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METEOROLOGY

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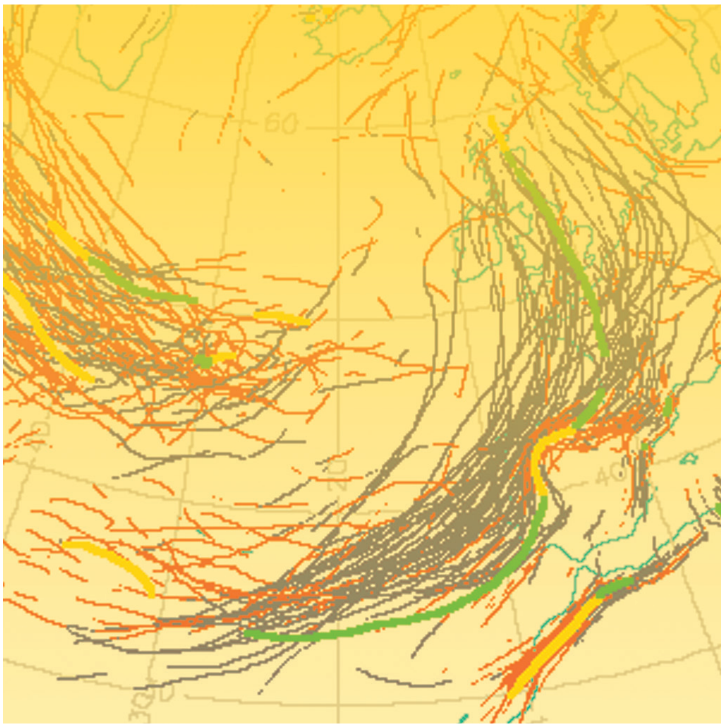

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# Progress in the implementation of Hydrological Ensemble Prediction Systems (HEPS) in Europe for operational flood forecasting

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The past decade has seen the operational flood forecasting community increasingly using Hydrological Ensemble Prediction Systems (HEPS) for their forecasts. Many research studies over the past decade have shown that HEPS-based forecasts add value and can increase warning lead times. However, despite this, at present only a few flood forecasting centres around the world implement HEPS flood forecasting systems operationally (for a summary see *Cloke & Pappenberger,* 2009). There are many reasons for this, including a range of scientific, technical and cultural issues. For example, HEPS must receive and process large amounts of data generated by medium-range Ensemble Prediction System (EPS) weather forecasts (*Thielen et al.,* 2008; *Zappa et al.,* 2008). Furthermore, the computational burden of computing the flood forecasts themselves is also significant, as are the difficulties in understanding how best to base flood warning decisions on probabilistic forecasts.

Recent progress in early flood warning and system development was reviewed at the 4th Annual Workshop of European Flood Alert System (EFAS) held at ECMWF – see Box A.

In this communication, six European HEPS-based flood forecasting systems are briefly reviewed to encourage the further operational uptake of HEPS within the operational flood forecasting community. The excellent set of studies which demonstrate the potential for improving forecasts are not repeated here (see a review in *Cloke & Pappenberger,* 2009). Instead, this work concentrates on discussing how the six HEPS moved from research to operational status and describing current flood forecasting practice based on these HEPS.

### 4th Annual Workshop of EFAS (European Flood Alert System), 28–29 January 2009, held at ECMWF — A

The workshop provided a forum for 43 developers and operational forecasters to discuss various topics including:

- The performance of EFAS and the national forecasting systems during flood events in 2008.
- Progress achieved in 2008 in terms of the EFAS development and planned system improvement.
- Research findings related to skill and post-processing of hydrological ensemble forecasting.
- Status of data collection systems in support of EFAS.

Also there was a training session led by ECMWF and EFAS staff on communication of probabilities and the EFAS Information System.

Presentations from the workshop are available from: http://www.ecmwf.int/newsevents/meetings/worksops/2009/EFAS/presentations

More information on EFAS can be found in Thielen et al., 2009, *Hydrology and Earth System Sciences,* 13, 125–140 and at: http://floods.jrc.ec.europa.eu

During the workshop, alongside information on EFAS, five national institutions responsible for flood forecasting from Finland, Sweden, The Netherlands, Hungary and France provided an overview of the implementation of HEPS in their national operational flood forecasting chain. More details about these six institutions are given in Table 1.

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## From research to operational implementation of HEPS in Europe

In order to develop a more complete, probabilistic approach to hydrological prediction in their systems, the institutions represented in Table 1 mostly started using the ECMWF EPS between 1999 and 2000, which is about 10 years after the launch of operational EPS in meteorology. For four of these institutions, EFAS (European Commission), Rijkswaterstaat (The Netherlands), SMHI (Sweden) and VITUKI (Hungary), work with probabilistic flood forecasting began through participation in the EU FP5 research project 'European Flood Forecasting System' (EFFS) (de *Roo et al.,* 2003). Some National Meteorological Services also instigated ideas about probabilistic-based hydrological forecasts in their national institutions (e.g. SYKE in Finland, SMHI in Sweden and SCHAPI in France). Knowledge exchange within the European flood forecasting community helped foster the development of HEPS: for example, the EFAS project contributed to the introduction of EPS-based flood forecasting to SCHAPI from 2005 onwards, shortly after the SCHAPI was founded.

At the time of writing (July 2009), the situation is as follows.

- Only SMHI and SYKE are routinely using HEPS for operational flood forecasts, including decision makers interacting with the forecasts.
- EFAS is currently running an HEPS in a pre-operational mode and disseminates results to the flood forecasting expert end-users in European National Hydrological Institutions.
- Rijkswaterstaat, SCHAPI and VITUKI are still at a more experimental stage.

With the exception of SYKE, which implemented an HEPS without a formal preliminary research phase, the institutions took between 4–8 years before starting to use an HEPS for operational, or at least pre-operational, activities. One major reason for this was that SYKE did not need any significant additional IT and personnel investment to implement EPS-based forecasts and thus could quickly move to an operational phase. SMHI, which also started to use their HEPS relatively quickly, was also able to rely on existing hardware. For all other institutions the setting up an HEPS represented a considerable IT investment due to the heavy computational load and disk storage requirements. However, the benefits of implementing HEPS-based forecasts were seen to be worth this investment.

All the institutions listed in Table 1 use the ECMWF EPS as input to their HEPS, but almost all use these forecasts at a resolution of about 80 km, even though higher-resolution EPS forecasts (at ~50 km) have been available since September 2007. Reasons for this include the increased downloading time of the higher resolution data to the local IT environment, the increased disk storage requirements, and the fact that using EPS data at higher resolution would introduce a discontinuity in the data time series.

Some HEPS use not only the ECMWF-EPS, but also higher-resolution, limited area EPS weather forecasts (which use the ECMWF EPS as initial and boundary conditions) as input to their HEPS: in addition EFAS, Rijkswaterstaat and VITUKI incorporate COSMO-LEPS (the Limited Area Ensemble Prediction System developed within the COSMO consortium to improve the short-to-medium range forecast of extreme and localised weather events). These, higher-resolution LEPS (Limited-area Ensemble Prediction System) weather forecasts are considered to be more suitable and of higher quality for shorter forecasting times.

It is worth mentioning two other areas of research and development. SYKE has started developing and testing the value of HEPS forecasts on a monthly and a seasonal time scale for use in water management, while VITUKI has been assessing the value of a multi-model approach to hydrological probabilistic prediction by incorporating information from the NCEP (National Centers for Environmental Prediction) EPS in addition to the ECMWF EPS. Multi-model EPS are thought to provide higher reliability in the forecasts than single EPS, but more detailed exploitation of the multi EPS THORPEX-TIGGE archive for hydrological applications is needed to provide a better quantitative assessment of such added value for probabilistic flood forecasting (see *Pappenberger et al.,* 2008 and *He et al.,* 2009).

## Visualisation of probabilistic results

Broadly speaking, there are two essential types of visualization used by the six institutions listed in Table 1:

- Spatial overviews in the form of maps – see Figure 1.
- Time series evolution at points – see Figure 2.

The examples in Figures 1 and 2 illustrate that visualizing probabilistic results effectively demands a strategy involving combinations of colours, numerical information and statistical plots, but that there are a range of useful ways of achieving this.

| Country | Hydro-meteorological/ flood forecasting institution | HEPS inputs | Description of HEPS |
|---|---|---|---|
| **Europe** | European Flood Alert System of the European Commission, Joint Research Centre (EFAS) | ECMWF EPS and COSMO-LEPS | European Flood Alert System (EFAS) with Lisflood hydrological model |
| **Hungary** | Water Resources Research Centre (VITUKI) | ECWMF EPS, NWS-NCEP | National Hydrological Forecasting System (NHFS) with several conceptual hydrological model components. |
| **Sweden** | Swedish Meteorological and Hydrological Institute (SMHI) | ECMWF EPS | Hydrologiska Byråns Vattenbalansavdelning Sweden (HBVSv) with HBV hydrological model |
| **Finland** | Finnish Hydrological Service (SYKE) | ECMWF EPS | Watershed simulation and forecasting system (WSFS) with hydrological model of conceptual HBV style |
| **The Netherlands** | Rijkswaterstaat | ECMWF EPS and COSMO-LEPS | Flood Early Warning System (FEWS NL) with hydrological model HBV and routing model SOBEK |
| **France** | SCHAPI (French Hydrometeorological and Flood Forecasting Service) | ECMWF EPS and Arpege EPS | SAFRAN-ISBA-MODCOU (SIM) with land surface model ISBA and hydrogeological model MODCOU |

| | Pre-processing | Post-processing | Research on HEPS began in... | Operational? |
|---|---|---|---|---|
| **Europe** | Height correction of temperature; precipitation correction using ECMWF re-forecasts (in research phase) | ARMAX (in research phase) | 1999 | Yes, 'pre-operational' since 2005 |
| **Hungary** | Global kriging utilizing regional elevation dependents of meteorological elements | – | 2000 | Yes, but only for emergency situations. |
| **Sweden** | Statistical downscaling according to sub-basins | – | 2001/2 | Yes, since 2004 |
| **Finland** | Height correction on temperature and precipitation | Gaussian adjustment for real time hydrological maps | 2000 | Yes, since 2000 for 10 day EPS |
| **The Netherlands** | – | – | 1999 | No, but anticipated by end of 2009 |
| **France** | Statistical and dynamical downscaling | – | 2006 | No, but in test phase since 2008 |

**Table 1** From research to operational implementation: six examples of flood forecasting systems in Europe that use ECMWF EPS weather forecast inputs. For references to the individual forecast systems see *Cloke & Pappenberger* (2009).

**a** Example from EFAS **b** Example from SMHI

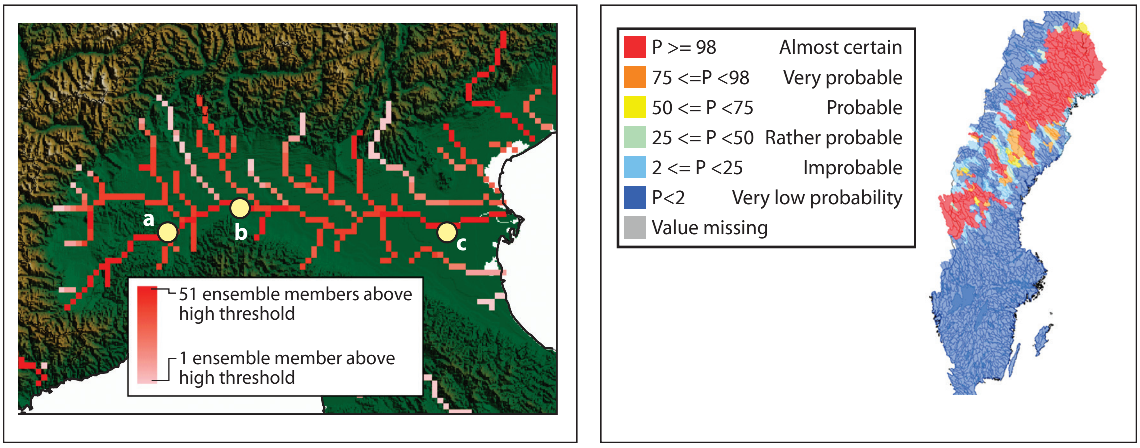


**Figure 1** Example of flood probability maps from (a) EFAS showing the combined flood probability of exceeding the EFAS high flood alert from 3–10 days in advance for river pixels only from a forecast from 28 April 2008 and (b) SMHI showing the probability of exceeding the national flood level 1 which corresponds to a 2–10 year return period for May 2008. In both examples the flood threshold levels correspond roughly to return periods of 210 years.


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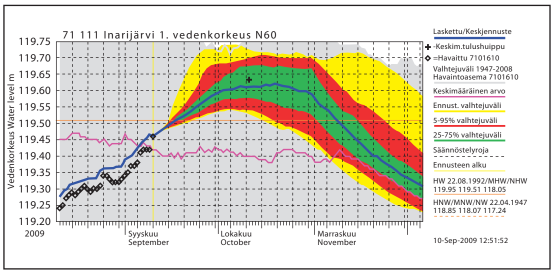
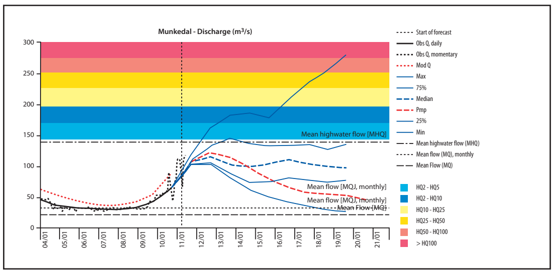
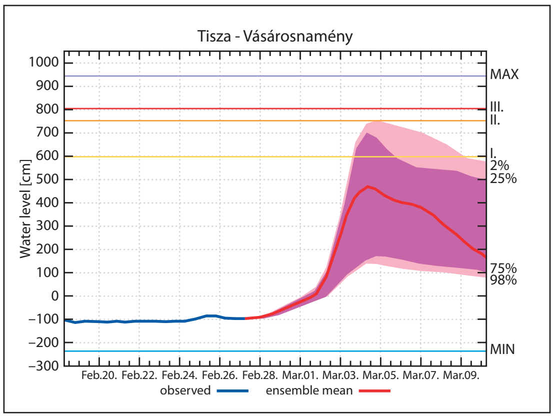
**a** Example from SYKE



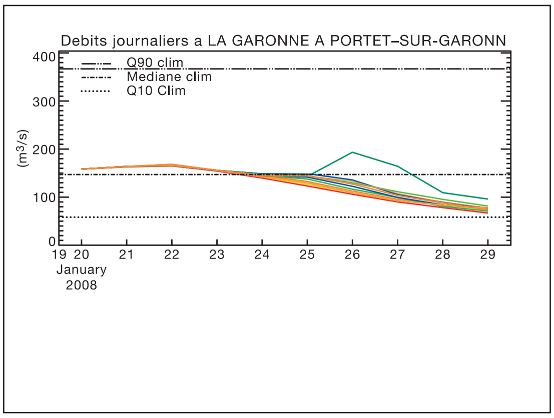

**b** Example from SMHI



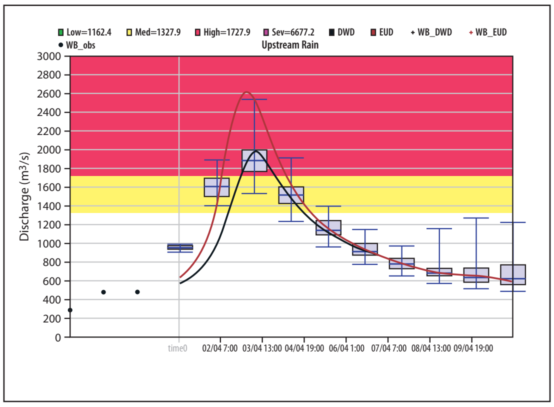

**c** Example from VITUKI



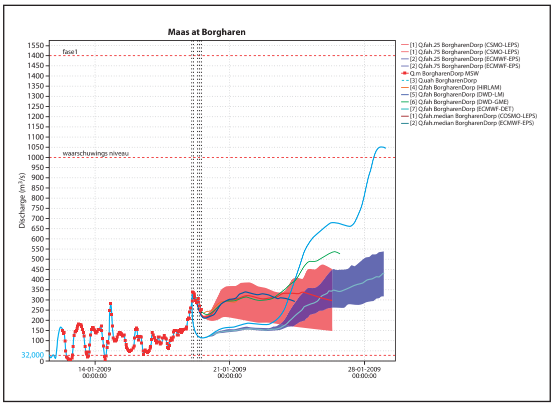

**d** Example from SCHAPI




**e** Example from EFAS




**f** Example from Rijkswaterstaat




**g** Example from EFAS

| Forecast Day | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| DWD | | | | | | | | | | |
| ECMWF | | | | | | | | | | |
| EUE > HAL | | 9 | 42 | 5 | | | | | | |
| EUE > SAL | | | | | | | | | | |
| COS > HAL | | 16 | 16 | 16 | 1 | | | | | |
| COS > SAL | | | | | | | | | | |

**h** Example from VITUKI

| River | Station | 2008.03.01 6:00 | 2008.03.01 18:00 | 2008.03.02 6:00 | 2008.03.02 18:00 | 2008.03.03 6:00 | 2008.03.03 18:00 | 2008.03.04 6:00 |
|---|---|---|---|---|---|---|---|---|
| Túr | Garbolc | 16 | 53 | 135 | 230 | 295 | 331 | 352 |
| Bodrog | Bodrogszerdsahely | 355 | 376 | 439 | 535 | 617 | 663 | 685 |
| | Felsőberecki | 268 | 288 | 346 | 425 | 484 | 524 | 547 |
| | Sárospatak | 281 | 294 | 335 | 402 | 458 | 496 | 512 |
| Fekete Körös | Tenkefürdő | 129 | 163 | 302 | 408 | 436 | 415 | 361 |
| | Talpas | 145 | 162 | 305 | 593 | 703 | 736 | 721 |
| | Nagyzerénd | 136 | 146 | 192 | 322 | 511 | 693 | 781 |
| | Ant | 75 | 94 | 143 | 264 | 411 | 565 | 663 |

**Figure 2** Examples of time series information at particular locations from various flood forecasting institutions

***Spatial overview maps***

Spatial overview maps are produced by EFAS and SMHI. EFAS produces maps with a combined flood probability value for each river pixel in the map. This value is calculated from flood models which use the full set of 51 members from the ECMWF EPS and 2 weighted runs based on the single, high-resolution forecasts from ECMWF and the German Weather Service (DWD) (Figure 1a). The values shown represent the probability of exceeding two flood threshold levels (e.g. high alert level and severe alert level) which have been previously calculated for every pixel in the map. The information is published on a password protected website for the flood forecasting experts of the EFAS partner network. SMHI publishes similar information (based on HEPS only) but based on statistical calculations on sub-catchment level (Figure 1b) and for three flood threshold levels, which correspond to the national warning levels for hydrology. For ease of access, the maps are published for the civil protection services in the provinces on a public website, but the pages are hidden and thus the link must be known by the end-users before it can be accessed. Therefore this measure ensures that the access to the data are fast but that it can only viewed by experts that have previously been trained on the product.

***Time series information***

All institutions visualize river level time series information, usually summarised as either percentiles or quantiles of the ensemble flood forecast members. Typical intervals are minimum/maximum, 25%, 50% and 75%. In some cases the probabilities are expressed as coloured shaded areas (Figure 2a) or as lines (Figure 2b). Critical thresholds are plotted as lines (Figure 2b) or shaded areas (Figure 2c). All representations include the median. Usually continuous line diagrams are used, with SCHAPI presenting results also as an ensemble of individual hydrographs (spaghetti plot) (Figure 2d).

EFAS shows box-plot diagrams summarizing the EPS results in daily information of quantiles, but also shows in the same diagram the results based on the higher-resolution deterministic forecasts (Figure 2e). Through a different representation Rijkswaterstaat can actually visualize results from multiple EPS and poor-man ensembles in one complex diagram, but without losing clarity of information (Figure 2f).

Visualizing information as threshold exceedance has the advantage that the consistency between different forecasts is also visually represented at a glance. For example, Figure 2g clearly shows that all flood forecasts (based on DWD and ECMWF single high-resolution forecasts as well as on the ECMWF-EPS and the COSMO-LEPS) predict the exceedance of the EFAS high flood threshold for day 2 (2 April). The EFAS high flood alert threshold (HAL) is indicated by the red colour, the EFAS severe alert threshold (SAL) by purple. The numbers in the boxes represent the number of EPS members exceeding the corresponding EFAS flood threshold. In this case none of the ensemble members predict the exceedance of the severe alert level (SAL). The consistency between multiple forecasts can be a useful criterion for decision making.

The analysis of two years of EFAS forecasts by *Bartholmes et al.* (2009) suggested that taking into account persistence in the forecasts can reduce the number of false alarms in early flood warning. Consequently the persistence of forecasts from one forecasting day to another is also represented by some systems (not shown here).

VITUKI has opted for a similar representation but instead of showing results of different forecasts in one diagram, the exceedance of thresholds at different locations are shown. The stations are clustered by river basin and listed by upstream position (Figure 2h).

## Verification of probabilistic flood forecasts

Verification of flood forecasts is an important issue for establishing trust in, and the value of, an operational system, and this becomes especially important in probabilistic flood forecasting systems. However this has proved to be difficult for extreme events such as floods. Skill scores for ‘normal’ conditions are computed using a long time series or a large number of cases. They have low uncertainty, are statistically sound and reflect long-term forecast performance. However, a statistically sound evaluation of extreme flood events (e.g. return periods of once every 50 to 100 years) is practically impossible to achieve, since there will probably never be enough events to verify the probability distributions. What is important is that a transparent evaluation is carried out on the longest time series of forecasts available.

For many reasons, flood forecasting centres tend not to publish their skill scores (e.g. hit rates, flood predicted correctly, and false alarm rates, flood predicted when no flood happened) on their website, neither in a qualitative nor quantitative form. However, practice is beginning to change. For example, since the beginning of 2008, EFAS has published a monthly qualitative summary of their flood alerts listing to whom the alerts were sent and if flooding or high water was reported, and skill score calculation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and publication is currently being implemented. With new products continuously being added to forecasting systems, skill assessment is difficult and until a sufficient number of time series are available, these must be evaluated visually and by simple scoring.

For the five national HEPS presented in Table 1, a range of visual comparison and skill score comparisons are currently used internally. For example, VITUKI assesses skill by comparing the Nash Sutcliffe values of their HEPS with the naive forecast. Also SMHI evaluates forecasts using several statistical measures including both threshold and percentile based scores (see *Olsson & Lindstrom,* 2008). Other organisation, complement verifications by benchmarking their forecasts, for example, the forecasts issued by SHAPI is in the process of being compared to the EFAS system.

## Communication of probabilistic flood forecasts

Interpreting probabilistic forecasts is not straightforward. Whilst single forecasts provide an easier-to-interpret (yes-or-no) answer for end-users, probabilistic forecasts by their nature shift responsibility towards the end-user for the interpretation of results for decision making. For example, what is the minimum probability value when it makes sense to issue a warning for a severe flood event? Since the minimum probability is linked to the cost/loss ratio of taking a protective action (see the example and discussion in *Buizza et al.,* 2007), the end-users are the only ones with the information (i.e. the cost/loss ratios) to be able to define it. Are these probabilities thresholds the same for medium and severe events? For end-users that are used to having forecasts that predict an exact amount of flooding at a particular point in time, how can they begin to use probabilistic information instead?

Increased communication between the developers of probabilistic systems and the end-users, and more targeted, end-user training can help in identifying the correct answer to these questions. End-users need to become familiar with probabilistic forecast products. In particular, they need to understand exactly what probabilistic forecasts are (and what they are not), and in what ways they are more useful than single, yes-or-no forecasts (such as better potential for early warning and capturing uncertainty). Commonly used training approaches used by EFAS and other flood forecasting centres range from lectures and games in an artificial setting to training in realistic case studies and in situ training. For example, EFAS trains end-users using case studies of real flood events from Europe and thus allows a realistic participatory learning approach. In these case studies, participants have to undertake role playing where they must make decisions and issue warnings to civil protection based on a replay of real flood forecasts. SHAPI communicates by daily briefings with regional forecasting centers. SMHI has a strong communication network with their end-users and has chosen to organize training on HEPS flood forecasts within the local authorities in Sweden. This is likely to be very important if probabilistic forecasting is to be adopted by such end-users.

## Outlook for probabilistic flood forecasts

Ensemble flood forecasting has emerged as the state of the art in medium-range flood forecasting over the last five to six years. Europe is at the forefront of exploiting a probabilistic approach in flood forecasting. The evidence points to more and more operational flood forecasting centres looking to use the ECMWF-EPS and/or higher-resolution, limited area ensemble systems (e.g. COSMO-LEPS) in their HEPS to increase the early warning capacity of their systems. While achievements in implementing HEPS are significant and should not be downplayed, the authors of this communication think that more research is needed to further improve the current systems, and that further effort should be put into visualizing, verifying, developing user-specific applications for, and communicating the value of probabilistic flood forecasts.

## Further reading

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