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HESS Opinions
"Forecaster priorities for improving probabilistic flood forecasts"

F. Wetterhall[1], **F. Pappenberger**[1], **L. Alfieri**[1], **H. L. Cloke**[2], **J. Thielen-del Pozo**[3], **S. Balabanova**[4], **J. Daňhelka**[5], **A. Vogelbacher**[6], **P. Salamon**[3], **I. Carrasco**[7], **A. J. Cabrera-Tordera**[8], **M. Corzo-Toscano**[8], **M. Garcia-Padilla**[8], **R. J. Garcia-Sanchez**[8], **C. Ardilouze**[9], **S. Jurela**[10], **B. Terek**[10], **A. Csik**[11], **J. Casey**[12], **G. Stankūnavičius**[13], **V. Ceres**[14], **E. Sprokkereef**[15], **J. Stam**[15], **E. Anghel**[16], **D. Vladikovic**[17], **C. Alionte Eklund**[18], **N. Hjerdt**[18], **H. Djerv**[18], **F. Holmberg**[18], **J. Nilsson**[18], **K. Nyström**[18], **M. Sušnik**[19], **M. Hazlinger**[20], and **M. Holubecka**[20]

[1]European Centre for Medium Range Weather Forecasts, Reading, UK
[2]University of Reading, Reading, UK
[3]European Commission, Joint Research Centre, Ispra, Italy
[4]National Institute of Meteorology and Hydrology, Sofia, Bulgaria
[5]Czech Hydrometeorological Institute, Prague, Czech Republic
[6]Bayerisches Landesamt für Umwelt, Augsburg, Germany
[7]Confederación Hidrográfica del Ebro, Zaragoza, Spain
[8]Environmental Information Network of Andalusia, Cuenca, Spain
[9]Service Central d'Hydrométéorologie et d'Appui à la Prévision des Inondations, Toulouse, France
[10]Hydrological and Meteorological Service Croatia, Zagreb, Croatia
[11]Environmental Protection and Water Management Research Centre, Budapest, Hungary
[12]Office of Public Works, Dublin, Ireland
[13]Department of Hydrology and Climatology, Vilnius University, Vilnius, Lithuania
[14]State Hydrometeorological Service, Ghimet, Moldova
[15]Rijkswaterstaat, Lelystad, the Netherlands
[16]National Institute of Hydrology and Water Management, Bucharest, Romania
[17]Republic Hydrometeorological Service of Serbia, Belgrade, Serbia
[18]Swedish Meteorological and Hydrological Institute, Norrköping, Sweden
[19]Slovenian Environment Agency, Ljubljana, Slovenia
[20]Slovak Hydrometeorological Institute, Bratislava, Slovakia

Correspondence to: F. Wetterhall (fredrik.wetterhall@ecmwf.int)

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Abstract. Hydrological ensemble prediction systems (HEPS) have in recent years been increasingly used for the operational forecasting of floods by European hydrometeorological agencies. The most obvious advantage of HEPS is that more of the uncertainty in the modelling system can be assessed. In addition, ensemble prediction systems generally have better skill than deterministic systems both in the terms of the mean forecast performance and the potential forecasting of extreme events. Research efforts have so far mostly been devoted to the improvement of the physical and technical aspects of the model systems, such as increased resolution in time and space and better description of physical processes. Developments like these are certainly needed; however, in this paper we argue that there are other areas of HEPS that need urgent attention. This was also the result from a group exercise and a survey conducted to operational forecasters within the European Flood Awareness System (EFAS) to identify the top priorities of improvement regarding their own system. They turned out to span a range of areas, the most popular being to include verification of

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an assessment of past forecast performance, a multi-model approach for hydrological modelling, to increase the forecast skill on the medium range (> 3 days) and more focus on education and training on the interpretation of forecasts. In light of limited resources, we suggest a simple model to classify the identified priorities in terms of their cost and complexity to decide in which order to tackle them. This model is then used to create an action plan of short-, medium- and long-term research priorities with the ultimate goal of an optimal improvement of EFAS in particular and to spur the development of operational HEPS in general.

1 Introduction

Flood forecast systems are the chief instrument used to inform decision makers of oncoming floods. Coupled hydrometeorological prediction systems are the most widely used strategy in operational flood forecasting in which observations and forecasts are used together with hydrological and hydraulic models (Schaake et al., 2006; Addor et al., 2011; Pappenberger et al., 2011; He et al., 2011; Demeritt et al., 2013; Pappenberger and Brown, 2013). These systems are in place in many parts of the world, and examples of operational (or semi-operational) systems are listed in Table 1 (Pappenberger et al., 2013a). These systems are constantly under development regarding a number of aspects (Table 2). To be clear on the terminology, in this paper we define a *forecaster* as the expert user of a forecasting system who then disseminates the forecast to the *end user*, with some knowledge of the system. Furthermore, the end user might also be a *decision maker*, but not necessarily.

There are always challenges in balancing the integration of new research and the development of forecasting systems according to what operational forecasters might prioritise. Implementing and adequately testing state-of-the-art research developments within operational systems can be very rewarding, as evidence of improving forecast skill demonstrates (Pappenberger et al., 2011). Resources for development of operational systems are on the other hand often limited, and subsequently only individual elements of a system can be prioritised for development. There is a lack of guidance on what improvements are most crucial for operational forecasting systems and how research and development are focused to accommodate these. For the sake of argument, we propose a simple model of ranking priorities in terms of financial cost and technical complexity to optimise the resources available for HEPS development. This paper sets out to (1) provide a discussion of the user preferences in current HEPS, (2) identify the most important development and research priorities in operational HEPS; and (3) suggest a strategy to achieve these priorities and map the road to future forecasting tools with the limited available resources in mind. This opinion paper spawned from the results of a group exercise at the 7th annual European Flood Awareness System (EFAS) workshop, which was held 12–13 June 2012 at the Swedish Meteorological and Hydrological Institute (SMHI) in Norrköping, Sweden, followed by an individual survey conducted via email to the workshop participants.

2 Background

2.1 Areas of potential improvements of HEPS

Priorities on what improvements are necessary vary according to the system in use, geographical conditions and forecaster needs. The urge to improve forecasting of floods is not surprisingly often triggered by severe events, such as the flooding in Sweden in 2000 (SOU 2007:60, 2007) and in the UK in 2007 (Pitt, 2008). The severe flooding in the Danube and Elbe in 2002 was the starting point for the development of EFAS (see Section 2.3). From these reports, the prioritised improvements can be broadly divided into four categories:

1. *Process-driven improvements*: a desire to include more of the hydrological processes of flooding in the system (e.g. better representation of snowmelt processes, flood wave routing or parameterisation of unrepresented processes such as debris blocking and ice jams);

2. *Expansion of the limits of the forecasting system*: for example the redesign and use of the system for the detection of a wider range of phenomena, such as to capture local flash floods or urban surface water flooding or to provide forecasts in areas where verification is difficult (Brown et al., 2010; Liechti et al., 2013; Silvestro and Rebora, 2012);

3. *Improving the dissemination platform*: for example to include uncertainty information and tools to evaluate forecast skill. This can also include adding other kinds of metadata, such as system performance during calibration/validation and geographic layers of population density and economically valuable areas.

4. *Need for decision support information*: for example how to translate river discharge forecasts into preventive action or mitigation.

2.2 Forecast dissemination and communication

The decision to act on forecast information is often guided by experience, but as systems become more complex there is also an increasing need for a more rigorous and structured guidance of what actions to take in specific situations and how to interpret forecasts best (Zappa et al., 2013; Demeritt et al., 2007, 2013; Pappenberger et al., 2013b; Frick and Hegg, 2011; Ramos et al., 2010). With the technology available today, an automatic system can provide forecasts and raise alarms, but unforeseen errors can still cause false

Table 1. Forecast centres with operational or pre-operational HEPS.

Forecast centre name	Provider	Domain	Reference
European Flood Awareness System (EFAS)	European Commission (Copernicus)	Europe	http://www.efas.eu, Thielen et al. (2009); Bartholmes et al. (2009)
Global Flood Awareness System (GloFAS)	European Commission (JRC)/ECMWF	Global	http://www.efas.eu, Alfieri et al. (2013)
Flood-PRObabilistic Operational Forecasting System (FLOOD-PROOFS)	Compagnia Valdostana delle Acque (CVA) S.p.a	Valle d'Aosta (northern Italy)	http://www.cimafoundation.org/, Laiolo et al. (2013)
Joint Flood Forecasting System	Environment Agency/Met Office	UK	http://www.ffc-environment-agency.metoffice.gov.uk/, Price et al. (2012)
Climate Forecast Applications in Bangladesh (CFAB)	Consortium of Bangladeshi and international organisations and institutes	Bangladesh	http://cfab.eas.gatech.edu/cfab/cfab.html, Webster et al. (2010)
EDF-EPS	EDF	France and Rhine	http://www.lthe.fr/PagePerso//chardon/doc/chardonEGU2012.pdf
Hydrologic Ensemble Forecasting Service (HEFS)	US National Weather Service	USA	CN River Forecast Center, Demargne et al. (2013)
Meteorological Model Ensemble River Forecasts (MMEFS)	US National Weather Service	USA	http://www.erh.noaa.gov/mmefs/
Emilia-Romagna Warning operational center	Emilia-Romagna Regional Agency Prevention and Environment	Emilia-Romagna Italy – Po basin (northern Italy)	http://hepex.irstea.fr/operational-heps-systems-around-the-globe/
French Hydro-meteorological Ensemble Prediction System	Meteo France/ French Service for Flood Prediction (SCHAPI)	France	http://www.vigicrues.ecologie.gouv.fr/index.php, Thirel et al. (2010a,b)
Watershed simulation and forecasting system (WSFS)	Finnish Environment Institute (SYKE)	Finland	http://www.ymparisto.fi
Swedish flood-forecasting system	Swedish Meteorological and Hydrological Institute (SMHI)	Sweden	http://www.smhi.se/, Arheimer et al. (2011)
Swiss FEWS-HBV, FEWS-PREVAH, FEWS-WaSiM-ETH	Switzerland	Swiss Rivers: Rhine up to Basel, Linth and Sihl, the Emme, the Rhone	http://www.hydrodaten.admin.ch/en/index.html#vorhersagen, Liechti et al. (2013); Zappa et al. (2013)
WSL Flood Forecasting	WSL	Sihl, Ticino, Linth and Thur	http://hydro.slf.ch/sihl/chysghl/, Liechti et al. (2013); Zappa et al. (2013)
3Tier	3Tier	Various	http://www.3tier.com/en/packagedetail/powersight-basin-monitor-forecasting/
BoM	BoM	Australia	http://www.bom.gov.au/water/ssf/index.shtml
Scottish Flood Forecasting Service	SEPA and Met Office	Scotland	http://www.floodforecastingservice.net/

Table 2. Recent developments in operational forecasting.

Aspect of development	Reference
Choice and combination of meteorological inputs	Olsson and Lindström (2008); He et al. (2009); Liu et al. (2013); Liechti et al. (2013)
Weather forecasting model resolutions	Marty et al. (2013)
Probabilistic ensemble techniques	Cloke and Pappenberger (2009); Marty et al. (2013); Pagano et al. (2013)
Pre-processing	Schaake et al. (2010); Gaborit et al. (2013)
Radar blending	Parkes et al. (2013); Liechti et al. (2013)
Pre/postprocessing	Wilks (2006); Bogner and Pappenberger (2011); Bogner et al. (2012); van Andel et al. (2013); Brown and Seo (2013)
Data assimilation	Liu et al. (2012); Liu et al. (2012)
Hydrological model development	de Roo et al. (2000); Lindström et al. (2010)
Verification	Brown et al. (2010); Liguori and Rico-Ramirez (2013)
Communication and understanding of forecasts	Pappenberger et al. (2013b); Demeritt et al. (2010, 2013); Ramos et al. (2010)

alarms, such as errors in the driving data, the observational network or the modelling system itself. Human interaction is always needed in any early warning system at the final dissemination step. The dissemination is also a way to add information that is not contained within the early warning system (EWS), such as local conditions at the time of flooding. However, a fully streamlined and consistent procedure to issue forecasts would make it easier to evaluate and improve the performance of the system.

Nobert et al. (2010) underlined the importance of effective communication and collaboration in the development of an ensemble forecasting system. They found that the success of HEPS relied on (1) a close working relationship between national forecasters and local institutions, (2) locally tailored and delivered training for HEPS users, (3) active involvement of end users in the design of HEPS and (4) that end users will embrace HEPS if they can see the added value in their daily operational routines. Demeritt et al. (2013) found that institutional obstacles hindered the full embrace of probabilistic forecasts. All of these factors are thus essential to consider when attempting to prioritise of future developments in HEPS.

2.3 The European Flood Awareness System (EFAS)

The European Flood Awareness System (EFAS; Thielen et al., 2009; Bartholmes et al., 2009) provides its members with pan-European overview maps of flood probabilities up to 10 days in advance as well as detailed forecasts at stations where the national services provide real-time data. Since 2011 EFAS has been a part of the Copernicus (previously known as Global Monitoring for Environment and Security) Emergency Management Service and was transferred to operational service in late 2012. More than 30 hydrological services and civil protection services in Europe are part of the EFAS network. The majority of these are hydrological forecasting centres of the European member states with national, regional or local responsibilities and a few civil protection agencies whose access is coordinated through the forecasting centres.

Since the start of the pre-operational run of EFAS in 2006, each year an EFAS annual workshop has been organised, including interactive training sessions for the partners covering topics on meteorological and hydrological ensemble prediction, communication of probability and uncertainty for early warning systems and how this information is disseminated to expert forecasters and end users.

3 Gauging forecaster priorities: a user preference exercise

To start off the discussion, we decided to engage with operational forecasters within the EFAS network to gauge their preferences regarding research and development of HEPS. The forecasters all have different backgrounds and experiences, but they are either involved in EFAS as forecasters, end users or decision makers. The group is not homogenous, which is a strength since it assures that most parts of the system are covered in the discussions.

The first part involved a group exercise in prioritisation of improvements at the EFAS meeting, and the second part was a follow-up questionnaire. Here follows a short summary of the main results; for more details how these were done and a full list of all priorities we refer the reader to the Supplement. In the first exercise the participants in the EFAS meeting were told to have a group discussion in order to identify the one most important priority. They then pitched this idea in front of their peers, who then subsequently voted on all suggestions in order to rank them. The highest ranked pitch was one that suggested a multi-model approach and this priority received almost twice as many votes as the least favourite, to improve standardisation of hydrological data (Table 3). After the highest ranked priority, there were three that were closely grouped together, namely report on past performance, building a European infrastructure and improving the physical model representations.

Part 1 was followed up by an email questionnaire in which the participants were asked to sort all the priorities that came up during the discussions in the EFAS meeting. The results

Table 3. Result after the voting with 10 SEK after the pitch before the expert panel. 268 of originally 300 krona was recovered, meaning a total of 32 krona was kept by the participants. The column "Cat" denotes which category each priority belongs to, and "Rank" which rank the priority was given in the questionnaire.

Priority	Money	Cat.	Rank
Report past performance for the hydrological and meteorological forecasts	55	4	1
Improve standardisation of hydrological data	41	5	7
Improve physical model representations (in particular snow) including better snow forecasting	51	3	10
Introduce more NWP ensembles for meteorological input and introduce multi-model approach for hydrological modelling	70(65*)	3	2/5
Building a European flood forecasting infrastructure	56	1	6

* This topic had a 5-krona piece (and none were distributed), so either the person needed small change, or boosted the topic themselves

Table 4. The five most popular and least popular priorities from the survey.

Best voted	Cat.	Importance	Worst voted	Cat.	Importance
Report past performance for the hydrological and meteorological forecasts	4	1.77	Replace/expand web forum by social networks	1	3.83
Introduce multi-model approach for hydrological modelling	3	1.86	Distinguish between different flood situations	4	3.09
Increase the average skill of the medium-range forecast (> 3 days)	3	1.90	Increase the frequency of forecasts	2	3.08
Education and training of how to use and interpret forecasts	1	1.91	Increase the temporal resolution of the forecast	3	2.91
Improve physical model representations	3	1.96	Blending of national and EFAS forecasts	5	2.68

from the survey partly confirmed the results from the first exercise in terms of the most popular priorities. However, the highest ranked priority from the survey was number 18 – "Report past performance of forecast skill" – which was voted as the second most important in part 1 (Table 4). The most popular priority from part 1, a multi-model system forecasting system, was the second (hydrological models) and fifth (meteorological models) most popular in part 2 (in the questionnaire the questions were divided between the numerical weather prediction (NWP) multi-model system and hydrological multi-model system). Also the other pitched priorities from part 1 scored highly in part 2. The remaining among the top five priorities in in part 2 were "10. Increase the skill of the forecast" and "3. Education and training on how to use forecasts".

The priorities differed substantially between forecasters, and they were classified to belong to five different categories, which were focussed on improving the following: (1) cooperation and collaboration and training between forecasters and modellers, (2) existing decision making tools, (3) the general performance of the forecast, (4) tools to evaluate and compare forecasts, and (5) data quality checking, collection and processing (Table 5). This could imply that there is no consensus on the most important priority, but rather a number of different aspects of the forecasting system that are important. All the suggested topics are fairly separate from each other and require different types of resources. Although this is not surprising given the relatively large group of forecasters from different organisations, it leaves the question open of how we can identify a coherent way forward in HEPS development.

4 What is the way forward in improving HEPS?

Certainly the forecasters as a group have varying priorities; on close inspection, particular aspects of a priority area may be more or less important than the category as a whole. However, in order to discuss thematic priorities with ease they will hereafter be discussed according to the categories in Table 5. These categories are not always clear-cut, and there are some

Table 5. Categories of the research priorities for the EFAS forecast system.

Category	Description
1	More cooperation, training, scenarios, workshops, etc. to improve cooperation between forecasters
2	Improve your existing decision making tools (better graphics, visualisation, frequency of forecasts, etc.)
3	Improve the general performance of the forecast
4	Better tools to evaluate and compare forecasts
5	Improve data collection and processing, e.g. blending techniques, satellite data, remote sensing (radar) data

priorities that fall in more than one category, but they should be seen as merely a means for discussion.

4.1 Improve cooperation between forecasters

There are networks and steps taken to improve cooperation between forecasters, but there is much more effort needed in this area, such as further development of a European flood forecasting infrastructure, which would serve as a common platform of sharing information on flooding. There is also a need and request for training and knowledge exchange between forecasters. There is a designated portion of the EFAS annual meetings devoted to this purpose, and maintaining and further developing these efforts would be important in ensuring forecasters are all aware and trained in state-of-the-art forecasting techniques and that the computational, communicational, educational and personnel exchange networks around Europe are all improved. These priorities were both considered to be very important in our forecaster exercise, especially the education and training priority. This implies that the EFAS network is deemed very important and that the efforts to build a working infrastructure should continue, and even more focus should be put into training courses and exercises.

The use of social forums as a means to disseminate results was the least popular priority. Although this could be an effective way to reach a wider audience with forecast information, forecasters themselves already have known and trusted communication channels with civil protection and other end users. The question was not split into "dissemination" and "information", and this could have influenced the result. Social forums are increasingly used in real time during crisis situations by civil protection agencies (for example during the Sandy Hurricane, in October 2012), but since EFAS is an early warning system, this may not apply here. However, as a forum where news and updates on the present hydrological situation are presented, social media can be a very effective information source during flood situations.

4.2 Improve existing decision making tools

Having sufficient decision making tools is naturally important for forecasters, and areas of priorities ranged from improving the dissemination platform to enhancing the product generation and visualisation of forecasts. This category was the least popular with the forecasters in the exercise taken as a whole, which could imply that the tools available today are sufficient. On the other hand, there might be many ways to improve existing systems to enable the forecasters to have access to more information to make better forecasts, given that they are presented as simple and intuitive as possible. Priorities of a more technical nature (such as to increase the temporal resolution and the frequency of issuing forecasts) ranked amongst the least important, and the priority to increase the spatial resolution of the forecast also ranked lowly. This would imply that the detail in the issued forecasts is of the right order of magnitude, especially for an early warning system such as EFAS. However, the priority to improve the forecast dissemination ranked as the ninth most important overall, indicating that more effort is needed to develop the existing dissemination platforms.

4.3 Improve the general performance of the forecast

Improving the general performance of the forecast is a demand usually made by forecasters of their tools, as it is easy to see from a scientific point of view how improving the reliability and skill of forecasts makes a forecaster's life easier. However, improvements to forecasting systems are usually expensive in terms of resources and time, and the benefit can be difficult to measure.

It is clear that the most important area of priority is to improve the general performance of the systems. What is not clear is whether the forecasters are unhappy with the current performance of the systems they are using, or whether they think it is sufficient, but that it can be further improved. It should also be noted that it is virtually impossible to build a completely failsafe system, and that in the future there will still be missed floods and false alarms. The million dollar question is whether improving the system is really worth the effort, or if other areas should be prioritised instead.

In our exercise, the priorities noted in this category were diverse, ranging from very broad priorities such as "increase the skill of the forecast at certain time ranges" to very specific requests such as improvements of model physics (better representation of snow water equivalent) and multi-model approaches (hydrological as well as meteorological), which e.g. was also the most successful topic in terms of financial investment (Table 4). The inclusion of more models indicates the desire for a better quantification of uncertainty, rather than a sharp forecast. In the survey, meteorological and hydrological multi-model systems were two separate questions, and the forecasters thought it more important to prioritise a hydrological multi-model system. However, the survey was done within the EFAS framework, where forecasters are already using meteorological multi-model system, which could have influenced the results in terms of their priority.

It is a more important priority for the forecasters to improve the forecast in the medium range (> 3 days), rather than the short range (< 3 days; see Supplement). This opinion could also be biased since the EFAS system is an early warning system for the medium range, and the national forecasting centres often have their own systems to predict floods for shorter lead times. However, this contradicts in part the wish for more hydrological models, since most of the skill in the longer lead times depends on the driving meteorological model rather than the hydrological.

4.4 Better tools to evaluate and compare forecasts

Having better tools to evaluate and compare forecasts means that decision making by the forecaster can be made more straightforward and perhaps more transparent. This is especially important as multi-model probabilistic systems become more and more complicated, meaning that forecasters must be able to interpret advanced forecast results and a multitude of sometimes contradictory information.

The priorities in this category range from reporting the skill of the model to having more robust ways to calculate flood frequencies. The priority that received the third most financial investment (see Supplement) in the pitching exercise and the most prioritised from the survey was to include past performance of the model as an aid in the forecasting. Also the priorities to recalculate probabilities and to include more historical data in the system were prioritised.

Clearly, there is a need for tools to evaluate forecasts, but the priority to see past performance could also be seen as a demand for a more transparent system. To have access to previous skill scores can give information on the reliability of the forecast system and also its accuracy. These measures can be used to create more trust in the forecast system and guide a forecaster to make the right decision. However, skill scores are mostly a tool to improve the performance of the forecast and cannot provide information on a single event's a priori predictability.

4.5 Improve data collection and processing

Data collection and processing are the bugbears of hydrological science (Hannah et al., 2011), and it is not surprising that this issue was prioritised by our forecasters. This category deals with data collection, quality checking and processing. The priorities ranged from adding national forecasts to defining a standard for hydrological data exchange. Although, the priority to standardise hydrological data format was selected as the least popular out of the five topics pitched, one should not forget that it was chosen as the most important in the groups. It was also among the top 10 priorities from the survey. This points to the problem of different data formats, and how much effort goes into harmonising databases.

The other priority in this category was the blending of national and EFAS forecasts, which received a very low priority. It is clear that the national systems and EFAS should stay in parallel in the opinion of the forecasters.

4.6 A note on limitations in undertaking forecaster workshop exercises and surveys

In this piece we have built our discussion based on the opinions provided in an exercise and survey undertaken as part of the EFAS annual workshop. How individuals rewarded certain priorities was most probably influenced by how they were presented during the exercise, not only on how much they agreed with the priority. This was also a reason to follow up with a survey, where the priorities were presented more anonymously without the layer of the presentation as well.

It was not within the scope of the survey to ask in-depth questions on the reasons behind each forecaster's choice, which could have revealed underlying agendas to their preferences. For example, the inclusion of more hydrological models in the system could be governed by the wish to include the forecaster's hydrological model of choice, and not necessarily the idea of a full uncertainty system. Such in-depth exploration of priorities is something that is planned for future exploration within the EFAS context.

5 A strategy to improve the forecasting system

Scientific and technical improvements of operational forecast systems are often driven by either the model developers themselves or through catastrophic events that show weaknesses in the system. Even though the former can be justified through a scientific analysis of what is needed to improve the system, it might not always be what the forecasters need. The most important priority for forecasting system development is currently a generally improved forecast skill, as shown by our exercise respondents. We did not specify which parts of the forecasting system that should be improved, so this should be interpreted as an improvement in the overall skill of the system. As the other priorities discussed show, other issues are also important for development. Therefore, more resources should be targeted towards a range of priorities.

As a way forward, we propose to organise the priorities according to their complexity and cost in order to consider which can be addressed immediately and which would need large financial and development investment. This would aid in the future development of HEPS given that the allocated means are limited. Figure 1 shows how the 10 highest ranked priorities would fall within such a diagram. The cost is the estimated effort in terms of resources, which can be both financial and human. The complexity is the estimated level of technical and/or scientific development that is required,

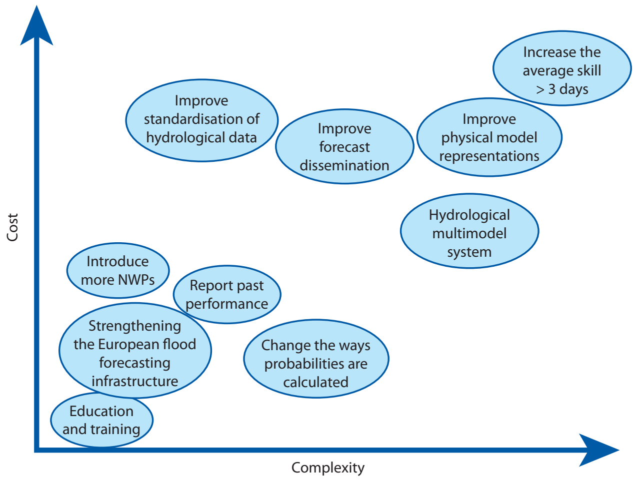

Fig. 1. Schematic view of the relative cost and difficulty of the top 10 priorities from the survey.

which also means that addressing these priorities would take time. A high level of complexity also implies a risk of not accomplishing the goals.

The obvious suggestion is first to pick the "lowest hanging fruits", in terms of cost and complexity, which will yield the highest return from the investment. The more costly and complex improvements should be addressed, but on longer timescales and with well-allocated resources. With this information it is necessary to review the current operational framework and make sure that resources are used optimally, as outlined in the road map below.

5.1 Secure funds for the priorities that yield most benefit to a low cost and with low complexity

Some of the points can fairly easily be addressed. For example there is already an ongoing effort in training and collaboration between forecasters at national and international level through the EFAS and HEPEX networks. This training and collaboration needs to be further developed and maintained to ensure that the forecasts and warnings issued are consistent and that new operational forecasters quickly can gain an understanding of their forecasting tool. A "user guide" for hydrological probabilistic forecasting could be one way to improve interpretation of forecasts. Also e-learning tools designed to show the added benefit of using HEPS could be useful (Ramos et al., 2013).

5.2 Plan and coordinate activities to deal with intermediate cost/complexity priorities

Reporting on past performance through forecast verification scores would be a useful tool to show the benefit of the forecasting system as well as increasing trust in the forecasts. This would allow the forecaster to assess the long-term performance at specific points, as well as how HEPS behaves in typical situations. Also clearly showing calibration and validation results would potentially increase the trust in the system (Demeritt et al., 2013). Research activities are already initiated to address this issue. The issue of a multi-model system is to some extent fulfilled in the meteorological part of many systems (including EFAS) but can be further extended and optimised, for example by including freely available NWPs into the EFAS system.

5.3 Set up a long-term strategy to coordinate research and development activities to address the priorities that are costly and/or complex

A multi-model hydrological system would to a large extent improve the skill and potentially benefit the decision making (Velásquez et al., 2011). However there would be a more explicit accounting of the uncertainty in the predictions, and thus the decisions would potentially have to be taken under an apparently larger uncertainty than in the current format. Such a system would also take a longer time to implement, unless the existing systems agree to share data where they overlap and blend local systems with those at the global and/or regional scale. However, this kind of development was not seen as a priority within the study, and for the time being the systems should be kept separated. Standardisation of hydrological data collection has already been identified as a key element to facilitate the exchange of data for testing and validation of models as well as real-time observations for forecasts. There are projects (e.g. GEOWOW, http://www.geowow.eu/) that are directly or indirectly trying to create standards and databases of easily accessible data, but these efforts needs to be coordinated and extended beyond the lifespan of individual projects.

The priority to improve forecast dissemination would need to address both the technical development of the tools themselves as well as the understanding of how decisions are best made under uncertainty. Many of the suggested priorities in HEPS do not deal with improvement in the models themselves, but rather in the way HEPS are presented and how the output is interpreted. This issue was not covered in the survey, but previous research has pointed to the existing gap between theory and practice when it comes to HEPS (e.g. Demeritt et al., 2010; Nobert et al., 2010). The benefit of using probabilistic forecasts is still not accepted in many institutions in Europe (Demeritt et al., 2013). This area is perhaps not receiving enough attention in terms of funds and efforts, and it is our opinion that more projects and funding should be directed to address these issues.

5.4 Collaboration with the scientific community on long-term improvements of HEPS

The final points on the "wish list" of priorities include improving the physical representations in the used models and a general improvement of the forecast on lead times greater than 3 days. The first could for example concern better descriptions of specific complex non-linear hydrological processes, such as ice dams and flood plain interaction. The latter regards improvement in NWPs, which will improve the medium-range forecasts. Both these priorities are questions that need to be addressed by the research community as a whole, both academic and institutional, and one approach for the operational forecast community is to monitor the scientific progress carefully and incorporate new changes into their system. However, it is also very important to point to deficiencies in the modelling system, both to the hydrological and the meteorological research community, to stimulate research in the areas which would benefit the HEPS community.

6 Conclusions

This opinion paper is the result of an expert workshop during the annual meeting of the partners of the European Flood Awareness System. It was developed from the opinions of a large group of professional flood forecasters on the best ways to improve existing operational flood warning systems. The opinions are mainly from a European perspective.

Often considerable effort and resources are focused on the technical aspects of forecasting systems, whereas dissemination, collaboration and education receive less attention, and this is one of the areas which is a priority for development. Other areas that need more attention are verification of past performance, uncertainty assessments and multi-model approaches. The past performance could be expressed as skill scores for certain points, seasons or situations depending on the need. Uncertainty is already an inherent part of the system as it is built on ensembles of NWPs. A true multi-model system with more than one hydrological model could facilitate structural uncertainty error estimation as well as allow for more robust decisions since potentially a wider range of flow situations could be described. Given the limited resources, we propose a simple model to identify the costs and levels of complexity associated with the most urgent priorities in terms of improving HEPS. From this, a "road map" was derived, where the identified priorities are organised in different categories and dealt with accordingly:

1. secure funds to address the identified priorities that have low cost and complexity;
2. plan and coordinate activities that deal with the priorities with intermediate cost and/or complexity;
3. set up a long-term strategy to coordinate research and development to address the priorities which are costly and/or complex;
4. collaborate with the scientific research community to stimulate activities that have potential to lead to better hydrological forecasts.

The first category focuses on increasing collaboration, training and knowledge exchange between forecasting centres and researchers. The second category addresses relatively straightforward changes to the existing systems, such as verification tools for HEPS and increasing the number of NWPs that contribute to the meteorological driving data. The priorities that fall into this category are achievable with relatively moderate funding and at a low risk. The priorities in category 3 need more concerted research efforts to be accomplished, such as joint research collaboration under the framework programme of the European Commission. Examples of priorities here are how to implement a full multi-model system and better understanding of the decision making under uncertainty. The demand for a multi-model framework does for example highlight the importance in the general search for a flexible model structure. The fourth category consists of priorities that are not achievable through individual projects, but rather through a close collaboration with the research community to emphasise the need to improve the parts of the forecasting chain that are most crucial for HEPS.

A possible platform to discuss the way forward is through the HEPEX community (http://hepex.irstea.fr/). The readers are invited to join the initiative to develop a new science and implementation plan for the Hydrological Ensemble Prediction System experiment for the next decade, which in many parts embraces the priorities identified in this paper (see http://hepex.irstea.fr/science-and-implementation-plan/).

Supplementary material related to this article is available online at http://www.hydrol-earth-syst-sci.net/17/4389/2013/hess-17-4389-2013-supplement.pdf.

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