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Visualising probabilistic flood forecast information: expert preferences and perceptions of best practice in uncertainty communication

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Abstract

The aim of this paper is to improve the communication of the probabilistic flood forecasts generated by Hydrological Ensemble Prediction Systems (HEPS) by understanding perceptions of different methods of visualising probabilistic forecast information. This study focuses on inter-expert communication, and accounts for differences in visualisation requirements based on the information content necessary for individual users. The perceptions of the expert group addressed in this study are important because they are the designers and primary users of existing HEPS. Nevertheless, they have sometimes resisted the release of uncertainty information to the general public because of doubts about whether it can be successfully communicated in ways that would be readily understood to non-experts. In this paper we explore the strengths and weaknesses of existing HEPS visualisation methods and thereby formulate some wider recommendations about best practice for HEPS visualisation and communication. We suggest that specific training on probabilistic forecasting would foster use of probabilistic forecasts with a wider range of applications. The result of a case study exercise showed that there is no overarching agreement between experts on how to display probabilistic forecasts and what they consider the essential information that should accompany plots and diagrams. In this paper we propose a list of minimum properties that, if consistently displayed with probabilistic forecasts, would make the products more easily understandable.

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Introduction

Risk communication is central to international disaster risk reduction strategies (e.g. UN/ISDR 2004; IKSIR 2005; IFRC 2009; Pitt 2007), because preparedness and response measures depend not simply upon the soundness of the underlying scientific risk assessments but also on the effectiveness with which that information is conveyed to those responsible for acting upon it. Given the potential for errors in any scientifically driven product, it is now increasingly recognised that communicating the uncertainty associated with scientific forecasts is as important for risk management as increasing their accuracy and timeliness (NRC 2006). In the specific context of hydro-meteorological modelling, formal assessments of uncertainty are thus now a prominent feature of meteorological, hydro-meteorological and climatological research and forecasting (Cloke and Pappenberger, 2009, Bogner and Pappenberger 2011). While important technical advances have been made in the ability to characterize and quantify hydro-meteorological forecast uncertainty, new tools are required to translate this information into clear and effective visualisations that might be easily communicated to specialist decision makers and the general public at large. The application of ensemble prediction methods to operational flood forecasting has started only recently (Cloke and Pappenberger, 2009). In this still early stage of technical development, the designers of hydrological ensemble prediction systems (HEPS) have relied on conventional visualisation techniques, for example simple ‘spaghetti’ plots or classical box-plot diagrams widely used to display distributions of data. With the scientific validity and practical value of HEPS now widely accepted, the effectiveness of different visualisation approaches is now being explored (Ramos et al., 2010, Zappa et al., 2010, Bruen et al., 2010, Cloke et al., 2009).

Experience in other domains suggests that the design and framing of uncertainty information is important in shaping how it is understood and acted upon by recipients (NRC 1989). In health risk communication, for example, it is well recognized that drug treatments are regarded more favourably when described in terms of relative rather than absolute risk reduction or the number of patients needed to be treated in order for one actually to benefit (Covey, 2007). Kurz-Milcke et al. (2008) have assessed the effectiveness of visual displays in communicating relative as against absolute risks. Gigerenzer (2002) has shown that medical professionals and the lay public alike understand risk better when it is communicated in terms of natural frequencies rather than probabilities, although Joslyn and Nichols (2009) found the opposite to be true in the case of weather forecasts. There is also an extensive body of research on how probability of precipitation forecasts are understood by the general public (Murphy et al. 1980; Gigerenzer et al. 2005; Morss et al. 2008) as well as other work on public responses to the idea of the 100-year flood (Bell and Tobin 2007) and to the cone of uncertainty visualisations used by the US Hurricane Centre to communicate the likelihood of different storm track paths (Broad et al. 2007). Proceeding from an implicit ‘deficit model’¹, much of this work has focused on how the design of risk messages can improve public

¹ The deficit model is the name given by sociologists of science to the widespread instinct in science policy circles to attribute public opposition to nuclear energy, GM foods and other programmes of science and technology to a deficit of knowledge about them. The assumption is that once this deficit is closed through better communication that public opposition will disappear (Wynne 1995; Sturgis and Allum 2004).

understandings of scientific uncertainty (Demeritt et al. 2011). However, it is increasingly clear that hydro-meteorological forecasters (Doswell 2004; Elia and Laprise 2005; Demeritt et al. 2007), like other professional groups (Kostopoulou et al. 2009), are not immune to cognitive and other biases that may distort their understanding of uncertainty and risk, and so there are calls for more attention to be paid to the communication of uncertainty between the different professional groups (i.e. from meteorologists to hydrologists, and from hydrologists to civil protection authorities) involved in flood incident management (Faulkner et al. 2007).

To that end the aim of this paper is to contribute to improving the communication of the probabilistic flood forecasts generated by HEPS. Demeritt et al (2010) and Ramos et al (2010) have documented a wide range of opinion among operational forecasters across Europe about what is the most important information to extract from HEPS. There are any number of different ways in which such information could be displayed, but there is, as yet, no systematic assessment of their communicative effectiveness. Different users are likely to require different kinds of information from HEPS and thus different visualisations; expert users may require access to multiple parameters, such as previous observed values, skill scores and the full suite of ensemble members, all combined in a single, information-rich display, whereas other users may prefer simpler displays showing simply the probability of threshold exceedance. In this paper we focus on hydrological forecasters and their preferences and beliefs about the best way to communicate probabilistic flood forecast information. The perceptions of this expert group are important both because they are the designers and primary users of existing HEPS and because they have sometimes resisted the release of uncertainty information to the general public because of doubts about whether it can be successfully communicated in ways that would be readily understandable to non-experts. By exploring those views we seek to assess the strengths and weaknesses of existing (and potential) HEPS visualisation methods and thereby formulate some wider recommendations towards best practice for HEPS visualisation and communication.

Background

Hydrological Ensemble Prediction Systems (HEPS) generate hydro-meteorological forecasts that take account of the inherent uncertainty in the atmospheric forcing and the hydrological model. Instead of a single forecast, multiple forecasts for the same time range are issued. HEPS are attracting widespread attention as a possible method for both extending the temporal horizon of predictability for floods and for quantifying the uncertainty in the resulting forecasts. A considerable body of scientific research concentrates on important technical issues such as pre-processing, post-processing, data assimilation or limits of predictability (Thielen et al. 2009, Bartholmes et al., 2009, Pappenberger et al., 2011 and 2008, Schaake et al, 2010, Voisin et al., 2011, Bogner and Pappenberger et al. 2011, Thiemiig et al., 2010). In addition HEPS have been adopted in operational and pre-operational frameworks across the globe (Cloke and Pappenberger, 2009²). These systems use a variety

² for an updated list see http://wedit.ecmwf.int/staff/florian_pappenberger/heps_review.html

of different methods for visualising their probabilistic forecasts. A small number of scientific studies concentrated on assembling a number of demonstrations / case studies illustrating this variety of practical approaches (see e.g. COST731 in Bruen et al. 2010 and Rossa et al. 2011 or Cloke et al. 2009). These papers demonstrate the multiple ways uncertainties can be displayed and also illustrates the diversity of information which can be shown.

There appears to be a common assumption among operational forecasters that civil protection authorities and other decision makers prefer to base their decisions on deterministic yes/no forecasts rather than having to deal with the additional probabilistic information generated by a HEPS (Ramos et al. 2010, Demeritt et al. 2007, Pappenberger and Beven, 2006, Demeritt and Nobert 2011). Flood forecasters therefore often claim that decision makers do not want to have this information. However, the study by Nobert et al. (2010) has clearly shown that this may not always be true. In the case of Sweden, for example, HEPS have been successfully implemented by the forecasting centres and probabilistic products are accepted by the Swedish Civil Contingencies Agency.

One obstacle to increasing the uptake and application of HEPS to operational flood incident management is improving the communication of the resulting probabilistic information. To that end it is important to consider not only what information is regarded as crucial to operational decision-making, but also identifying what is less important, so that the important information does not get lost amidst the 'noise' of other extraneous information. Such judgments about relevance clearly depend on the decision-maker for whom the information is to be relevant, and in that regard the starting point in the information cascade from HEPS to front-line emergency service are the flood forecasters themselves, whose communications with each other will inevitably shape subsequent communication farther down the chain. Therefore in this study we focus on expert users of the HEPS forecast and in particular the communication between these experts. Further research would be required to assess the suitability of HEPS visualisations for other audiences.

Research Design

To explore these issues, we conducted three interactive exercises with 57 forecasters and other flood experts attending a workshop convened as part of an annual meeting of the European Flood Alert System (<http://floods.jrc.ec.europa.eu/>) and KultuRisk project (<http://www.kulturisk.eu/>). Working both individually and as members of small groups, participants were asked to perform a series of sketching, writing, and discussion tasks designed to elicit their views about the communication of probabilistic flood forecast information. These exercises yielded data in the form of hand drawn sketches of preferred forecast visualisations, textual annotations recorded on yellow post-it notes and flip charts, and notes collected by the authors of the discourse data arising in the course both of small group and plenary discussions.

In all there were 57 participants drawn from 15 different European countries and working in 32 institutions, largely national hydro-meteorological services as well as some participants

from universities and research institutes (Table 1). The ratio between operational forecasters and researchers was about 1:1. The majority of participants were professional hydrologists, meteorologists or flood forecasting experts, though there were also some IT specialists, and a handful of participants with backgrounds in the social sciences or in policy making in the area of flooding and other, primarily water-related, natural hazards. Most participants had some prior knowledge of ensemble forecasting.

Participants were subdivided into small groups of 5-9, carefully designed to ensure a mixture of nationalities and institutions in each team. The aim was to generate unfamiliar pairings so as to force group members to articulate tacit assumptions that might otherwise go unsaid when working with colleagues from the same national background or institution. The workshop was convened in English and most participants are fluent, however, some misunderstandings have to be expected (Kaur, 2011). Participants were promised that their contributions would not be individually attributable, a promise that encouraged frank discussion and creative thinking.

The stimulus material used in the exercises was limited to graphs typically encountered within the setting of a medium range probabilistic flood forecasting system with a lead time of 10 days. Focus was on forecasts for individual locations rather than on overview maps. The predictive variable was discharge. The setting for the exercises was very limited and encompasses by no means the full set of types of forecasts encountered within the forecast environment. However, they represent the most commonly used display types. For the purpose of the workshop, we created three exercises which served to assess the success of different visualisation of uncertain prediction:

Exercise (Ex1) consisted of distributing pen and paper to participants and asking them to individually draw a 10 day probabilistic forecast of discharge at one single location. They were given the choice of using one or more plots. Participants were informed that the plot(s) should be constructed for analysis by professional hydrologists who had heard of probabilistic forecasts but were not necessarily expert in their analysis and use. Accordingly, participants were told that their plot should include all the necessary information for someone receiving the plot to be able to analyse it. Each group was then asked to discuss the various plots they produced and to select their favourite visualisation form. At the following plenary session, each group explained to the other groups their rationale for preferring this plot over others.

In the **second exercise (Ex2)**, the participants returned to their respective groups and were given small sticky notepaper and instructed to write down all the features which could be displayed on a 10 day probabilistic forecast of discharge at one single location. As in Ex1, this was carried out individually, and they could use one or multiple plots. The instructions were given verbally and displayed on an overhead projector. Participants were encouraged to write down the most unusual as well as the most typical elements. The notes were put in the middle of the discussion circle for everyone in the small group to read. Each group was then asked to choose the 3 most common and three most unusual contributions from those generated by their group members.

In the **third exercise (Ex3)** different ways of displaying probabilistic hydrographs were presented to the groups (blueprints were taken from typical examples found in literature, (Cloke et al. 2009)). These examples were chosen to provide coverage of all the main types of hydrograph currently in circulation. As a group exercise, the participants were then asked to annotate each visualisation with all the features they liked about that particular plot, to suggest improvements and to choose one favourite graph. This involved group discussion, which was partially observed and noted by the conveners, constrained by the ratio of conveners to groups (3 to 6).

Results

Results of Ex1 are presented in Tables 2 and 3 and some of the drawings are shown in Figures 1 to 7. Ex2 is summarized in Tables 4 and 5. The comments on all graphs and the graphs themselves (Ex3) are shown in figure 8 and Table 6.

Displaying the familiar

A total of 34 drawings were collected from workshop participants as part of Ex1 and were analysed according to their features (see Table 2 and 3). The vast majority of plots (85%) feature fairly conventional, hydrograph-style representations of discharge or flow (y axis) against time (x axis), although some plots tried to supplement this by displaying other forecast properties e.g. stage (see Table 2, which shows that 29 plots have been of the standard type). For example, Figure 1 is such a standard plot and is very similar to Figure 8a, displaying nearly identical features in terms of boxplots and deterministic forecasts. In addition a spaghetti plot type of display (see Figure 4, which is similar to 8c) was used in 6 drawings meaning that a minority of participants decided to opt for that type of display. Such a plot type is very close to the traditional display of a single discharge hydrograph. Spaghetti plots have the additional advantage of allowing an instant impression of the number of ensemble members (thus establishing more trust in a forecast if several members indicate the same magnitude and direction). This way of depicting discharge suggests that a rich web of information has gone into the forecast, and therefore implies greater reliability.

The importance of the discharge variable itself as display variable can also be seen in Ex3. Two of the displayed graphs (A6 and A4) do not show discharge and in both cases it is either suggested to add (A6) or the graph is seen as an accompanying graph (A4).

There was no strongly preferred standard for visualising discharge; individuals in Ex1 sketched a wide variety of different plots, similar in their range to those in current operational use (see A1-A6), and there was no clear favourite among them to emerge in Ex3 of the exercise. No graph got more than 2 votes (most of them got 1) by the individual groups – only one type of display got no votes. The single most criticised issue was with regard to the colour schemes (A5, A6, A3, A2, A1). The wide range of expressed preference could be interpreted as evidence that there is no consensus, as yet, on what is best. Alternatively it

could simply be that personal preference for colour is quite varied. This feature could not be monitored in the drawings of the individuals as only single coloured pens had been provided.

This kind of visualisation of HEPS is clearly modelled on the familiar hydrograph which hydrologists are accustomed to working with every day. While this familiarity means that for hydrologists at least, this style of HEPS visualisation is easy to understand; its interpretation requires considerable tacit knowledge to translate flow in m^3/sec into water levels or other thresholds that might trigger some particular kind of response. On its own this kind of hydrographic-style visualisation would not be immediately useful to the broad general public, at least not without some supplementary information, though many agencies (e.g. US National Weather Service, UK Environment Agency) do make real-time hydrographs accessible on the internet for interested users, albeit showing river stage rather than discharge. Almost by definition, though, people able to dig out such information are likely to be expert enough to make some sense of it, which in turn requires some knowledge about the range of past behaviour and its relationship to the present.

Compared to standard discharge related plots which were drawn 29 times, probability plots (Figure 2 and 3, drawn 6 times see Table 2) were much less popular. In showing the range of likely flows for any given time step, these probability plots go beyond the traditional deterministic flow hydrographs toward a 'next generation' displays of probabilistic forecasts. This type of display is novel, indicating that forecasters are adapting to a new forecast environment (see more discussion below).

All figures so far have been based on displays which can be illustrated on a static piece of paper. However, as one participant remarked:

"It is important to look at new ways to display information and integrate modern technology"

There have been 5 different speciality plots suggested (see Table 2) of which an areal overview was the most common one. Figure 6 represents such an approach and also seeks to experiment with new technology. It shows information of a country (mainland Italy) on a grid (probabilistic discharge exceeding warning levels), but dynamically iterates through lead time. Such a single display would not be possible on a static paper (unless one produced multiple plots) and thus represents an embrace of new web technology, which does not just replicate static figures on a map.

Despite the importance of historic information for interpreting a forecast, only a minority of participants thought of explicitly showing return periods, which were included in just a total of 5 (21%) of the displays (Table 2). However, return periods were mentioned as important in graphs A6, A2 and A1 from Ex3. The return period concept is just one way to link forecasts to historical values. The strongest preference was for displaying information about recent observations (9x see Table 2) alongside the predicted hydrograph, though it was also suggested that historical flood levels (1x see Table 2) or warning levels (3x return periods, 1x discharge thresholds and 4x other thresholds see Table 2) might also be shown, either instead or in addition to past observations. This is already standard hydrological practise for example

by the UK Environment Agency (see <http://www.environment-agency.gov.uk/homeandleisure/floods/riverlevels>). As with the hydrograph itself, there was more agreement about the general idea of showing some historical information to help contextualise the forecast than about exactly what historic information is required or how it should be displayed. This is also confirmed by the results of Ex2 resulting in 7 entries in Table 4. In the group discussion results (Table 5), 30% of all mentioned issues in the category 'not common' are with respect to historical conditions proving that they are seen as important. The display of historic data (simulations and observations) is the most commented issue either in liked or improvements (Figures 8a, c, e, d, f g and table 6). Historical information also includes model performance information (e.g. skill scores, how forecast varied over time, former mistakes see Tables 4 and 5). It is clear that such information is needed to establish trust in the forecast and assess its reliability in the current forecast setting. It would be impossible to derive an interpretation of the current forecast without such information. The importance of historic and current information culminates in the mentioning of initial / current conditions (see Tables 4 and 5). On the one hand they establish trust in the current set-up of the model as given by the historic information, on the other hand they are clear skill indicators for the current forecast, as errors in snow cover, for example, will lead to difficulties in predicting a snowmelt driven flood.

Displaying additional information

Additional information and meta-data are key to understanding the setting and environment of a forecast. Location is probably the single most important one. However, location information was drawn only 3 times (see Table 3). It is possible that in the experimental setting of the workshop, the location information and associated meta-data was seen as less crucial. This confirms earlier results by Nobert et al. (2010) that training exercises are difficult in an artificial setting. This may also be the reason why meta information (e.g. location name) was only stated as an improvement once (Figure 8e, see table 6) in Ex3. It also suggests that such information might not be an essential part of the main display. That hypothesis is confirmed by Table 5 which lists the most common information as river sections, name of the station and area of basin. However, Table 5 also states that meta-data in general were classed as uncommon in graphical forecast displays: some types of meta-data are very common, however, usually not integral part of the graphical display. The fact that it is mentioned in Table 5 indicates that more information would be appreciated as side information. Such required additional information stretches from geographical information (e.g. location or river section as indicated in total 8 times in Table 4), to more physical parameters (e.g. land-use, geomorphologic conditions, hydro-climatology or upstream area see Table 4).

It is clear that the interpretation of such additional information as well as of the forecasts itself will require the involvement of an expert forecaster or at least the possibility of contacting someone for further advice and clarification. Research has found that Public Weather Service advisors play a key role in helping to translate forecast information and

make it meaningful for emergency services officers (Demeritt and Nobert 2012) Therefore, contact point and name / logo of institute is mentioned explicitly in Table 4.

Visualising and embracing uncertainty

The challenge of visualising uncertainty seems not to have been particularly difficult for the participants. There was not a single display without some kind of representation of uncertainty. Maybe it was obvious that this workshop was designed to consider uncertainty, and peer pressure resulted in compliance. Some participants clearly had a very detailed understanding of uncertainty in probabilistic forecasting. For example, Figure 1 highlights one important difference to the standard plot: on the y axis the lead times are summarized from day 6 onwards, expressing a very deep understanding of uncertainties involved in predicting lead times several days ahead. The numerical skill of any particular forecast is increased by summarizing forecast lead times (as a larger average is built over time) whilst still displaying the full uncertainty. Therefore, in this plot the balance between detail and conciseness has been actively tackled by offering a summarized solution.

In this plot as in many others, the uncertainty has been displayed by some form of percentiles (see Figure 5 and Table 3 and 4). The number of percentiles and whether one should display the mean or median is contested, which may on the one hand simply reflect local customs or on the other hand indicate that this may be an irrelevant detail (as long as enough information is provided). In addition, there is one clear discrepancy in that only a very small number of participants displayed the worst case scenario in terms of maximum and minimum (each 3x times see Table 3). However there was a clear desire for this information (see comments on figure 8 b, c, d, e, f in table 6 in the standard plots of Ex3. Having promised participants anonymity, we cannot cross-tabulate user type against expressed preferences for means and percentiles as opposed to max/min values and worst case scenarios to see whether they reflect individual proclivity or systematic differences by user types and their operational requirements for decision making. There is one topic on which all participants seem to agree: plots of uncertainty bands have to be transparent (see Figure 8a, c, e and table 6).

Displaying uncertainty does not necessarily mean that uncertainty is understood or indeed considered as part of the standard decision making process. This can be illustrated on Figure 4 which shows a ‘spaghetti plot’ showing the flow over time of each ensemble member. One participant remarked in the plenary discussion of favourite plots that such a display allows them to follow the performance of a single forecast, which was echoed and criticised by another workshop participant:

“Spaghetti plots are only displayed as they allow to misuse probabilistic forecast by following a single line”

This can be interpreted to mean that a probabilistic forecast is treated in a deterministic fashion picking one forecast trace as the most likely rather than a decision process based on the full probability distribution. Assuming that a single line of the forecast is the most likely event does contradict the design of many ensemble prediction systems (in which each member is supposed to be equally likely). However, forecaster experience cannot be neglected and the prior assumption of a uniform distribution of ensemble probability may be

inaccurate (see comment regarding possible improvements: “To put weight on every ensemble member according to forecasting experience” to Figure 8f in table 6). In a well-designed system such experience should have been built into the design of the forecast system resulting again in equal probabilities - hence the desire to pick a single forecast as the most likely illustrates a mistrust or unfamiliarity with a probabilistic system. Fundamentally, it is of course possible to weight individual ensemble members or cluster several members if it is not done in real time (e.g. using lagged ensembles) or they are part of a modelling cascade (Brochero et al., 2011). A concept which seems to be partially understood by many participants, hence the request for “lagged forecasts” as an improvement to Figure 8c in table 6. Such a weighting or clustering is only useful if it is targeted, meaning a general cluster algorithm which does not involve the user focus is not desirable and if it is used as a cluster by the end-user recognizing that a single cluster line represents multiple forecasts.

Not all participants used percentiles to display forecast uncertainty. Some, for example, used probability plots (as discussed above). These displays also embrace the probabilistic concept. Indeed deterministic forecasts look ‘odd’ in such displays (see e.g. dotted line in Figure 8b in table 6). Probability plots have the advantage of focusing information on the variable most important for forecast consequences (i.e. exceeding a threshold), but they can only be interpreted properly if the underlying concept of probabilistic forecasting is understood.

Display of risk, vulnerability and consequence information

One interesting issue is the audience for whom participants imagined themselves to be drawing plots. Most were drawing plots that they themselves would want to receive (either from their colleagues or an external organisation like the European Flood Alert System), so as to inform their own internal decision making on what kind of a qualitative forecast to issue. However, some workshop participants were explicit that they were drawing plots they might disclose to their users or to the general public (although this was not the objective of their drawings as outlined in the instructions).

The goal of the exercise was to evaluate the communication of uncertain forecasts among experts. But our experimental set-up clearly underestimated the warning-centric thinking of many of the participants (see for example the type of sticky notes drawn for Ex2 in Figure 7). Risk related information also featured in Table 4, which is based on these figures, and was mentioned once (Figure 8d and table 6) as an improvement to the standard plots. Apart from a tiny handful of plots drawn by participants (e.g. Figure 2), most of the plots drawn by participants did not specify any action or provide other information to enable plot recipients to interpret the significance of the HEPS for their purposes. This means that they expected the recipients to already to know the range of potential responses that might be triggered by the forecast.

In part, such displays link probabilistic forecasts to deterministic actions (display of consequences). However, risk, vulnerability and consequences can also be within the probabilistic domain – see for example Figure 3 in which probability on the left hand y axis directly links into risk/consequence on the right hand y axis. This plot was clearly designed to

overlay decision making and forecast information to extract a maximum of useful information.

Conclusions and Discussion

The aim of this paper is to improve the communication of the probabilistic flood forecasts generated by Hydrological Ensemble Prediction Systems (HEPS) by understanding perceptions of different methods of visualising probabilistic forecast information. This study focused on inter expert communication and on understanding differences in visualisation requirements based on the information content necessary for individual users. This was investigated in a series of exercises (hand drawing, listing of most important features, and critiquing of pre-produced probabilistic forecast) carried out by experts in flood forecasting within the wider setting of a workshop. The perceptions of the expert group addressed in this study are important both because they are the designers and primary users of existing HEPS but also because they have sometimes resisted the release of uncertainty information to the general public due to doubts about whether it can be successfully communicated in ways that would be readily understandable to non-experts. In this paper we explore the strengths and weakness of existing (and potential) HEPS visualisation methods and thereby formulate some wider recommendations about best practice for HEPS visualisation and communication. The following questions remain to be discussed:

Do we really want uncertainty information for operational decision making?

The setting of this workshop was in a probabilistic framework and the exercise was clearly about the communication of probabilistic forecast amongst experts. Some participants opted for displays of clear probabilistic nature (e.g. A4) in which deterministic forecasts look out of place (dotted line), hence providing some evidence that the attitude towards probabilistic forecast are changing. However, the desire for deterministic information and interpretation could be seen throughout:

- Some displays were preferred because they allow viewers to follow individual ensemble members and make an expert judgement on which one is best (Comment to Figure 8f in table 6: "*To put weight on every ensemble member according to forecasting experience*"). Although HEPS are designed so that all members should be equally likely, our users did not treat them that way, which reflects a tacit desire for deterministic forecasts, as well as mistrust in the skill of HEPS (maybe out of experience).
- Deterministic forecasts are a popular addition to probabilistic predictions, maybe serving as an anchoring point.

In many ways there seem to be a desire to include the probabilistic information within a traditionally deterministic decision framework. Indeed one participant noted:

"Communication (meaning between me and my colleague) mean[s] that we have to come to the same decision, thus probabilities are deterministic."

In this context, the display of probabilistic information may be of secondary importance to updating the culture within an organisation.

It could be argued that a probabilistic forecast system does not produce a decision, but serves merely to provide information to inform decision making. Such a claim, however, ignores the way in which decisions are often closely coupled to thresholds built into the actual forecasting system. Such decision thresholds might be formally distinguishable from model thresholds, but in practice the two are often so closely coupled that it is difficult to distinguish between the forecast input and the decision output. A forecaster may be deterred from exercising their discretion and overturning the model output both in highly rule-bound institutional contexts, such as those prevailing in many Napoleonic code countries (Demeritt and Nobert 2011) or contexts where blame management is a concern and following standard operating procedures offers a defense in the event of institutional failure (Rothstein et al. 2011). In these contexts decision support systems are often set up in a way that decisions will almost be made automatically once pre-determined thresholds have been crossed. While provision for 'soft' factors allows forecasters some discretion to trigger at lower thresholds, the discussion about them presumes that these would only allow for additional alerts, rather than the suppression of alerts even when thresholds are just barely crossed.

There are thus some fundamental questions here about whether uncertainties, however effectively they may be displayed, are actually understood, and if even they are, whether and how that understanding is actually applied in operational flood warning and incident management. Those are important questions but they lie beyond the scope of this study, which focused simply on visualisation preferences and what expert suggestions about communicative effectiveness.

What is the core information needed on a graph?

There are several key ingredients needed for the display of probabilistic flood forecast:

- Discharge
- Lead time in the form of a fully written date and time
- Warning/Alert levels and/or return period
- Observations and past model performance (either in a statistical format, or as a graphic that can be examined)
- Representation of uncertainty with no clear consensus on how many quantiles or even the exact percentage of the quantiles - therefore maybe those should be individual user defined
- Worst/Best scenario (meaning maximum and minimum of information)
- Meta information, which needs to state location, the forecast provider (either organization or forecaster) and who to contact for further questions.
- A risk measure (cost, population affected etc.)

Complexity was not penalised if information is presented unambiguously. The responses suggest that maybe more additional information should be available (meta-information). For example there is a small proportion of participants who would like to see spaghetti plots - therefore an option for those individuals to see this information should be available. It is also clear that every designer of a forecast plot can be confident that there will be a considerable number of forecast recipients who will dislike the colour scheme. Current web-technology does allow for a large degree of individuality in display and therefore this request for individuality could be accommodated. It is very clear that a simple producer-derived opinion of the way this information has to be displayed is not adequate and needs to be developed in close collaboration with the perceived main end-user.

Do experts agree?

More fundamentally, one could actually question whether such an agreement on the method of communication can be expected in principle. All the participants have a different educational and institutional backgrounds, and there are significant differences even with participants who have the same job description. A flood forecaster in one country may handle the entire process from the production of the forecast to the communication of warnings, whereas in another country the communication stops at the level of civil protection. There are institutions which provide a strong research background, whereas others have no research environment. Fundamentally, there is no general and overarching agreement on what should be included on a probabilistic flood forecast. However, there is also no fundamental disagreement on what to exclude from a forecast. For example there were no objections raised to any of the suggestions made during Ex2. Even in post workshop discussions none of the suggestions was dismissed as far-fetched. This may have been due to professional courtesy (many of the participants knew each other well from previous workshops). Obviously, the communication of uncertain flood forecast information needs to be adapted to the recipients (who may include operational forecast officers, decision makers, civil protection authorities, the public and other stakeholders such as water resource managers), and there will be no 'one size fits all' solution (Broad et al. 2007). For instance there was a considerable desire among workshop participants for 'icon' style warnings or deterministic actions so as to reduce the probabilistic to simple actions. That style of visualisation seems more appropriate as part of the communication process to civil protection stakeholders or the public than for expert users. There are important questions to address in future research about how visualisation needs might differ by consumer type, level of expertise, and decision-making context, but these are not issues we were able to explore in this study.

What can user preference actually tell us?

In this study we have examined the preferences of those attending the workshop. However we have seen some examples of information being preferred but misused (e.g. following the individual ensemble members in the spaghetti plots). It is possible that this was not an isolated case – those who are unsure what a particular representation means might be unlikely to speak up. It therefore follows that while user preference is important--decision makers have to feel comfortable using a particular representation-- it is also extremely important that the representations used can allow the decision makers to make the right decisions, and not

lead to misunderstanding. Accordingly, future research should consider not only user preference, but also how the information content and type of visualisation can affect user comprehension and promote a common understanding.

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Table 1: Background of participants

Country	N° participants	N° Institutions	Type of Institution
Czech Republic	1	1	Hydrological forecasting service
France	3	2	Hydrological forecasting service, Re-Insurance company
Germany	3	3	Hydrological forecasting service
Hungary	2	1	Hydrological forecasting service
Ireland	1	1	Public institution
Italy	14	7	Hydrological forecasting service(s), University, Water agencies,
Lithuania	1	1	University
Netherlands	4	3	International research institution, University, Hydrological forecasting service
Romania	1	1	Hydrological forecasting service
Slovakia	2	1	Hydrological forecasting service
Slovenia	2	2	Hydrological forecasting service, University
Spain	1	1	Hydrological forecasting service
Sweden	1	1	Hydrological forecasting service
Switzerland	3	2	International research institution, Research Institute
UK	3	3	Research Centre, Meteorological forecasting service
JRC	15	1	Research Centre

Table 2: Features of drawings submitted. Please note that a plot can contain several feature at the same time (please note that number of answers differ from Table 1 as all features of a plot have been recorded e.g. a plot can show rainfall and discharge)

Y-axis	
24	Discharge (y axis)
3	Level
4	Level or Discharge (not clear from plot which one)
1	Rainfall
1	Probability type plot of risks of failure of levee
3	Return Period
1	Risk/Consequence
2	Probability type plot of exceeding return periods(one with error bounds)
X axis	
20	Time
1	Summarized days (e.g. forecast for day 6-7)
Plot type/style	
29	Standard flow plot (see Figure 1 or 2)
6	Probability plot (see Figure 2 or 3)
Specialty plots	
1	Pie charts
2	Areal plot (look down on country, river network)
1	4D (areal plot, colour scale displaying discharge, with rotation through time)
1	Plot with 3 bars of water level exceeding severe threshold for next 10 days. The 3 bars represent the probability of being above

	threshold; remaining normal and drop below threshold
Thresholds/Warning levels	
3	Return Period
1	Discharge thresholds (Q99 & Q90)
4	Thresholds (unspecified origin)
Information about past	
9	Past observations
7	Past model performance
1	Historical flood levels

Table 3: Features of drawings submitted. Please note that a single plot can contain multiple features.

Probability visualisation	
5	Spaghetti plots
18	Quantiles
2	Boxplot ⁽¹⁾
3	Full probability distributions (pdf)
13	2 Quantiles
7	4 Quantiles
3	Max & Min
5	5% & 95%
6	10% & 90%
2	25% & 75%
1	33% & 66%
1	Unspecified percentages (e.g. graphs says low and high Probability)

2	Mean
5	Median
2	Mean or Median or similar (unspecified what is meant)
Misc	
3	Location information
3	1 Deterministic forecast shown
1	2 Deterministic forecasts shown
1	Discharge capacity

(1) Note: a boxplot does represent quantiles, but quantiles are not necessarily shown in a boxplot

Table 4: Post-it notes of what could be on a forecast

Initial / current conditions	<p>Observations of level and discharge x2</p> <p>Initial condition (general e.g. soil moisture, snow cover etc) x3</p> <p>Model simulations of observed period incl. information on spin-up period x2</p>
Information about the past	<p>Historical flood levels x4</p> <p>Historic data with associated damages</p> <p>Highest discharge of the past 365 days</p> <p>Highest discharge ever recorded</p> <p>Return period</p> <p>How forecast has varied over time</p> <p>Skill scores</p>
Risk related information	<p>Risk Levels (1...5) x 2</p> <p>Impact/vulnerability information (general) x</p>

	<p>6:</p> <p>Costs (false) alerts x2</p> <p>(socio economics) damages and consequences x4</p> <p>Population affected</p> <p>Acceptability of stakeholders</p> <p>Evacuation plan</p>
Representation of uncertainty	<p>Median of Ensembles x2</p> <p>Average of Ensembles x2</p> <p>Ensemble Spread:</p> <p>Forecast range indicated by 5% (10%) and 95% (90%)</p> <p>Inter-quartile range</p> <p>Main quantiles</p> <p>Standard deviation bands</p> <p>General statements: probability distribution/bands (x2); error bounds; ensemble spread</p> <p>Indicator of uncertainty in Discharge/level (x4) including multi-model (x1)</p> <p>Probability of out of bank flow</p> <p>Box plot for each lead time</p>
Flow/Level	<p>Peak Level/Flow x 4</p> <p>Discharge x7</p> <p>Water level x5</p> <p>Flood magnitude x2</p> <p>Time to peak x4</p>

	<p>Bankfull level (x2)</p> <p>Need for communication of certain point of magnitude</p>
Inundation	<p>Flood plain inundation (x4)</p> <p>Percentage change in properties flooded</p> <p>Area of Town inundation</p>
Threshold and Warning levels	<p>(Flood) thresholds and alert levels (12x)</p> <p>Country alert level</p> <p>Warning levels: Smiling faces to describe general situation</p> <p>Important section with Alarm control</p> <p>Exceeded threshold “High”</p> <p>Threshold of acceptability from stakeholders</p> <p>Probability of exceeding threshold and alert levels (4x)</p>
Graphical display and warning messages	<p>Correct time and date of forecast (x2)</p> <p>Date and time of forecast incl. lead times (x6)</p> <p>Date/Time in days (after T0)</p> <p>Date/Time in hours</p> <p>Description of x- axis & y -axis</p> <p>Names</p> <p>Title</p> <p>Graphs</p>
Additional Information	<p>Whom to contact & communication point (x2)</p> <p>Location x7 (River name, coordinates etc.)</p> <p>Upstream area (x2)</p>

	Name/Logo of institute
	Copyright
	Geomorphologic conditions
	River sections
	Land-use
	Population
	Hydro-climatology

Table 5 Post-it notes of what is common or not common at a forecast display

Not common	Common
Initial / current conditions	
Spin up period of forecast	
Information about the past	
Skill scores	
Former mistakes	
Historic data	
Risk/Vulnerability related information	
Cost ratio	Population affected (S-E Damages)
	Impact on different targets
Representation of uncertainty	
Risk/Uncertainty	Uncertainty
Flow/Level	
	Flood magnitude
Inundation	
Threshold and Warning levels	

	Threshold (2x)
Graphical display and warning messages	
Pictures of what to do warnings (example on Figure 6)	Title
Happy/sad faces for warnings (example on Figure 6)	Axis description
Additional Information	
Meta data	River sections
Pictures from camera	Name of the station (2x)
	Area of basin

Table 6: Graph descriptions and comments by participants for blueprint

Fig. No	Graph description	No. of times chosen as favourite	Liked	Improvements
8a	Discharge is displayed on the y-axis and time (day of month) is displayed on the x axis. Three different warning levels are shown as blue areas. The forecast driven by a high resolution weather model is shown as yellow. The ensemble forecast is displayed by boxplots, indicating the maximum, 75%, 25% and minimum as well as the median.	2x	4x Observations; More Information than any of the other plots; 2xTime/hour instead of day number	Overlay simulations over observed period; Different colours for different thresholds; Probability exceeding different thresholds with secondary axis; Colour scheme; Add return periods; 2x Better legend labelling

	Remark: 1 Day is missing (mistake by authors)			
8b	<p>Probability of exceeding a threshold is displayed on the y-axis and time (day of month) is displayed on the x axis. The ensemble forecasts show exceedance for a medium and a low threshold.</p> <p>Probabilistic forecast can have any values between 0% and 100%. The deterministic forecast is shown as a dotted line and can only have values of 0% and 100% (nothing in between).</p>	1x	<p>Straightforward information on the peak timing and probability of thresholds exceedance; 2 Level probability distribution; Specified probability not complicated by other stuff; very clear graph</p>	Better labels; better as an accompanying graph than stand alone; add actions based on threshold exceedances
8c	<p>Discharge is displayed on the y-axis and time (day of month) is displayed on the x axis. Warning thresholds are displayed in yellow and orange colours. The forecast driven by a high resolution weather model is shown as a dotted line. The red lines show the result of multiple forecasts (an ensemble of them)</p>	1x	<p>Spaghettis ; 3x thresholds; 2x Easy to understand → more direct message; Information about the timing of each member; 3x Obvious how many ensemble members there are; Same colour for each forecast same importance; Easy read of maximum discharge; Clear scale; Captures all data</p>	Add observations; add return periods; display total number of ensembles; show lagged ensembles
8d	Discharge is displayed on the y-axis and time (day of	1x	<p>5x Display of distribution; 5x Percentage</p>	Display Maximum discharge; Change colour scale; Make background

	<p>month) is displayed on the x axis. Warning levels are shown as grey areas. The forecast driven by a high resolution weather model is shown as a dotted line. The probabilistic forecast is shown in different percentiles with the 90%, 75%, mean, 25% and 10 % clearly marked.</p>		<p>description; Good when there is local knowledge; 1xVery clear; Alert levels; Comparison with deterministic forecast</p>	<p>see through plot; add observations; write full date; add risk information</p>
8e	<p>Discharge is displayed on the y-axis and time (day of month) is displayed on the x axis. Mean flow, Mean monthly flow and mean high-water flow are shown in green colours. High water quantiles or return periods are displayed in yellow and orange colours. The dotted vertical line indicates the start day of the forecast. The forecast driven by a high resolution weather model is shown as a dotted line. The blue area indicates the ensemble forecast with the median, 40th and 60th percentiles. The maximum (worst case scenario) and minimum (best case</p>	2x	<p>Very comprehensive; Historical context; Observations; 2x Colours; Display of worst ensemble member; Now line; Hydrological regime; High resolution forecast; thresholds in particular MQ, MQJ, MQH</p>	<p>2x Add legend; Make thresholds visible for any lead times; 3x Add past observations; Add Costs/vulnerability; ; 2xInclude 90th and 10th percentile ;Include full date; location name</p>

	scenario) represent the maximum and minimum of the ensemble forecast.			
8f	Return periods are displayed on the y-axis and time (day of month) is displayed on the x axis. Three different warning levels are shown as yellow/orange areas.. The forecast driven by a high resolution weather model is shown as dotted line. The ensemble forecast is displayed by blue area indicating the maximum, 75%, 25% and minimum as well as the mean.	1x	Return periods give a good overview or when thresholds are not known; Display of 3 warning levels; That forecast start is indicated; Good number of bands; Direct communication of warning thresholds; Information on the severity of event (return period)	Different colour scheme; Labelled percentages; Display no of members; Add discharge to y axis; Better axis description; To put weight on every ensemble member according to forecasting experience; Like to see threshold lines on the ensemble; Warning levels; Comparison with deterministic forecast; Reference for return periods; Normal levels also included; Percentile levels for the EPS discharge Forecast
8g	Discharge is displayed on the y-axis and time (day of month) is displayed on the x axis. Two different warning levels are shown as grey areas. The forecast driven by a high resolution weather model is shown as a blue line. The ensemble forecast is displayed by indicating the 90% and 10% as well as the mean.	0x	Uncertainty bounds; Thresholds; Display of high-resolution; Easy to understand spread; Easy to read; show more percentile levels; 2x display observations	Display of Mean

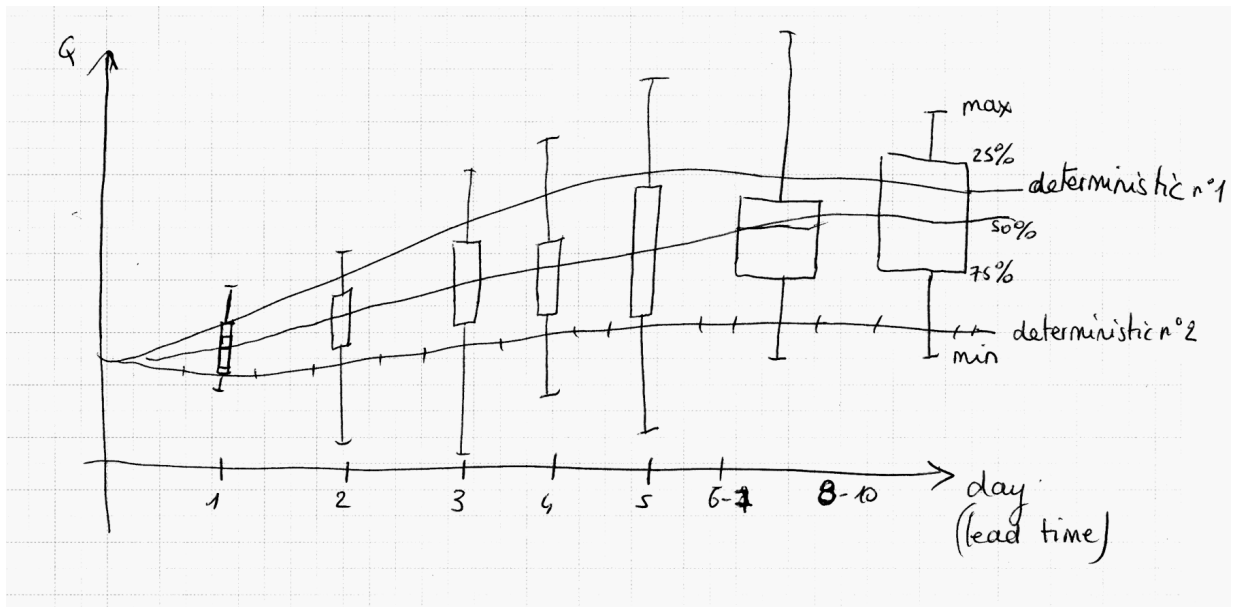


Figure 1: Box-plot of ensemble discharge predictions (very similar to Figure A1)

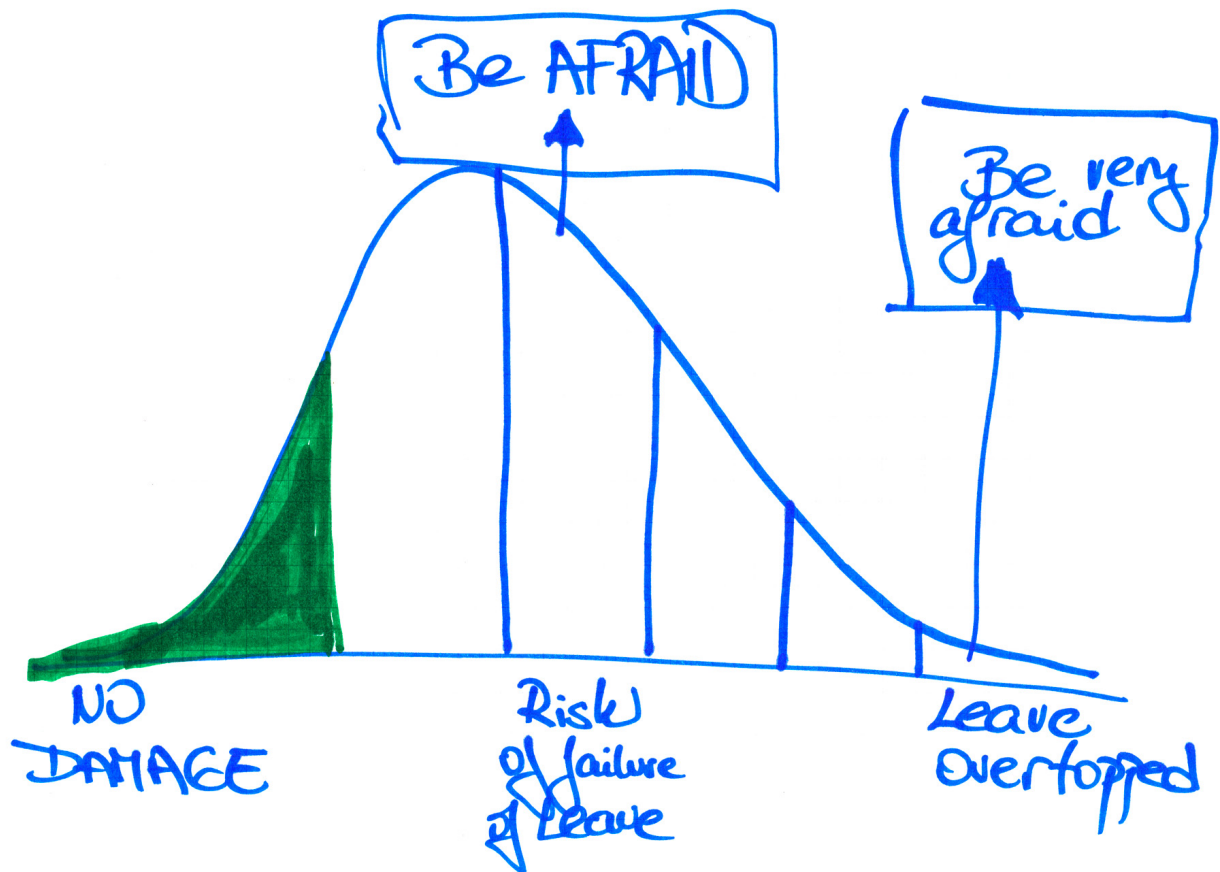


Figure 2: In this example the probabilistic flood forecasting information is displayed as a probability distribution of the risk of levee overtopping

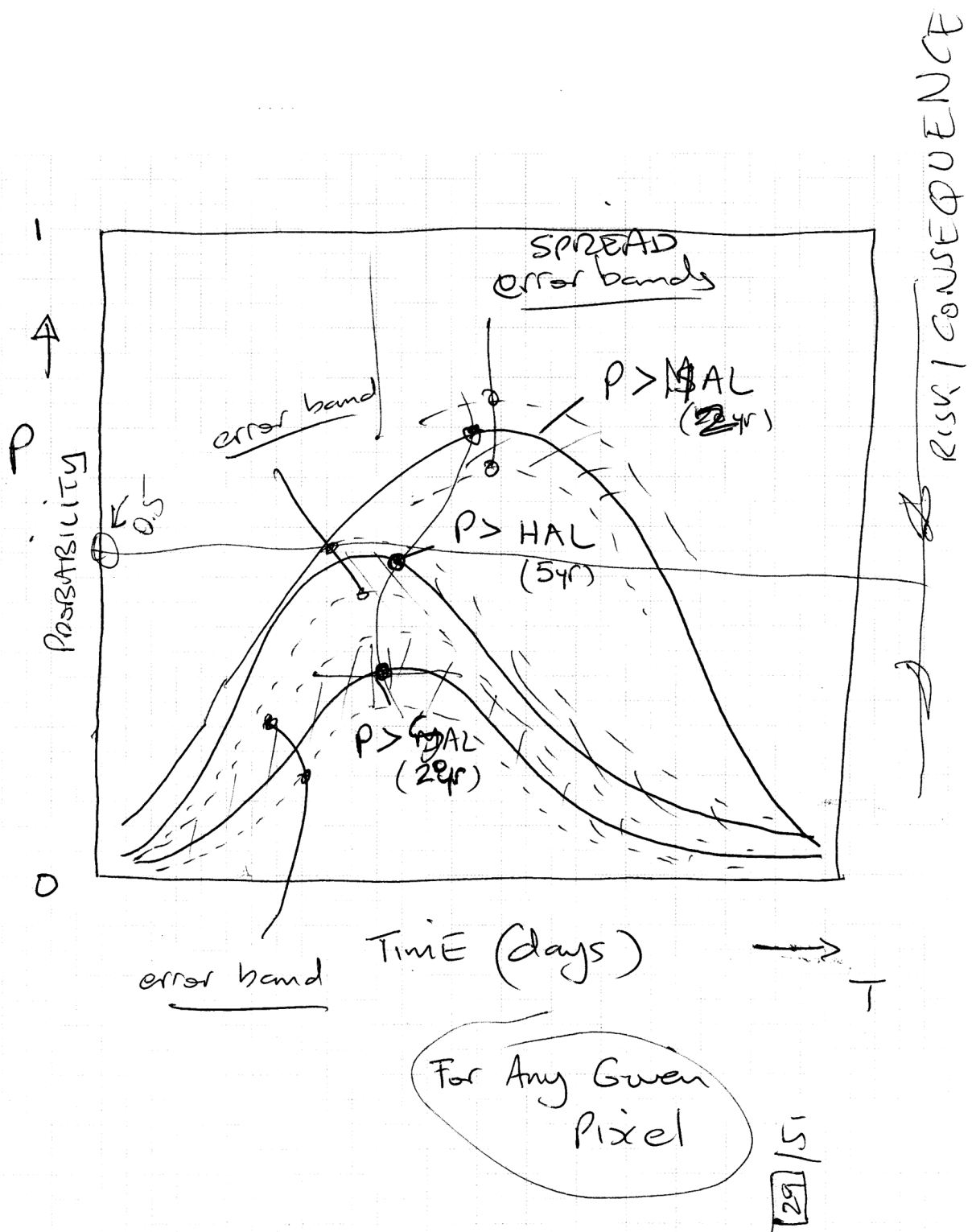


Figure 3: In this example the participant has displayed the information as a probability of exceeding a particular annual return period flow over time

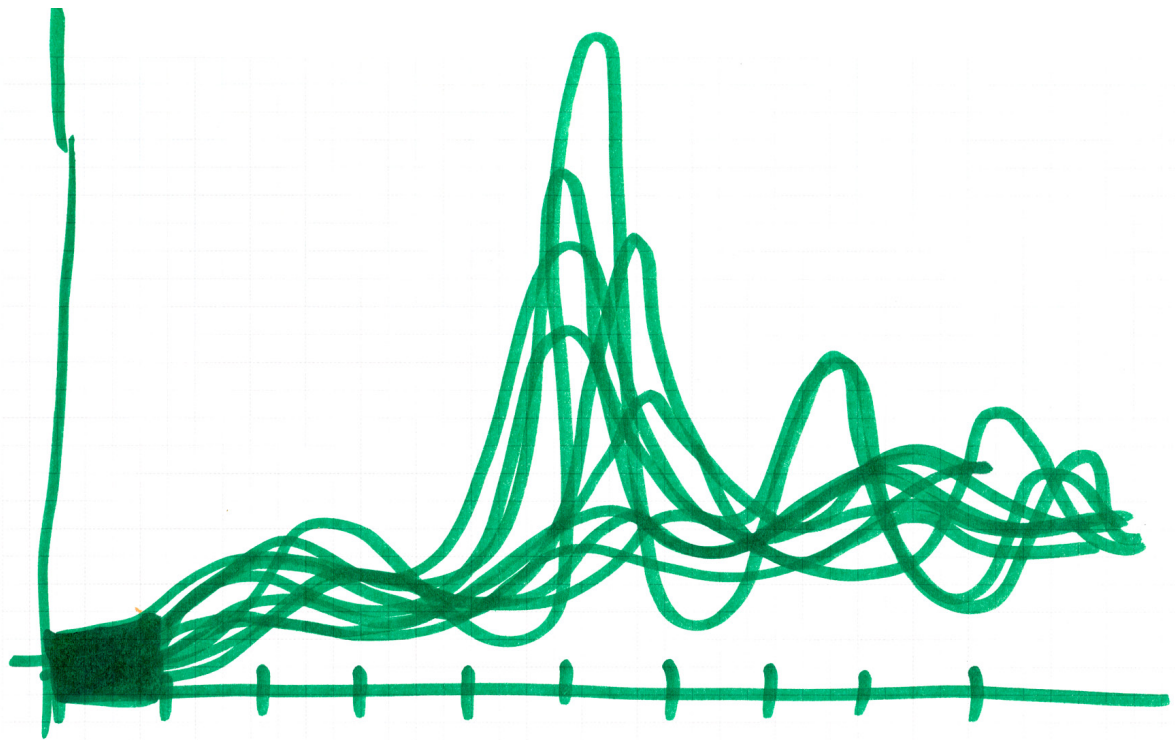


Figure 4: An example of a 'spaghetti plot' showing the flow over time as predicted by each ensemble member

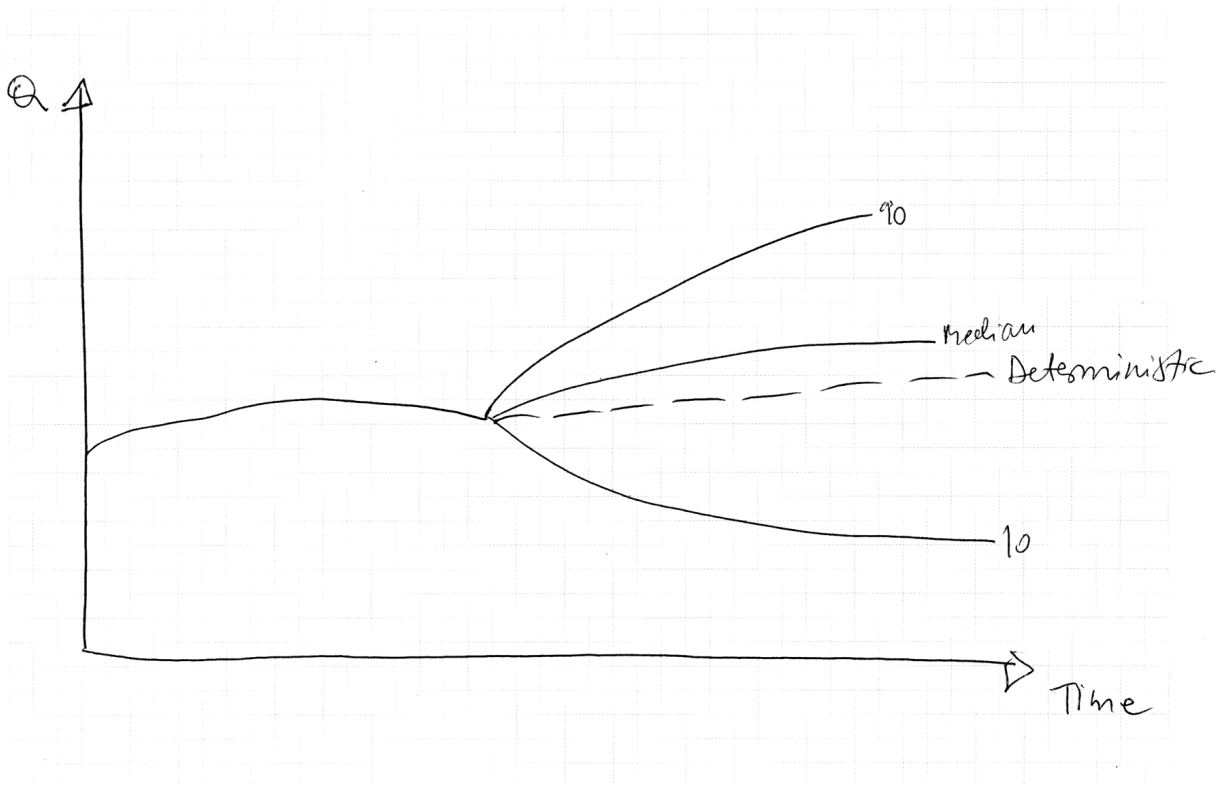


Figure 5: An example of a simplification of the information provided by the ensemble members, showing the ensemble spread, the median and the deterministic forecast.

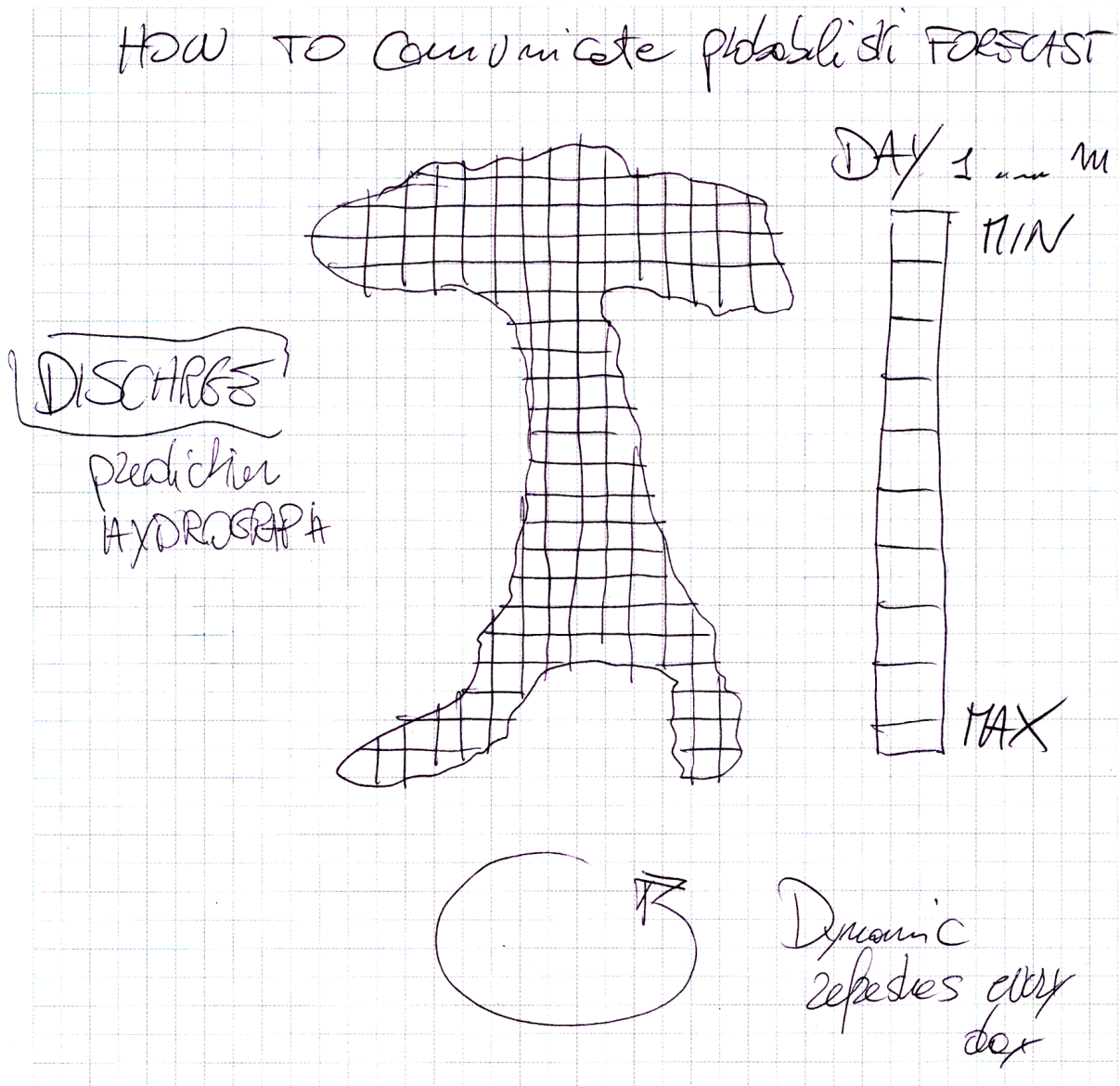


Figure 6: Drawing of participants on communication of forecast - probabilistic forecast information displayed on a grid, dynamically updating through every forecast lead time. The grid represents mainland Italy.

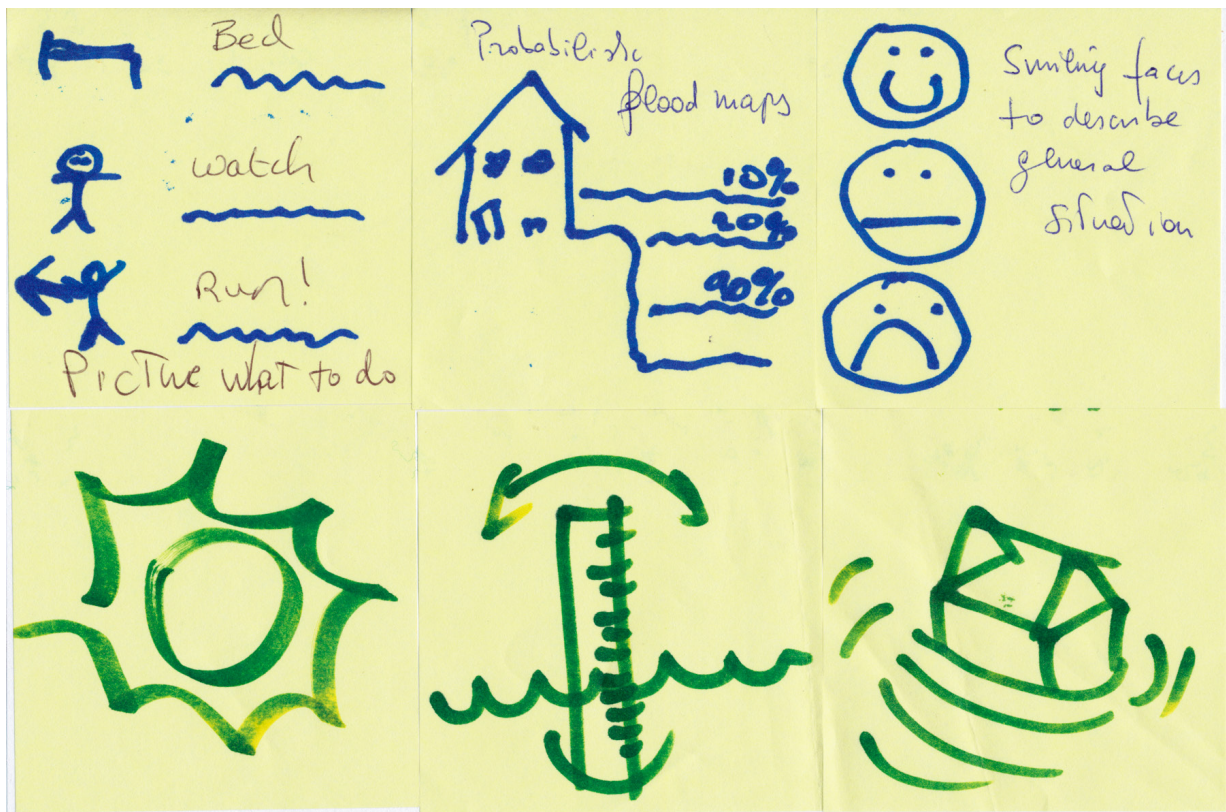


Figure 7: Drawing of participants on the post-it note exercise

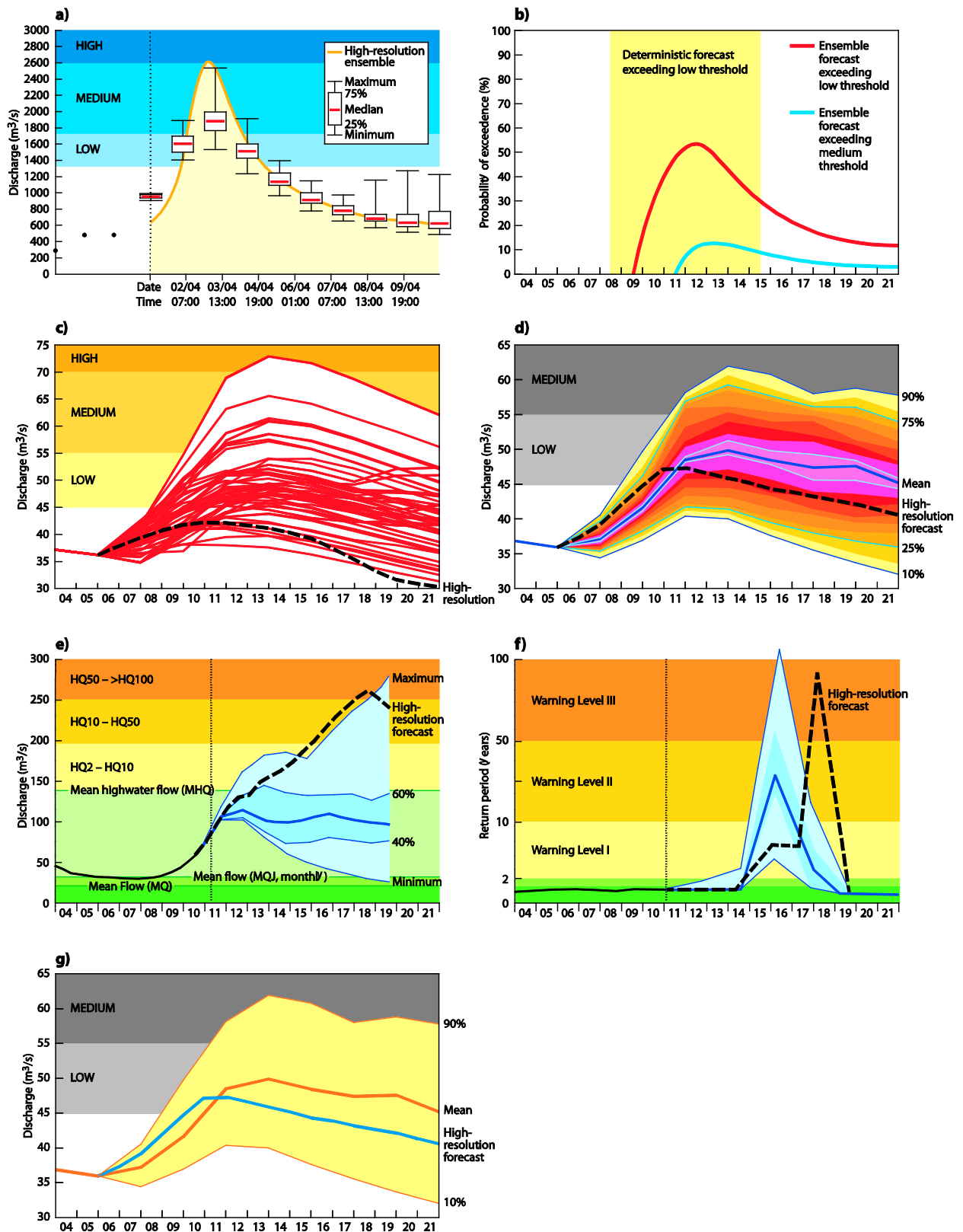


Figure 8: Blue prints of probabilistic hydrographs presented to the participants at the workshop