standard deviation for the snow water equivalent are derived using 10-day average values from the LISFLOOD long-term run.

7 Forecast Dissemination

Dissemination of the forecasts to end user is carried out in two ways. The first is through the use of a password protected web based interface; the EFAS Information System (EFAS-IS) accessible only to registered users. The second is for the dissemination centre to pro-actively contact end users when alerts are issued within their domain. In the following these two methods are introduced.

7.1 EFAS-IS

The EFAS-IS (https://www.efas.eu) is a Rich Internet Application (RIA, Figure 9) providing the same level of interactivity and responsiveness as desktop applications. It was carefully designed alongside the forecast products with the aims of end users in mind. The EFAS-IS allows control and management of the content within the web portal based on user specific roles and permits various workflows in a collaborative environment. It grants end-users the ability to contribute to and share information and helps improve communication by allowing users to raise queries with the EFAS centres. Alongside restricted information for EFAS partners public information, such as the bimonthly bulletins designed to review recent floods and inform about ongoing system improvements, are available on the web portal.

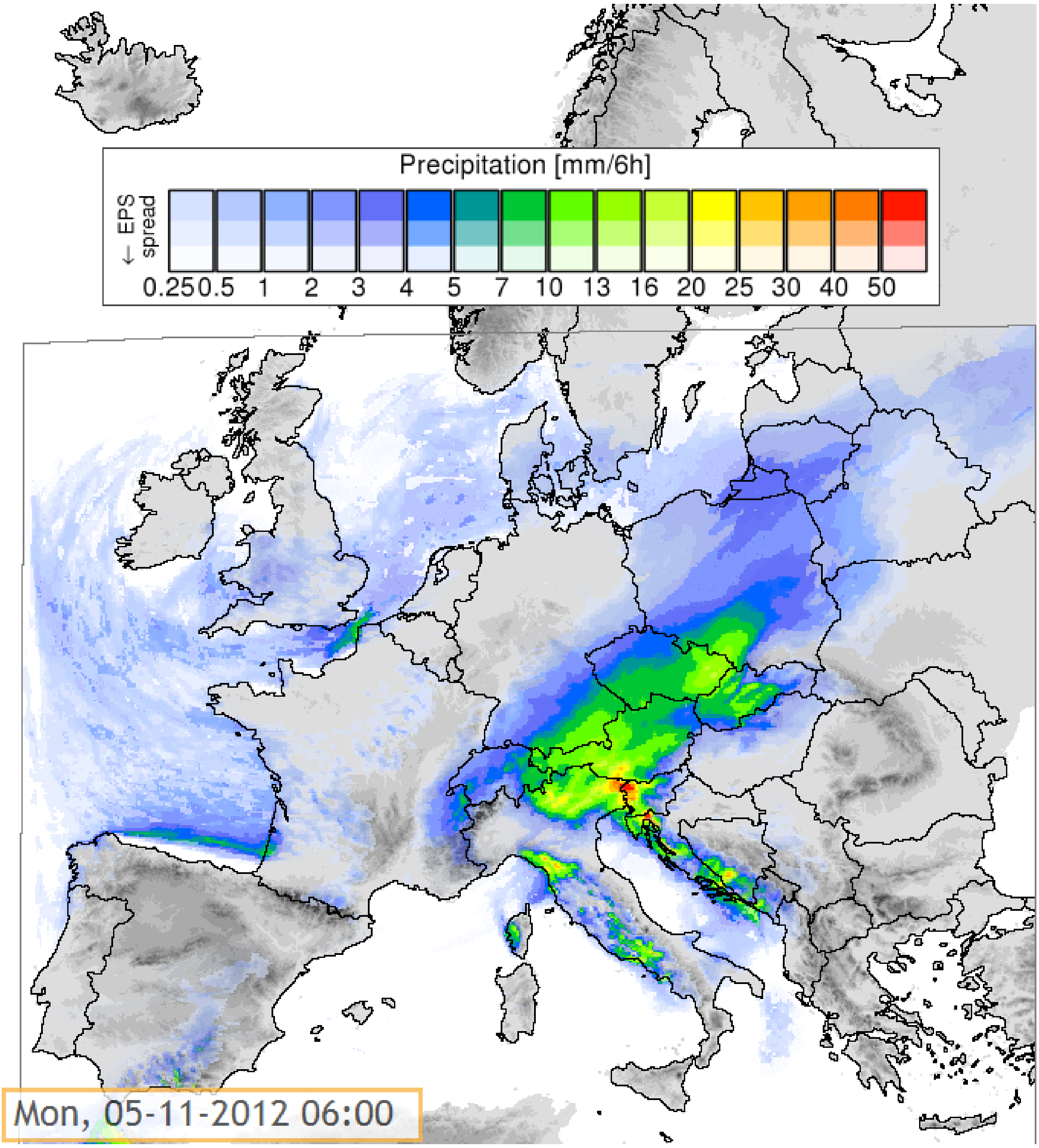

Figure 8: 6-hour ensemble precipitation forecast from COSMO-LEPS run of 3/11/2012 12 UTC. Forecast lead time of 36 to 42 hours

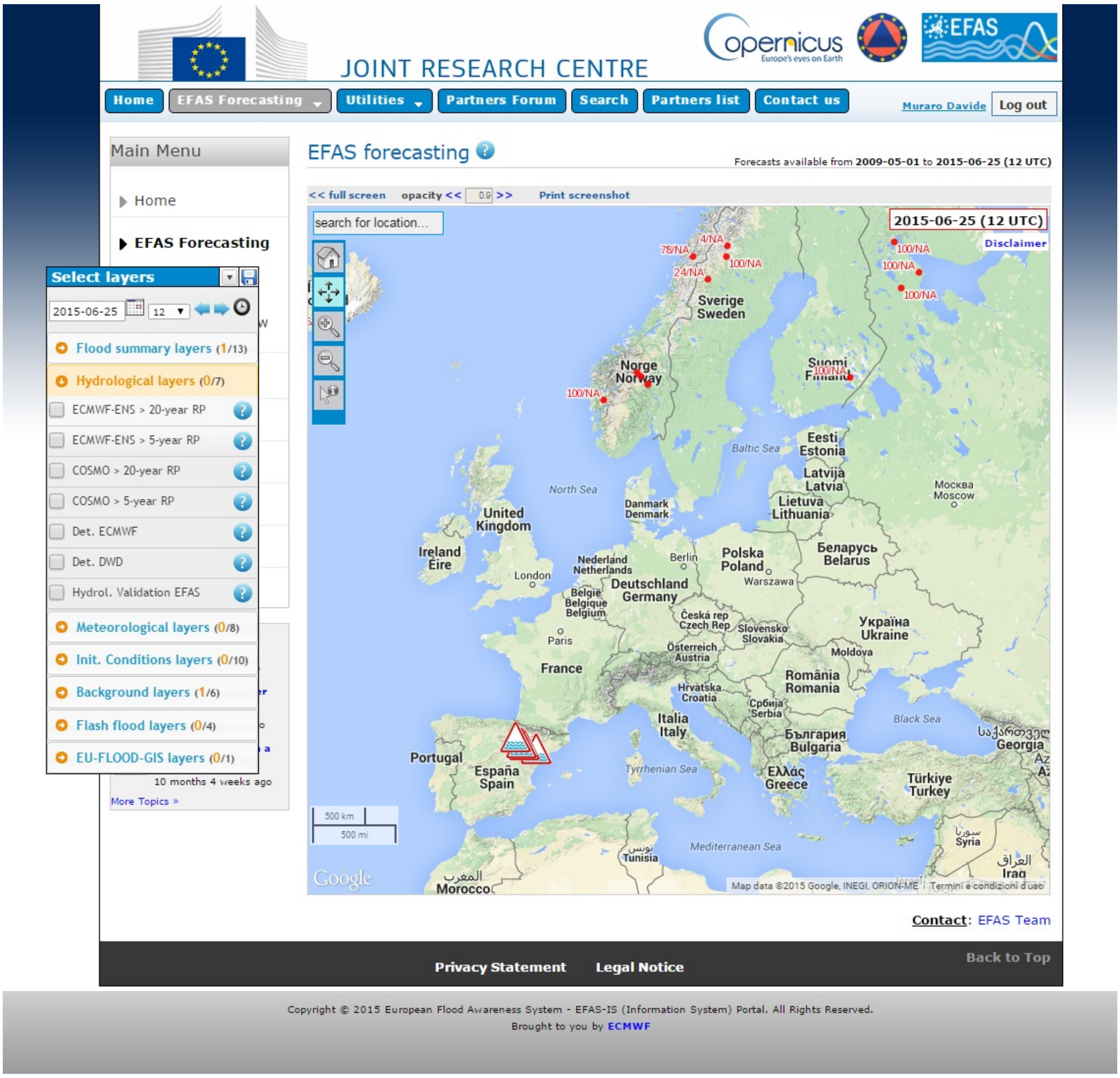

Figure 9: Screen shot of the EFAS-IS showing the tabbed layout and menu for selection of products to be visualised.

7.1.1 EFAS web services

Alongside EFAS-IS two services are provided to partner organisations for downloading data from EFAS for further analysis and incorporation into their own systems. These services use Open Geospatial Consortium (OGC) standards to deliver either data about individual points; the EFAS SOS Sensor Observation Service) services; or maps; the EFAS WMS-T (Web Map Service Time).

7.2 Email alerts and daily overview

The EFAS dissemination centre sends out warning emails to the corresponding EFAS partners in order to inform them of a possible upcoming flood event. The emails are, however, just a call for attention to the concerned EFAS partners. More details can then be found on the EFAS-IS. In this situation three types of emails can be sent by an EFAS forecaster relating to three types of EFAS warning: EFAS Flood Alert; EFAS Flood Watch and EFAS Flash Flood Watch. There are strict criteria on the activation, upgrading and deactivation of these warnings, these are outlined in Table 4. Alongside these a daily overview is sent to the Emergency Response Coordination Centre (ERCC) of the European Commission which contains information on ongoing floods in Europe as reported by the national services, EFAS Flood Alerts, EFAS Flood Watches and EFAS Flash Flood Watches.

8 Operational Performance

8.1 Monitoring

The entire chain of EFAS computations as well as the underlying hardware and software infrastructure are monitored at all times to ensure uninterrupted availability and timely delivery of the EFAS products.

The core monitoring services and first-level support are provided by a dedicated team of operators who are available at the premises at all times. This core group follows established procedures to rectify issues themselves or forward the issue to the second level support staff. The second level support is provided by specialized teams of experts on 24/7/365 call-out duty with remote access ECMWF IT infrastructure. Finally, the third level support is provided by in-house and third party technical and scientific experts.

Operators on duty have several mechanisms at their disposal to monitor the activity of the EFAS system. The first one is built into the SMS job scheduling software - it's graphical user interface (Xcdp) visualises the progress of computations and instantly alerts operators on any failures. The second mechanism is a dedicated subset of EFAS watchdog jobs which are executed at specified times and check if EFAS computations have reached expected stage. Additionally, the state of the EFAS system and underlying infrastructure (computational cluster, web servers, network) is monitored by the OpsView service (http://www.opsview.com) which is a monitoring and alerting tool for servers, switches, applications and services. The acquisition of input data from external providers is monitored via the web interface built into the ECMWF Product Dissemination System (ECPDS) data acquisition system which for example raises an alarm if no new data has been received for prolonged period of time.

In Table 5 various services are listed along with the action which is taken following a failure, the response time and how the response is triggered. If the failures will result in late, incomplete or incorrect products the JRC and dissemination centre are informed.

<table>
<tr><th>Action</th><th>EFAS Flood Alert</th><th>EFAS Flood Watch</th><th>EFAS Flash Flood Watch</th></tr>
<tr><td>Activation</td><td>Catchment part of agreed list of catchments.
Catchment area is larger than 4000 km^2
Event more than 48 h in advance with respect to the forecast date
Forecasts are persistent (3 consecutive forecasts with more than 30% exceeding EFAS high threshold according to ECMWF ENS)
At least one of the deterministic forecasts (ECMWF or DWD) exceeds also the EFAS high threshold</td><td>Catchment part of agreed list of catchments.
Any of Flood Alert criteria is not met but the forecasters thinks the authorities should be informed
Any other doubt</td><td>Catchment part of agreed list of catchments.
Probability of exceeding the flash flood high threshold is forecast to be greater than 60%</td></tr>
<tr><td>Upgrading</td><td colspan="2">If an EFAS Flood Watch has been sent but in the following forecasts all the conditions for an EFAS Flood Alert are fulfilled then the EFAS Flood Watch can be upgraded to an EFAS Flood Alert</td><td></td></tr>
<tr><td>De-activation</td><td colspan="2">Observations reported by the national/regional hydrological service clearly indicate that the EFAS Flood Alert/Watch is a false alarm
Observations reported by the national/regional hydrological service clearly indicate that discharges/water levels have decreased already to normal values meanwhile EFAS simulations still show that simulated discharge exceed the EFAS high threshold
The simulated EFAS discharge at the reporting point(s) for which the EFAS Alert/Watch was issued falls below the EFAS high threshold</td><td>Probability of exceeding the flash flood high threshold is forecast falls to less then than 60%</td></tr>
</table>

Table 4: Rules for activation, upgrading and deactivation of EFAS flood Alerts and Watches

Service	Action	Response	Trigger
Data acquisition	operator informs the data provider	24/7	alarm raised in the ECPDS monitoring interface
EFAS computations	operator follows a recovery procedure or calls an analyst	24/7	failure/delay signalled by Xcdp or abnormal state detected by OpsView
EFAS web interface	operator follows a recovery procedure or calls an analyst	24/7	abnormal state detected by OpsView; an email or phone call from user.

Table 5: Summary of monitoring procedures for the operational EFAS system

Date	Delay	Description
17.04.2014	2 hours	All products delayed due to network filesystem issues
27.04.2014	1 day	Products based on COSMO-LEPS forecast delayed due to issues with the COSMO-LEPS model over the weekend.
24.06.2014	2 days	Products based on DWD forecast delayed due to unexpected change of DWD data format.
22.07.2014	2 hours	Products based on COSMO-LEPS forecast delayed due to late arrival of forecast data
27.09.2014	7 hours 30 minutes	Products based on COSMO-LEPS forecast delayed due to late arrival of forecast data
30.09.2014	3 hours 30 minutes	Products based on COSMO-LEPS forecast delayed due to late arrival of forecast data
26.11.2014	30 minutes	All products delayed as a result of unusually high workload on the computational cluster.
23.02.2015	12 hours	Products based on DWD forecast delayed - data not sent by the provider.

Table 6: Delays in EFAS products delivery for the period between 01.04.2014 and 01.04.2015.

8.2 System Performance

The current deadline for delivering EFAS 12 UTC and 00 UTC forecasts is 02:00 UTC and 14:00 UTC the following day respectively. Overall the performance of the system is very high with a greater than 99% reliability due to strict quality assurance measures allowing the system to capture and promptly correct the majority of problems as they arise.

Table 6 lists incidents between April 2014 and April 2015 which lead to delays and missed deadlines. In two of these incidents all products were delayed. The remaining six cases the delay involved only some of the products. In each case EFAS users were informed in a timely manner by email.

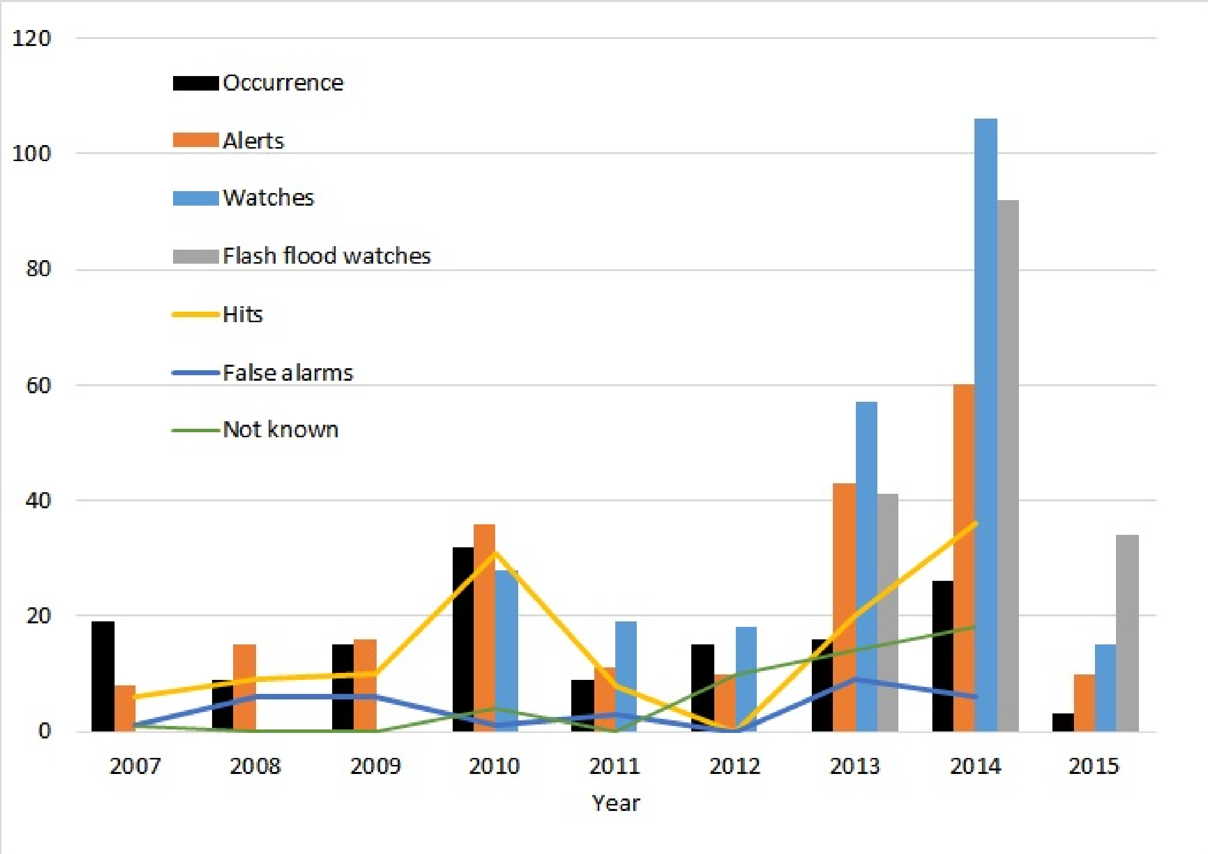

Figure 10: Number of Flood alerts, watches and flash flood watches sent since 2007. The lines shows the verified hits and false alarms over the first years of EFAS.

9 Case Studies

9.1 General performance

The forecast performance of EFAS is continually monitored in terms counting the number of watches, alerts and flood watches sent out. As far as possible, the alerts are counted as hits or false alarms in comparison with observed floods, otherwise they are assigned as unknown. Figure 10 shows a large inter-annual variation, and that 2013 and 2014 stand out as having a greater number of warnings. The main reason for this are two major events; the central European floods of 2013 and the Balkan floods of 2014 which are discussed below.

The observed occurrence of a flood in Figure 10 was extracted from the International Disaster Database (http://www.emdat.be/database, accessed 10 June 2015). There are clear trends in the data. It appears the system has increased in activity over the years when comparing the number of reported events with warnings and alerts. This could be due to the fact that the number of EFAS members have grown over the years, or that due to changes in the criteria for issuing alerts and watches more are being issued. However, there is a much higher correlation between the number of affected people and the number of issued flood alerts (0.89), than with the number of events (0.65). This is an effect of how an event is classified in the database. The number of people affected is a better measure of the total extent of the flood, and this is what is reflected in increase in the number of alerts. The performance of EFAS is also continu-

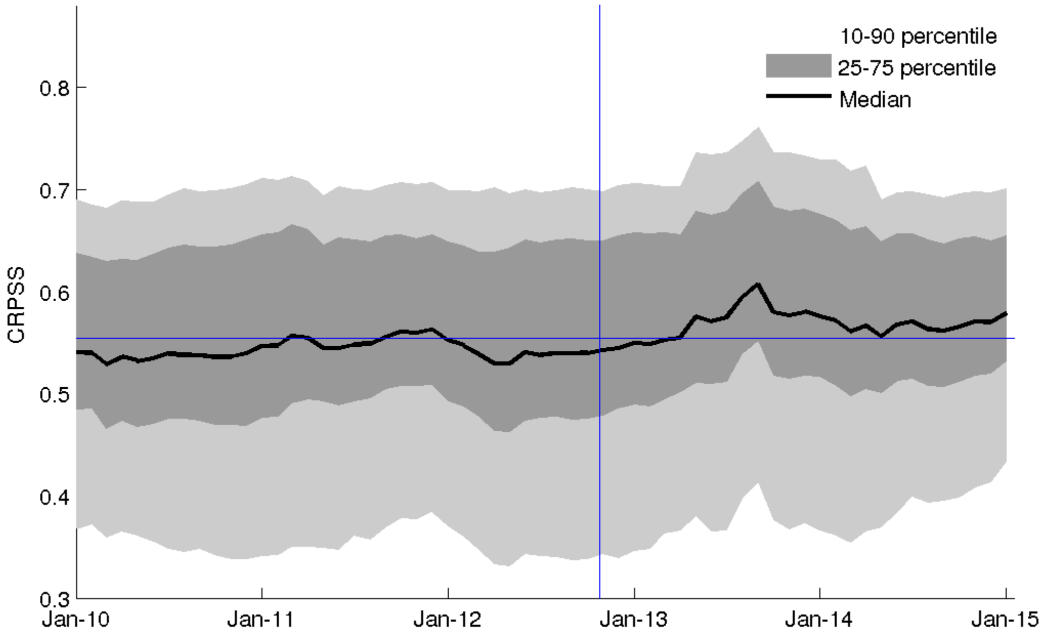

Figure 11: CRPSS of EFAS driven by ECMWF ENS over the period 1 January 2010 – 30 April 2015 as an annual running mean. The lighter grey areas show the 10-90th percentiles, and the darker grey 25-75th percentiles. The results are shown for all the areas larger than 4000 km^2.

ously monitored in terms of skill scores such as bias, Nash-Sutcliffe efficiency and continuous ranked probability scores (CRPS). Performance results are published in a bimonthly bulletin and the scientific literature (e.g. Alfieri et al., 2014; Pappenberger et al., 2011c). New user focused scores are developed as needed (e.g. Cloke and Pappenberger, 2008; Pappenberger et al., 2011a,b, 2008b). The system is evaluated against its own climatology which is the water balance run of LISFLOOD (Pappenberger et al., 2015b). The performance of the model is steadily increasing, however there are inter-annual variations (Figure 11). The recent drop in performance is due to the poor performance of the winter of 2015, which was difficult to predict for all weather centres.

9.2 Central European floods in summer 2013

The Central European flood event of June 2013 was the first large scale crisis during which the operational EFAS was actively reporting to the ERCC. ECMWF as a current EFAS operational centre published a detailed analysis of this event (Haiden et al., 2014; Pappenberger et al., 2013a). The June 2013 flood event was a severe, large-scale event that affected several countries and led to the loss of lives as well as considerable damages in two major European catchments (Danube, Elbe). Over the last week of May 2013, EFAS forecasts showed a rapidly increasing probability of exceeding flood warning thresholds for wide areas in Central Europe including Germany, Poland, Austria, Czech Republic and Slovakia. Between 28 and 31 May, 14 EFAS flood warnings of different severity levels (both flood alerts and watches) were issued for some of the major rivers (e.g. Elbe, Danube, Rhine and Odra) up to 8 days before the beginning of the extreme streamflow conditions (Figure 12). Cities such as Wittenberg (Germany) were severely affected by the rising waters of the Elbe, where the record high of the ‘flood of

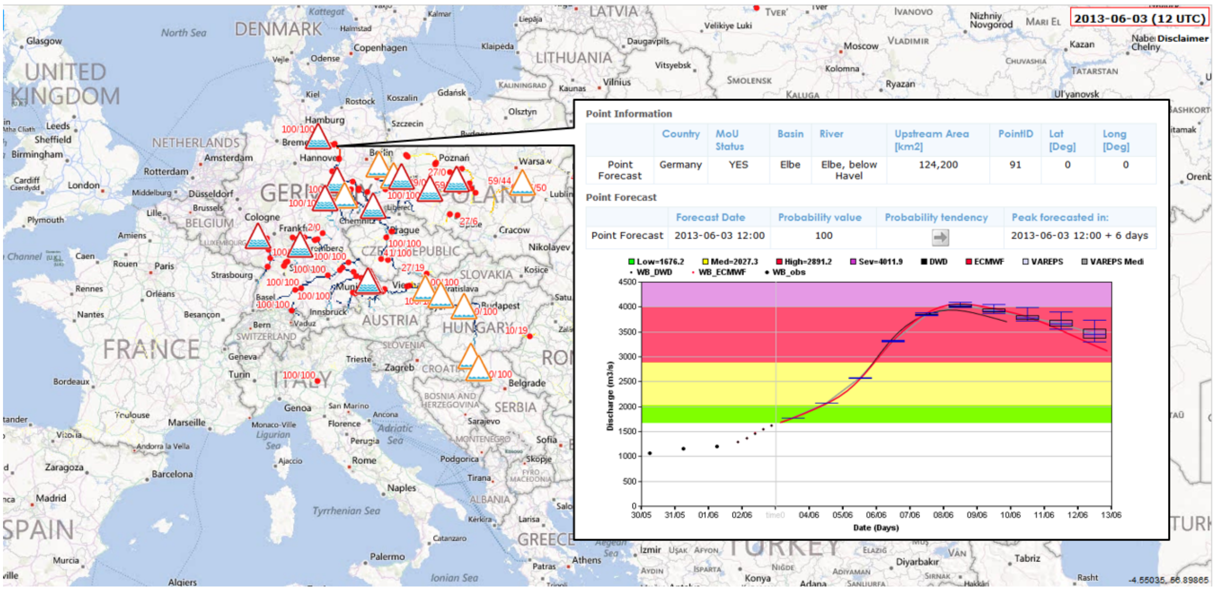

Figure 12: EFAS active alerts (red) and watches (orange) on 3 June 2013, and multi-model streamflow prediction for the Elbe River at Wittenberg, Germany, based on 12:00 forecasts on 3 June 2013 and valid for the next 10 days.

the century' in the year 2002 was surpassed by more than half a metre on 9 June 2013.

9.3 Floods on the Balkan in May 2014

Exceptionally intense rainfalls from 13th May onwards following weeks of wet conditions led to disastrous and wide spread flooding in the Balkans, in particular Bosnia-Herzegovina and Serbia. Critical flooding was also reported in other countries including Southern Poland, Slovakia, and the Czech Republic. The events in Bosnia-Herzegovina and Serbia are reported to be the worst in more than 100 years with 44 reported casualties (ECMWF, 2015). Also one person died in each of Croatia and the Czech Republic due to flooding. More than a million inhabitants are estimated to be affected by this flood event. Both Bosnia-Herzegovina and Serbia activated the EU Community Mechanism for help in the afternoon of the 15th May and again on the 17th for further assistance for Bosnia-Herzegovina. EFAS started providing the relevant national authorities and the ERCC with EFAS notifications from the 11th May onwards (Figures 13 and 14).

10 Conclusions

Following a devastating, trans-national flood event affecting several countries in Europe, the development of a pan-European flood forecasting system was launched to enhance the EU's capabilities for flood preparedness and coordination of aid. The European Flood Awareness System (EFAS) has been developed over a 10 year period from 2003 to 2012 before being transferred to a fully operational system under the Copernicus Emergency Management Service providing early flood warnings across Europe. The system has grown from research experiment used to provide forecast information on an ad-hoc basis to a complex operational system in which the hydrological model forms a small part of a sophisticated forecasting chain. This paper represents a snap shot of the current set-up forecasting system including the set-up of different operational centres and all the modelling components. The EFAS operational

Figure 13: EFAS interface showing all EFAS notifications to national authorities based on 12:00 forecasts from the 12th May 2014

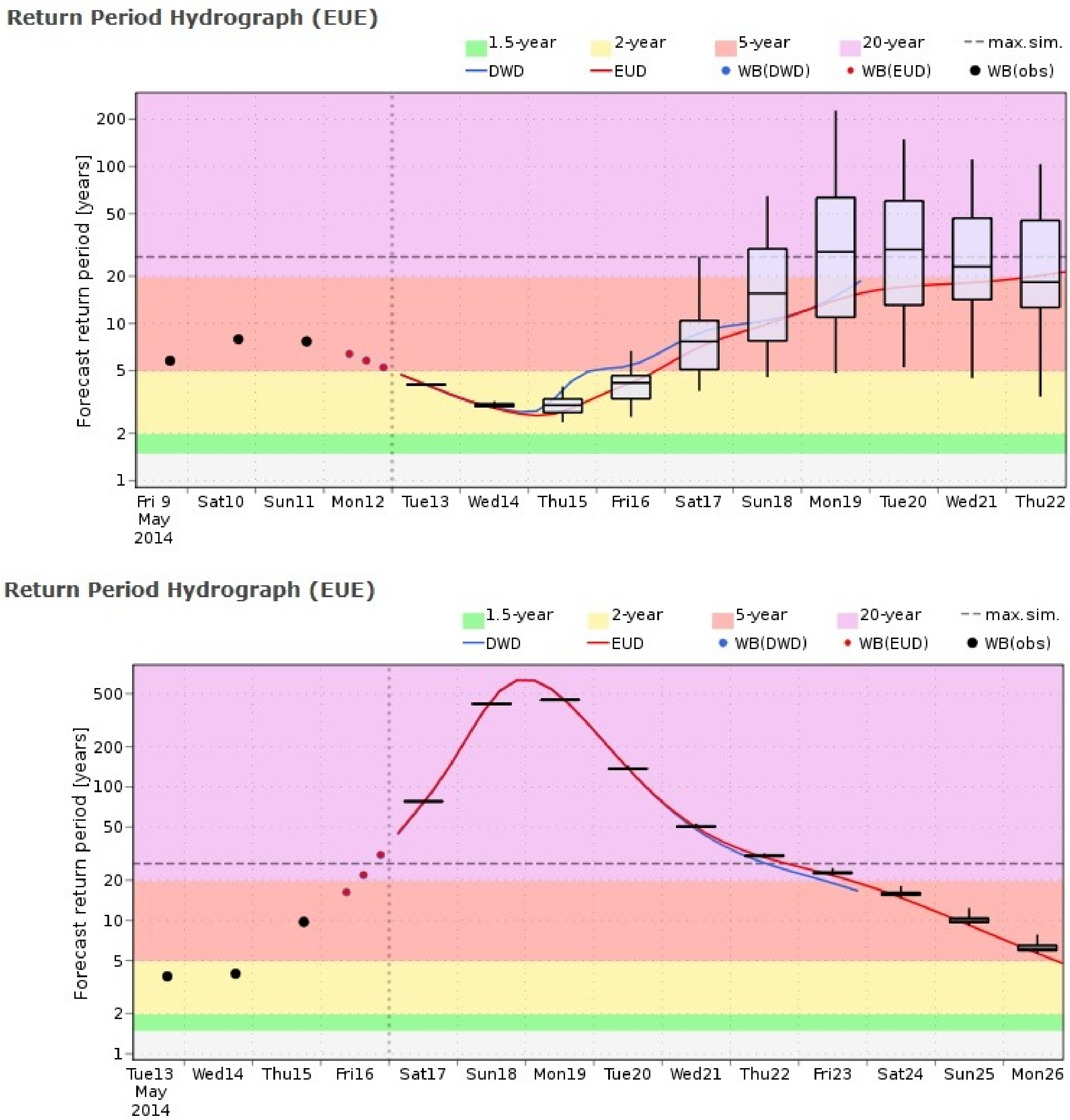

Figure 14: Return period for the flow in river Sava for a point close to Belgrade. The forecasts area initialised 9 May (top) and 13 May (bottom).

forecasting systems can be divided into six major function blocks:

1. **Data acquisition**, which includes the acquisition of all static and dynamic data used to operate the EFAS system incl weather forecasts, hydrological and meteorological observations or national warnings

2. **Model components**, which includes the hydrological model and general set-up of it

3. **Forecast infrastructure**, which relates to the underlying hardware infrastructure and the way the workflow of the forecasting system is managed

4. **Forecast Products**, which includes all products produced as part of the forecast including flood alerts, post-processing and auxiliary information such as rainfall animations or soil moisture/snow anomaly maps

5. **Forecast dissemination**, which deals will all aspects of disseminating products and as such includes the web site and data distribution services

6. **Performance monitoring**, which includes the monitoring of the technical system performance and reliability as well as statistical skill of the forecasts and warnings

This paper demonstrates how these function blocks successfully performed in two major floods across Europe in 2013 and 2014.

The described systems in continuously evolving by, for example, adapting to new temporal and spatial resolutions from the forcings (Wetterhall et al., 2011); adding and inventing new products to push the limits of predictability further in the future (Lavers et al., 2014; Thielen et al., 2009b); probing new methods such as data assimilation (Neal et al., 2009); exploring new avenues for decision making (Dale et al., 2012; Demeritt et al., 2012; Pappenberger and Brown, 2012; Ramos et al., 2013); transferring experience to new geographical domains such as Africa or China (He et al., 2010; Thiemig et al., 2014, 2010); or balancing the end user needs of a higher resolution information with scientific and operational demands (Beven et al., 2014; Beven and Cloke, 2012; Wood et al., 2011).

The latter is also a challenge which is key for many operational flood forecasting systems and whose challenges were generalized by Pagano et al. (2014) as: making the most of available data; making accurate predictions; turning forecasts into effective warnings; and operating a reliable operational service. It has been demonstrated that an early flood warning systems such as EFAS provides an immense monetary benefit (about 400 Euros for every 1 Euro invested, Pappenberger et al., 2015a). Nevertheless, there is a fundamental question whether a reliable service which is only needed for a small fraction of time (during the times of floods) is sustainable financially and scientifically in the long term. It may require a merger of parts of the system components in a wider framework of for example a natural hazard warning service to pool resources and exploit synergies (Pappenberger et al., 2013b), which is an exciting future journey and opportunity.

References

L. Alfieri and J. Thielen. A european precipitation index for extreme rain-storm and flash flood early warning. *Met. Apps*, 22(1):3–13, jun 2012. doi: 10.1002/met.1328. URL http://dx.doi.org/10.1002/met.1328.

L. Alfieri, P. J. Smith, J. T. del Pozo, and K. J. Beven. A staggered approach to flash flood forecasting – case study in the cévennes region. *Adv. Geosci.*, 29:13–20, 2011a. doi: 10.5194/adgeo-29-13-2011. URL http://dx.doi.org/10.5194/adgeo-29-13-2011.

L. Alfieri, D. Velasco, and J. Thielen. Flash flood detection through a multi-stage probabilistic warning system for heavy precipitation events. *Adv. Geosci.*, 29:69–75, 2011b. doi: 10.5194/adgeo-29-69-2011. URL http://dx.doi.org/10.5194/adgeo-29-69-2011.

L. Alfieri, P. Salamon, F. Pappenberger, F. Wetterhall, and J. Thielen. Operational early warning systems for water-related hazards in europe. *Environmental Science & Policy*, 21:35–49, aug 2012a. doi: 10.1016/j.envsci.2012.01.008. URL http://dx.doi.org/10.1016/j.envsci.2012.01.008.

L. Alfieri, J. Thielen, and F. Pappenberger. Ensemble hydro-meteorological simulation for flash flood early detection in southern switzerland. *Journal of Hydrology*, 424-425:143–153, mar 2012b. doi: 10.1016/j.jhydrol.2011.12.038. URL http://dx.doi.org/10.1016/j.jhydrol.2011.12.038.

L. Alfieri, P. Burek, E. Dutra, B. Krzeminski, D. Muraro, J. Thielen, and F. Pappenberger. GloFAS - global ensemble streamflow forecasting and flood early warning. *Hydrology and Earth System Sciences*, 17(3):1161–1175, 2013. doi: 10.5194/hess-17-1161-2013. URL http://dx.doi.org/10.5194/hess-17-1161-2013.

L. Alfieri, F. Pappenberger, F. Wetterhall, T. Haiden, D. Richardson, and P. Salamon. Evaluation of ensemble streamflow predictions in europe. *Journal of Hydrology*, 517:913–922, sep 2014. doi: 10.1016/j.jhydrol.2014.06.035. URL http://dx.doi.org/10.1016/j.jhydrol.2014.06.035.

G. Balsamo, C. Albergel, A. Beljaars, S. Boussetta, E. Brun, H. Cloke, D. Dee, E. Dutra, J. Muñoz-Sabater, F. Pappenberger, P. de Rosnay, T. Stockdale, and F. Vitart. ERA-interim/land: a global land surface reanalysis data set. *Hydrology and Earth System Sciences*, 19(1):389–407, 2015. doi: 10.5194/hess-19-389-2015. URL http://dx.doi.org/10.5194/hess-19-389-2015.

J. Bartholmes, J. Thielen, and M. Kalas. Forecasting medium-range flood hazard on european scale. *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards*, 2(4):181–186, dec 2008. doi: 10.1080/17499510802369132. URL http://dx.doi.org/10.1080/17499510802369132.

J. C. Bartholmes, J. Thielen, M. H. Ramos, and S. Gentilini. The european flood alert system EFAS – part 2: Statistical skill assessment of probabilistic and deterministic operational forecasts. *Hydrology and Earth System Sciences*, 13(2):141–153, 2009. doi: 10.5194/hess-13-141-2009. URL http://dx.doi.org/10.5194/hess-13-141-2009.

K. Beven, H. Cloke, F. Pappenberger, R. Lamb, and N. Hunter. Hyperresolution information and hyperresolution ignorance in modelling the hydrology of the land surface. *Science China Earth Sciences*, 58(1):25–35, nov 2014. doi: 10.1007/s11430-014-5003-4. URL http://dx.doi.org/10.1007/s11430-014-5003-4.

K. J. Beven and H. L. Cloke. Comment on "hyperresolution global land surface modeling: Meeting a grand challenge for monitoring earth's terrestrial water" by eric f. wood et al. *Water Resour. Res.*, 48(1), 2012. doi: 10.1029/2011wr010982. URL http://dx.doi.org/10.1029/2011WR010982.

K. Bogner and M. Kalas. Error-correction methods and evaluation of an ensemble based hydrological forecasting system for the upper danube catchment. *Atmospheric Science Letters*, 9(2):95–102, 2008. doi: 10.1002/asl.180. URL http://dx.doi.org/10.1002/asl.180.

K. Bogner and F. Pappenberger. Multiscale error analysis, correction, and predictive uncertainty estimation in a flood forecasting system. *Water Resour. Res.*, 47(7):n/a–n/a, jul 2011. doi: 10.1029/2010wr009137. URL http://dx.doi.org/10.1029/2010WR009137.

K. Bogner, F. Pappenberger, and H. L. Cloke. Technical note: The normal quantile transformation and its application in a flood forecasting system. *Hydrology and Earth System Sciences*, 16(4):1085–1094, 2012. doi: 10.5194/hess-16-1085-2012. URL http://dx.doi.org/10.5194/hess-16-1085-2012.

K. Bogner, D. Meiner, F. Pappenberger, and P. Salamon;. Korrektur von modell- und vorhersagefehlern und abschätzung der prädiktiven unsicherheit in einem probabilistischen hochwasservorhersagesystem. *Hydrologie und Wasserbewirtschaftung*, 2014. doi: 10.5675/HyWa_2014,2_2. URL http://dx.doi.org/10.5675/HyWa_2014,2_2.

R. Buizza, F. Pappenberger, P. Salamon, J. Thielen, and A. P. de Roo. Eps/efas probabilistic flood prediction for northern italy: the case of 30 april 2009. *ECMWF Newsletter*, 120:10–16, 2009.

P. Burek, J. T. del Pozo, V. Thiemig, P. Salamon, and A. P. de Roo. Das europische hochwasserfrhwarnsystem (efas). *Korrespondenz Wasserwirtschaft*, 2011(4):196–202, Apr 2011. ISSN 1865-9926. doi: 10.3243/kwe2011.04.001. URL http://doi.org/10.3243/kwe2011.04.001.

H. Cloke, J. Thielen, F. Pappenberger, S. Nobert, G. Balint, C. Edlund, A. Koistinen, C. de Saint-Aubin, E. Sprokkereef, C. Viel, and P. S. R. Buizza. Progress in the implementation of hydrological ensemble prediction systems (heps) in europe for operational flood forecasting. *ECMWF Newsletter*, 121, 2009.

H. L. Cloke and F. Pappenberger. Evaluating forecasts of extreme events for hydrological applications: an approach for screening unfamiliar performance measures. *Met. Apps*, 15(1):181–197, 2008. doi: 10.1002/met.58. URL http://dx.doi.org/10.1002/met.58.

M. Dale, J. Wicks, K. Mylne, F. Pappenberger, S. Laeger, and S. Taylor. Probabilistic flood forecasting and decision-making: an innovative risk-based approach. *Nat Hazards*, 70(1):159–172, nov 2012. doi: 10.1007/s11069-012-0483-z. URL http://dx.doi.org/10.1007/s11069-012-0483-z.

A. P. de Roo, B. Gouweleeuw, J. Thielen, J. Bartholmes, P. Bongioannini-Cerlini, E. Todini, P. D. Bates, M. Horritt, N. Hunter, K. Beven, F. Pappenberger, E. Heise, G. Rivin, M. Hils, A. Hollingsworth, B. Holst, J. Kwadijk, P. Reggiani, M. V. Dijk, K. Sattler, and E. Sprokkereef. Development of a european flood forecasting system. *International Journal of River Basin Management*, 1(1):49–59, mar 2003. doi: 10.1080/15715124.2003.9635192. URL http://dx.doi.org/10.1080/15715124.2003.9635192.

A. P. de Roo, J. Thielen, P. Salamon, K. Bogner, S. Nobert, H. Cloke, D. Demeritt, J. Younis, M. Kalas, K. Bódis, D. Muraro, and F. Pappenberger. Quality control, validation and user feedback of the european flood alert system (EFAS). *International Journal of Digital Earth*, 4(sup1):77–90, nov 2011. doi: 10.1080/17538947.2010.510302. URL http://dx.doi.org/10.1080/17538947.2010.510302.

D. Demeritt, H. Cloke, F. Pappenberger, J. Thielen, J. Bartholmes, and M. Ramos. Ensemble predictions and perceptions of risk, uncertainty, and error in flood forecasting. *Environmental Hazards*, 7(2):

115–127, 2007. doi: 10.1016/j.envhaz.2007.05.001. URL http://dx.doi.org/10.1016/j.envhaz.2007.05.001.

D. Demeritt, S. Nobert, H. L. Cloke, and F. Pappenberger. The european flood alert system and the communication, perception, and use of ensemble predictions for operational flood risk management. *Hydrol. Process.*, 27(1):147–157, jun 2012. doi: 10.1002/hyp.9419. URL http://dx.doi.org/10.1002/hyp.9419.

ECMWF. http://www.ecmwf.int/en/about/media-centre/news/2014/severe-floods-balkans, last accessed 14/07/2015, 2015. URL http://www.ecmwf.int/en/about/media-centre/news/2014/severe-floods-balkans.

EEA. Corine land cover raster database 2000. Technical report, European Environment Agency: The European Topic Centre on Terrestrial Environment, 2000. URL http://www.eea.europa.eu/data-and-maps/data/ds_resolveuid/M7OWTVWMMI.

European Commission. Communication from the commission to the european parliament and the council: The european community response to the flooding in austria, germany and several applicant countries - a solidarity-based initiative, 2002. URL http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52002DC0481.

European Commission. Communication from the commission to the european parliament and the council: Towards a stronger european disaster response: the role of civil protection and humanitarian assistance, 2010. URL http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52010DC0600.

European Union. Decision no 1313/2013/eu of the european parliament and of the council of 17 december 2013 on a union civil protection mechanism (1). *Official Journal of the European Union*, 56(L347):924–947, December 2013. doi: 10.3000/19770677.L_2013.347.eng. URL http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32013D1313.

European Union. Regulation (eu) no 377/2014 of the european parliament and of the council of 3 april 2014 establishing the copernicus programme and repealing regulation (eu) no 911/2010 (1). *Official Journal of the European Union*, 57(L122):44–66, 2014. URL http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2014.122.01.0044.01.ENG.

T. G. Farr, P. A. Rosen, E. Caro, R. Crippen, R. Duren, S. Hensley, M. Kobrick, M. Paller, E. Rodriguez, L. Roth, D. Seal, S. Shaffer, J. Shimada, J. Umland, M. Werner, M. Oskin, D. Burbank, and D. Alsdorf. The shuttle radar topography mission. *Rev. Geophys.*, 45(2), 2007. doi: 10.1029/2005rg000183. URL http://dx.doi.org/10.1029/2005RG000183.

B. T. Gouweleeuw, J. Thielen, G. Franchello, A. P. J. D. Roo, and R. Buizza. Flood forecasting using medium-range probabilistic weather prediction. *Hydrology and Earth System Sciences*, 9(4):365–380, 2005. doi: 10.5194/hess-9-365-2005. URL http://dx.doi.org/10.5194/hess-9-365-2005.

T. Haiden, L. Magnussona, I. Tsonevsky, F. Wetterhall, L. Alfieri, F. Pappenberger, P. de Rosnay, J. Muoz-Sabater, G. Balsamo, C. Albergel, R. Forbes, T. Hewson, S. Malardel, and D. Richardson. Ecmwf forecast performance during the june 2013 flood in central europe. *ECMWF Technical Memorandum*, 723, June 2014.

Y. He, F. Wetterhall, H. Bao, H. Cloke, Z. Li, F. Pappenberger, Y. Hu, D. Manful, and Y. Huang. Ensemble forecasting using TIGGE for the july-september 2008 floods in the upper huai catchment: a case study. *Atmospheric Science Letters*, 11(2):132–138, apr 2010. doi: 10.1002/asl.270. URL http://dx.doi.org/10.1002/asl.270.

R. Hiederer and A. de Roo. A european flow network and catchment data set. Technical report, Joint Research Centre, European Commission, 2003.

M. Kalas, M.-H. Ramos, J. Thielen, and G. Babiakova. Evaluation of the medium-range european flood forecasts for the march-april 2006 flood in the morava river. *Journal of Hydrology and Hydromechanics*, 56(2):116–132, 2008.

D. King, J. Daroussin, and R. Tavernier. Development of a soil geographic database from the soil map of the european communities. *CATENA*, 21(1):37–56, jan 1994. doi: 10.1016/0341-8162(94)90030-2. URL http://dx.doi.org/10.1016/0341-8162(94)90030-2.

J. M. V. D. Knijff, J. Younis, and A. P. J. D. Roo. LISFLOOD: a GIS-based distributed model for river basin scale water balance and flood simulation. *International Journal of Geographical Information Science*, 24(2):189–212, feb 2010. doi: 10.1080/13658810802549154. URL http://dx.doi.org/10.1080/13658810802549154.

D. A. Lavers, F. Pappenberger, and E. Zsoter. Extending medium-range predictability of extreme hydrological events in europe. *Nat Comms*, 5:5382, nov 2014. doi: 10.1038/ncomms6382. URL http://dx.doi.org/10.1038/ncomms6382.

A. Montani, D. Cesari, C. Marsigli, and T. Paccagnella. Seven years of activity in the field of mesoscale ensemble forecasting by the COSMO-LEPS system: main achievements and open challenges. *Tellus A*, may 2011. doi: 10.3402/tellusa.v63i3.15816. URL http://dx.doi.org/10.3402/tellusa.v63i3.15816.

J. Neal, G. Schumann, P. Bates, W. Buytaert, P. Matgen, and F. Pappenberger. A data assimilation approach to discharge estimation from space. *Hydrol. Process.*, 23(25):3641–3649, dec 2009. doi: 10.1002/hyp.7518. URL http://dx.doi.org/10.1002/hyp.7518.

V. Ntegeka, P. Salamon, G. Gomes, H. Sint, V. Lorini, M. Zambrano-Bigiarini, and J. Thielen. Efas-meteo: A european daily high-resolution gridded meteorological data set for 1990-2011. Technical report, EC-JRC, Luxembourg: Publications Office of the European Union, 2013.

T. C. Pagano, A. W. Wood, M.-H. Ramos, H. L. Cloke, F. Pappenberger, M. P. Clark, M. Cranston, D. Kavetski, T. Mathevet, S. Sorooshian, and J. S. Verkade. Challenges of operational river forecasting. *J. Hydrometeor*, 15(4):1692–1707, aug 2014. doi: 10.1175/jhm-d-13-0188.1. URL http://dx.doi.org/10.1175/JHM-D-13-0188.1.

F. Pappenberger and J. D. Brown. HP today: on the pursuit of (im)perfection in flood forecasting. *Hydrol. Process.*, 27(1):162–163, aug 2012. doi: 10.1002/hyp.9465. URL http://dx.doi.org/10.1002/hyp.9465.

F. Pappenberger, K. J. Beven, N. M. Hunter, P. D. Bates, B. T. Gouweleeuw, J. Thielen, and A. P. J. de Roo. Cascading model uncertainty from medium range weather forecasts (10 days) through a rainfall-runoff model to flood inundation predictions within the european flood forecasting system (EFFS). *Hydrology and Earth System Sciences*, 9(4):381–393, 2005. doi: 10.5194/hess-9-381-2005. URL http://dx.doi.org/10.5194/hess-9-381-2005.

F. Pappenberger, J. Bartholmes, J. Thielen, H. L. Cloke, R. Buizza, and A. de Roo. New dimensions in early flood warning across the globe using grand-ensemble weather predictions. *Geophysical Research Letters*, 35(10), 2008a. doi: 10.1029/2008gl033837. URL http://dx.doi.org/10.1029/2008GL033837.

F. Pappenberger, K. Scipal, and R. Buizza. Hydrological aspects of meteorological verification. *Atmospheric Science Letters*, 9(2):43–52, 2008b. doi: 10.1002/asl.171. URL http://dx.doi.org/10.1002/asl.171.

F. Pappenberger, K. Bogner, F. Wetterhall, Y. He, H. L. Cloke, and J. Thielen. Forecast convergence score: a forecaster's approach to analysing hydro-meteorological forecast systems. *Adv. Geosci.*, 29:27–32, 2011a. doi: 10.5194/adgeo-29-27-2011. URL http://dx.doi.org/10.5194/adgeo-29-27-2011.

F. Pappenberger, H. L. Cloke, A. Persson, and D. Demeritt. *H*ESS Opinions "on forecast (in)consistency in a hydro-meteorological chain: curse or blessing?". *Hydrology and Earth System Sciences*, 15(7): 2391–2400, 2011b. doi: 10.5194/hess-15-2391-2011. URL http://dx.doi.org/10.5194/hess-15-2391-2011.

F. Pappenberger, J. Thielen, and M. D. Medico. The impact of weather forecast improvements on large scale hydrology: analysing a decade of forecasts of the european flood alert system. *Hydrol. Process.*, 25(7):1091–1113, mar 2011c. doi: 10.1002/hyp.7772. URL http://dx.doi.org/10.1002/hyp.7772.

F. Pappenberger, E. Dutra, F. Wetterhall, and H. L. Cloke. Deriving global flood hazard maps of fluvial floods through a physical model cascade. *Hydrology and Earth System Sciences*, 16(11): 4143–4156, 2012a. doi: 10.5194/hess-16-4143-2012. URL http://dx.doi.org/10.5194/hess-16-4143-2012.

F. Pappenberger, E. Stephens, J. Thielen, P. Salamon, D. Demeritt, S. J. van Andel, F. Wetterhall, and L. Alfieri. Visualizing probabilistic flood forecast information: expert preferences and perceptions of best practice in uncertainty communication. *Hydrol. Process.*, 27(1):132–146, apr 2012b. doi: 10.1002/hyp.9253. URL http://dx.doi.org/10.1002/hyp.9253.

F. Pappenberger, F. Wetterhall, C. Albergel, L. Alfieri, G. Balsamo, K. Brogner, T. Haiden, T. Hewson, L. Magnusson, P. de Rosnay, J. Muoz-Sabater, and I. Tsonevsky. Floods in central europe in june 2013. *ECMWF Newsletter*, 136:9–11, 2013a. pp9-11.

F. Pappenberger, F. Wetterhall, E. Dutra, F. D. Giuseppe, K. Bogner, L. Alfieri, and H. Cloke. Seamless forecasting of extreme events on a global scale, climate and land surface changes in hydrology. In *Proceedings of H01, IAHS-IAPSO-IASPEI Assembly, Gothenburg, Sweden, July 2013 (IAHS Publ. 359, 2013)*, 2013b.

F. Pappenberger, H. L. Cloke, D. J. Parker, F. Wetterhall, D. S. Richardson, and J. Thielen. The monetary benefit of early flood warnings in europe. *Environmental Science & Policy*, 51:278–291, aug 2015a. doi: 10.1016/j.envsci.2015.04.016. URL http://dx.doi.org/10.1016/j.envsci.2015.04.016.

F. Pappenberger, M. Ramos, H. Cloke, F. Wetterhall, L. Alfieri, K. Bogner, A. Mueller, and P. Salamon. How do i know if my forecasts are better? using benchmarks in hydrological ensemble prediction. *Journal of Hydrology*, 522:697–713, mar 2015b. doi: 10.1016/j.jhydrol.2015.01.024. URL http://dx.doi.org/10.1016/j.jhydrol.2015.01.024.

A. E. Raftery, T. Gneiting, F. Balabdaoui, and M. Polakowski. Using bayesian model averaging to calibrate forecast ensembles. *Mon. Wea. Rev.*, 133(5):1155–1174, may 2005. doi: 10.1175/mwr2906.1. URL http://dx.doi.org/10.1175/MWR2906.1.

M.-H. Ramos, J. Bartholmes, and J. T. del Pozo. Development of decision support products based on ensemble forecasts in the european flood alert system. *Atmospheric Science Letters*, 8(4):113–119, 2007. doi: 10.1002/asl.161. URL http://dx.doi.org/10.1002/asl.161.

M.-H. Ramos, J. Thielen, and A. P. de Roo. Prvision hydrologique d'ensemble et alerte avec le systme europen d'alerte aux crues (efas) : cas des crues du bassin du danube en aot 2005. In J.-M. Tanguy, editor, *TRAIT DHYDRAULIQUE ENVIRONNEMENTALE ; Applications des modles numriques en ingnierie 1*, volume 7. HERMES, 2009.

M. H. Ramos, S. J. van Andel, and F. Pappenberger. Do probabilistic forecasts lead to better decisions? *Hydrology and Earth System Sciences*, 17(6):2219–2232, 2013. doi: 10.5194/hess-17-2219-2013. URL http://dx.doi.org/10.5194/hess-17-2219-2013.

D. Raynaud, J. Thielen, P. Salamon, P. Burek, S. Anquetin, and L. Alfieri. A dynamic runoff co-efficient to improve flash flood early warning in europe: evaluation on the 2013 central european floods in germany. *Met. Apps*, pages n/a–n/a, aug 2014. doi: 10.1002/met.1469. URL http://dx.doi.org/10.1002/met.1469.

M. Renner, M. Werner, S. Rademacher, and E. Sprokkereef. Verification of ensemble flow forecasts for the river rhine. *Journal of Hydrology*, 376(3-4):463–475, oct 2009. doi: 10.1016/j.jhydrol.2009.07.059. URL http://dx.doi.org/10.1016/j.jhydrol.2009.07.059.

H. Romang, M. Zappa, N. Hilker, M. Gerber, F. Dufour, V. Frede, D. Bérod, M. Oplatka, C. Hegg, and J. Rhyner. IFKIS-hydro: an early warning and information system for floods and debris flows. *Nat Hazards*, 56(2):509–527, mar 2010. doi: 10.1007/s11069-010-9507-8. URL http://dx.doi.org/10.1007/s11069-010-9507-8.

J.-P. Schulz. Introducing the lokal-modell lme at the german weather service. *COSMO Newsletter*, 5:158–159, 2005. URL http://www.cosmo-model.org/content/model/documentation/newsLetters/newsLetter05/newsLetter_05.pdf.

J. Thielen, J. Bartholmes, M.-H. Ramos, and A. de Roo. The european flood alert system – part 1: Concept and development. *Hydrology and Earth System Sciences*, 13(2):125–140, 2009a. doi: 10.5194/hess-13-125-2009. URL http://dx.doi.org/10.5194/hess-13-125-2009.

J. Thielen, K. Bogner, F. Pappenberger, M. Kalas, M. del Medico, and A. de Roo. Monthly-, medium-, and short-range flood warning: testing the limits of predictability. *Met. Apps*, 16(1):77–90, mar 2009b. doi: 10.1002/met.140. URL http://dx.doi.org/10.1002/met.140.

V. Thiemig, F. Pappenberger, J. Thielen, H. Gadain, A. de Roo, K. Bodis, M. D. Medico, and F. Muthusi. Ensemble flood forecasting in africa: a feasibility study in the juba-shabelle river basin. *Atmospheric Science Letters*, 11(2):123–131, mar 2010. doi: 10.1002/asl.266. URL http://dx.doi.org/10.1002/asl.266.

V. Thiemig, B. Bisselink, F. Pappenberger, and J. Thielen. A pan-african flood forecasting system. *Hydrology and Earth System Sciences Discussions*, 11(5):5559–5597, 2014. doi: 10.5194/hessd-11-5559-2014. URL http://dx.doi.org/10.5194/hessd-11-5559-2014.

M. Werner, J. Schellekens, P. Gijsbers, M. van Dijk, O. van den Akker, and K. Heynert. The delft-FEWS flow forecasting system. *Environmental Modelling & Software*, 40:65–77, feb 2013. doi: 10.1016/j.envsoft.2012.07.010. URL http://dx.doi.org/10.1016/j.envsoft.2012.07.010.

F. Wetterhall, Y. He, H. Cloke, and F. Pappenberger. Effects of temporal resolution of input precipitation on the performance of hydrological forecasting. *Adv. Geosci.*, 29:21–25, 2011. doi: 10.5194/adgeo-29-21-2011. URL http://dx.doi.org/10.5194/adgeo-29-21-2011.

F. Wetterhall, F. Pappenberger, L. Alfieri, H. L. Cloke, J. T. del Pozo, S. Balabanova, J. Daňhelka, A. Vogelbacher, P. Salamon, I. Carrasco, A. J. Cabrera-Tordera, M. Corzo-Toscano, M. Garcia-Padilla, R. J. Garcia-Sanchez, C. Ardilouze, S. Jurela, B. Terek, A. Csik, J. Casey, G. Stankūnavičius, V. Ceres, E. Sprokkereef, J. Stam, E. Anghel, D. Vladikovic, C. A. Eklund, N. Hjerdt, H. Djerv, F. Holmberg, J. Nilsson, K. Nyström, M. Sušnik, M. Hazlinger, and M. Holubecka. HESS opinions "forecaster priorities for improving probabilistic flood forecasts". *Hydrology and Earth System Sciences*, 17(11): 4389–4399, 2013. doi: 10.5194/hess-17-4389-2013. URL http://dx.doi.org/10.5194/hess-17-4389-2013.

E. F. Wood, J. K. Roundy, T. J. Troy, L. P. H. van Beek, M. F. P. Bierkens, E. Blyth, A. de Roo, P. Döll, M. Ek, J. Famiglietti, D. Gochis, N. van de Giesen, P. Houser, P. R. Jaffé, S. Kollet, B. Lehner, D. P. Lettenmaier, C. Peters-Lidard, M. Sivapalan, J. Sheffield, A. Wade, and P. Whitehead. Hyperresolution global land surface modeling: Meeting a grand challenge for monitoring earth's terrestrial water. *Water Resour. Res.*, 47(5), 2011. doi: 10.1029/2010wr010090. URL http://dx.doi.org/10.1029/2010WR010090.

J. Ye, Y. He, F. Pappenberger, H. L. Cloke, D. Y. Manful, and Z. Li. Evaluation of ECMWF medium-range ensemble forecasts of precipitation for river basins. *Q.J.R. Meteorol. Soc.*, 140(682):1615–1628, dec 2013. doi: 10.1002/qj.2243. URL http://dx.doi.org/10.1002/qj.2243.

J. Younis, S. Anquetin, and J. Thielen. The benefit of high-resolution operational weather forecasts for flash flood warning. *Hydrology and Earth System Sciences*, 12(4):1039–1051, 2008a. doi: 10.5194/hess-12-1039-2008. URL http://dx.doi.org/10.5194/hess-12-1039-2008.

J. Younis, M.-H. Ramos, and J. Thielen. EFAS forecasts for the march - april 2006 flood in the czech part of the elbe river basin - a case study. *Atmospheric Science Letters*, 9(2):88–94, 2008b. doi: 10.1002/asl.179. URL http://dx.doi.org/10.1002/asl.179.

Z. Zajac, M. Zambrano-Bigiarini, P. Salamon, P. Burek, A. Gentile, and A. Bianchi. Calibration of the lisflood hydrological model for europe - calibration round 2013. Technical report, Joint Research Centre, European Commission, 2013.

M. Zambrano-Bigiarini and R. Rojas. A model-independent particle swarm optimisation software for model calibration. *Environmental Modelling & Software*, 43:5–25, may 2013. doi: 10.1016/j.envsoft.2013.01.004. URL http://dx.doi.org/10.1016/j.envsoft.2013.01.004.

Acknowledgements

The authors wish to acknowledge that the ongoing operation and develop of EFAS has benefited from the contribution of many people, to numerous to name, and has received funding from multiple sources.