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Geoscience Communication Discussions

"Are we talking just a bit of water out of bank? Or is it Armageddon?" Front line perspectives on transitioning to probabilistic fluvial flood forecasts in England

Louise Arnal[1,2], Liz Anspoks[3], Susan Manson[3], Jessica Neumann[1], Tim Norton[3], Elisabeth Stephens[1], Louise Wolfenden[3], Hannah Louise Cloke[1,4,5]

[1]University of Reading, UK
[2]European Centre for Medium-Range Weather Forecasts, UK
[3]Environment Agency, UK
[4]Uppsala University, Sweden
[5]Centre of Natural Hazards and Disaster Science, Sweden

Correspondence to: Louise Arnal (l.l.s.arnal@pgr.reading.ac.uk)

Abstract. The inclusion of uncertainty in flood forecasts is a recent, important yet challenging endeavour. In the chaotic and far from certain world we live in, probabilistic estimates of potential future floods are vital. By showing the uncertainty surrounding a prediction, probabilistic forecasts can give an earlier indication of potential future floods, increasing the amount of time we have to prepare. In practice, making a binary decision based on probabilistic information is challenging. The Environment Agency (EA), responsible for managing risks of flooding in England, is in the process of a transition to probabilistic fluvial flood forecasts. A series of interviews were carried out with EA decision-makers (i.e. duty officers) to understand how this transition might affect their decision-making activities. The interviews highlight the complex and evolving landscape (made of alternative 'hard scientific facts' and 'soft values') in which EA duty officers operate, where forecasts play an integral role in decision-making. While EA duty officers already account for uncertainty and communicate their confidence in the system they use, they view the transition to probabilistic flood forecasts as both an opportunity and a challenge in practice. Based on the interview results, recommendations are made to the EA to ensure a successful transition to probabilistic forecasts for flood early warning in England.

We believe that this paper is of wide interest for a range of sectors at the intersection between geoscience and society. A glossary of technical terms is highlighted by asterisks in the text and included in Appendix A.

1 Introduction

One of the most recent and significant challenges in hydrology has been the inclusion of uncertainty information in flood forecasts. We live in a world where it is currently impossible to say with 100% certainty how the weather will evolve in the following days to months, or by how much exactly a river level is expected to change. This is due to the inaccurate measurement of hydro-meteorological observations*, errors in the mathematical models used to produce these forecasts (due to scientific and technical limitations) and, most importantly, nature's intrinsic chaos* (Lorenz, 1969; Buizza, 2008). In this world, probabilistic estimates of potential future floods are vital. Probabilistic forecasts* give a range of likely possible future outcomes, contrary to deterministic forecasts*, which indicate a single future possibility (Buizza, 2008). Probabilistic flood forecasts are generally produced by forcing* a hydrological model* with an ensemble* of future meteorological scenarios (Cloke and Pappenberger, 2009). By giving an idea of the uncertainty surrounding a prediction, probabilistic forecasts can give an earlier indication of potential future extreme events, such as floods, increasing the amount of time decision-makers have to prepare (Buizza, 2008; Stephens and Cloke, 2014).

In practice however, probabilistic forecasts can be challenging to use for operational decision-making*, given their uncertain nature (Nicholls, 1999; Cloke and Pappenberger, 2009; Demeritt et al., 2010; Nobert et al., 2010; Ramos et al., 2010; Stephens et al., 2019) . Having to translate a range of possible outcomes into a binary decision (such as sending out a flood warning) is intricate and requires careful interpretation, an understanding of probabilities, risk*, uncertainty* (Dessai and Hulme, 2004) and of the systems modelled. Furthermore, probabilistic forecasts are designed to capture scenarios that may not always realise, which in turn could lead to false alarms*. Decision-making can be based on a set of rules, such as threshold exceedance (Dale et al., 2013). It is, for example, possible to take decisions (e.g. send a flood warning) when a pre-defined threshold is reached with a minimum forecast probability (Thielen et al., 2009). However, the decision-making process is generally based on, and influenced, by several additional factors. These include the type of event considered (e.g. a localised small flood event vs a large scale extreme flood event), the costs of taking action vs not taking action, experience of past events, the decision-maker's trust in the forecast (which can be built up over time), their risk aversion, and the cultural context in which decisions are made (Cloke et al., 2009; Arnal et al., 2016; Neumann et al., 2018).

The Environment Agency (EA)* is responsible for managing risks of flooding in England and their flood incident management strategy* is often shaped by major flood events (Werner et al., 2009; Stephens and Cloke, 2014; Pilling et al., 2016). In the 1990s and early 2000s, the UK policy shifted from a 'flood defence' to a 'flood risk management' strategy, on the back of the 1998 and 2000 floods (McEwen et al., 2012), which has led to more forecast-based decision-making. The summer 2007 UK floods boosted the development of the National Flood Forecasting System and the Flood Forecasting Centre (FFC*; a UK Met Office and EA partnership), with the aim to improve national flood warning services (Pitt, 2008; Stephens and Cloke, 2014). The winter 2013/14 UK floods further demonstrated the value of the FFC and the use of ensemble surge forecasts* for flood preparedness* (Stephens and Cloke, 2014). It was also during the 2013/14 floods that the EA started using two fluvial (or river) flood scenarios* (a reasonable worst case* and a best estimate*, instead of a single prediction) for flood incident management. Following this, Defra (the UK government Department for Environment, Food & Rural Affairs)* published a National Flood Resilience Review (NFRR) in 2016 (HM Government, 2016; House of Commons - Environment, Food and Rural Affairs Committee, 2016). This review aimed at understanding and increasing the UK's resilience to river and coastal flooding from extreme weather over the next ten years. The NFRR recommends a better integration of probabilistic weather forecasts into flood forecast products, for an improved characterisation of uncertainty and an enhanced communication of flood risk and likelihood to inform a range of flood management measures*.

While catastrophic events can foster the uptake of state-of-the-art science (e.g. probabilistic forecasts) for decision-making, achieving a complete and successful transition relies on many elements. For example, the use of ensemble surge forecasts in 2013/14 might not have been possible without the prior shift to a flood risk management mindset and the creation of the FFC. Moreover, we do not want to be in a situation where we require a catastrophic event in order to begin implementing the best science into risk management practice; it is vital to understand a country's and institution's cultural landscape to ensure that science is not being under- or misused (Golding et al., 2017). In the case of probabilistic forecasts, making sure that they add value rather than uncertainty to operational decision-making is key (Nobert et al., 2010). Interviews can be an effective method to capture an institution's complex cultural landscape (Schoenberger, 1991; Pagano et al., 2004). They can provide interviewers with an understanding of the world (in this case the institution world) from the perspective of the informants, shedding light on their unique perceptions and information only known to them (Sivle et al., 2014).

As outlined by the NFRR, the EA is in the process of a transition to probabilistic fluvial flood forecasts, from the two flood scenarios they currently use operationally (Orr and Twigger-Ross, 2009; Sene et al., 2009). To capture the EA's forecasting practice landscape and understand how this transition might affect their flood decision-making activities, a series of interviews were carried out in the summer 2018 with EA 'Monitoring and Forecasting Duty Officers' (MFDOs) and 'Flood Warning Duty Officers' (FWDOs). These two roles are at the heart of the EA's flood risk management decision-making chain. The outcomes of these interviews were used as a basis for this paper, with the aim to highlight the potential opportunities and challenges that this transition might translate to for the duty officers, ahead of it happening.

2 Context: the Environment Agency's flood incident management strategy

The Environment Agency (EA) is an executive non-departmental public body, sponsored by Defra. The EA has an operational responsibility to manage risks of flooding from rivers and the sea in England, by warning and informing the public and businesses about impending floods. Flood warnings are sent with a 2-hour minimum lead time*, however, different lead times have recently been introduced to take into account the type of flooding and catchment characteristics*; i.e. flash flooding vs slow responding catchment. Under the Flood and Water Management Act 2010 (DEFRA, 2010), the EA takes a lead role on river and coastal flooding, whilst lead local flood authorities take a lead role on local flood risk (which covers flooding from other sources, including surface water, groundwater and minor watercourses). The EA also has a strategic overview role for all sources of flooding and works with lead local flood authorities by providing guidance, knowledge and support in responding to surface water flooding. The following schematic (Fig. 1) displays the EA's institutional landscape, with a particular focus on the flood incident management (FIM) information flow to and from MFDOs and FWDOs.

Historically, the EA was structured as a national body, delivering its work across England in six operational regional boundaries (i.e. regional boundaries were political delineations and were roughly aligned with the regional development fund boundaries). On 1st April 2014, the EA changed its operating structure to adopt area boundaries (i.e. broadly based on catchment delineations, but some catchments span different areas, especially at the borders with Wales and Scotland). These were aligned in 2016 with the Natural England (non-departmental public body, sponsored by Defra, and responsible for ensuring the protection and improvement of England's natural environment) boundaries. The EA is now operating over 14 areas with 7 forecasting centres (hereafter referred to as 'centres'; see Fig. 2).

To help manage flood risk, the EA receive hydro-meteorological forecasts* produced by the Flood Forecasting Centre (FFC; see Fig. 1) on a daily basis (more or less frequently depending on the forecasting product* – see Sect. 4.1.1). The FFC is a partnership between the EA and the UK Met Office. It combines the hydrological and meteorological expertise from both institutes to provide hydro-meteorological forecasting products (for all natural forms of flooding, including river, surface water, coastal and groundwater flooding) to emergency responders: category 1 (e.g. police services, fire and rescue authorities, including the EA for England), category 2 (e.g. utilities, telecommunications, transport providers, Highways Agency), Natural Resources Wales (for Wales) and the Met Office (for England and Wales).

The EA's FIM is based on the principle: 'think big, act early, be visible' (EA, 2018). This is part of a wider move from incident response to risk anticipation, with the aim to ensure that resources are put in place early and that the EA is prepared to scale-up or -down (i.e. preparations for measures implemented or not closer to the potential incident; e.g. expanded incident rotas with duty officers on standby, instigating requests for mutual aid to a different area, requests for equipment to support preventative and/or repair work, such as temporary barriers and pumps). As part of this strategy, the FFC forecasts are currently (and since the UK winter floods of 2013/14) used to produce two deterministic fluvial flood scenarios with a five-day lead time at the EA, a 'Best Estimate' and a 'Reasonable Worst Case'.

Several internal documents have been written to give guidance on how to use these scenarios to support decision-making for FIM activities, in line with the EA's principle. In summary, the Reasonable Worst Case gives an indication of what 'could' happen and should be used for preparation, information and response to flooding. The Best Estimate gives an indication of what 'should' happen and should be used as the basis for planning for warning. Together, the two scenarios provide the scale and size of the incident for planning and response preparations (FFC, 2017).

According to research done in the Thames river basin (UK), New et al. (2007) showed that probabilistic forecasts provide more informative results (enabling the potential risks of impacts to be quantified) than a scenario-based approach. The transition to the two scenarios can be seen as a stepping stone towards probabilistic fluvial flood forecasts. Ultimately, the EA would like to: 1) quantify uncertainty and communicate flood risk in a clear manner internally and externally, and 2) make decisions around incident preparation and escalation, operational activities and flood warnings effectively, intelligently and accurately. While the EA acknowledges that a potential benefit of probabilistic flood forecasts is the possibility to give earlier warnings, they question the extent to which probabilistic forecasts would reduce scientific and decision uncertainties in a FIM context (Orr and Twigger-Ross, 2009).

While work has already been done by the EA to investigate the technical feasibility of a transition to probabilistic fluvial flood forecasts (Orr and Twigger-Ross, 2009; Sene et al., 2009, Dale et al., 2013), this paper focuses on exploring the perceptions of the EA duty officers on the subject matter. This work is important as it will ensure the appropriate use of fluvial flood probabilistic forecasts for FIM decision-making activities, once operational. It should be noted that the EA already uses coastal flood probabilistic forecasts (Flowerdew et al., 2009); this work focuses on fluvial flooding. To this end, a series of interviews were carried out with EA 'Monitoring and Forecasting Duty Officers' (MFDOs) and 'Flood Warning Duty Officers' (FWDOs), as they are the two roles at the heart of the EA's internal forecast-led decision-making, building on the exchange between the MFDOs and the FFC (see Fig. 1; more information about their respective roles in Sect. 3.1 and 4.1).

3 Methods

3.1 Participants

The EA has several MFDO and FWDO roles, fulfilled by a number of different people. These are voluntary roles, added to the staff's day-to-day job, for which they follow relevant training. MFDOs receive, process and communicate forecast information to FWDO's, who are responsible for interpreting the information and working out the potential impacts on the ground. The duty officers' schedules are predetermined by a rota, and duty officers are on call for a period of one week at a time. During times of increased flood risk, when more forecasting or warning activities are required, additional rostering takes place. Duty officers receive a range of forecasts (nowcasting* products to monthly outlooks*) and are aware of potential situations from a month out. Five days ahead is when the activity really starts to build and is the focus of these interviews.

A total of six EA MFDOs and FWDOs from three different EA centres (one pair per centre) were interviewed to capture a range of perspectives in relation to this topic, following best practice (Sivle et al., 2014; participant information sheet provided as supplementary material). Forecasting and decision-making varies between EA centres due to different management approaches and different types of geography and catchment response. To protect anonymity, the three centres where interviews were carried out are shown in terms of the wider area they are responsible for: 1) the Yorkshire area (YOR) in the North (area 3), 2) the Thames area (THM) in the South East (area 11), and 3) the Solent and South Downs area (SSD) in the South East (area 14) (Fig. 2).

MFDOs and FWDOs were interviewed in pairs as they are used to working together and the information they use sits between these two roles. The thought was that by talking to the MFDOs alone we would lose the element of "and so what?", while talking to the FWDOs alone we would lose all the expertise about forecasting. All MFDOs and FWDOs interviewed had several years of experience and so were able to describe how current practice would change with a different type of forecast.

Participants were selected by EA study co-developer I1 to meet the above criteria. For the purpose of anonymity, the interviewees will thereafter be reported using codes. The three MFDOs interviewed will be referred to as MFDO1, MFDO2 and MFDO3, and the three FWDOs interviewed as FWDO1, FWDO2 and FWDO3 (interviewed pairs are however represented by the same number). As well as those from the MFDOs and FWDOs, quotes from two EA study co-developers are reported in this paper, I1 and I2, who helped the interviewer (Louise Arnal) by providing some context about the EA's organisational landscape, forecasting systems and MFDO and FWDO roles prior to the three interviews.

3.2 Interviews

By design, qualitative, semi-structured interviews are used to understand interviewees' perspectives, allowing the exploration of a research question that does not necessitate quantifying information and creating generalisations from the interview transcripts. The strength of such studies (compared to other survey methods) is that they are more sensitive to historical and institutional complexity and can capture the influence of local context (Schoenberger, 1991; Pagano et al., 2004). Moreover, they are flexible, allowing the interviewer to remodel questions throughout an interview and from one interview to the next, to follow up on new information discovered (Sivle et al., 2014).

A fixed set of open-ended questions were prepared in advance to guide the discussion and allow for comparability across all three interviews. To prompt discussion, all three MFDO and FWDO pairs were asked the same opening question: "Could you please walk me through what you would do ahead of a potential flood event?" The following questions were also prepared in advanced, but their order was changed, or they were skipped depending on whether the interviewees had already answered them:

- "Could you tell me about the uncertainties in the information you said you used in this context?"
- "How do you deal with these uncertainties?"
- "Could you tell me about how you communicate these uncertainties to each other?"
- "How would your job be influenced by a transition to probabilistic forecasts?"

Each interview lasted between 30 minutes and 1 hour 30 minutes. All interviews were conducted and digitally recorded by the first author (Louise Arnal) in meeting rooms at the corresponding EA centres.

3.3 Data analysis

All interviews were transcribed verbatim and transcripts were analysed qualitatively with respect to three main research questions. These research questions provide the structure for the results' section of this paper (Sect. 4).

1) What are the MFDOs' and FWDOs' roles and how do they interact with one another?
2) Where are the forecasts currently situated amidst their decision-making process?
3) Considering how the duty officers communicate confidence with one another at present, what might be the potential impacts of a transition to probabilistic forecasts on their roles?

Although interpretations might have been communicated by many interviewees, no frequencies are provided as quantitative generalisations cannot be inferred from this small and purposive sample. Following best practice, the results contain a mix of interviewees' perspectives, supported by quotes, and further interpretation of the interview transcripts by the authors, identifiable throughout the text (Davies et al., 2014).

4 Results

4.1 Roles and interactions between EA duty officers

Below, we summarise the MFDOs' and FWDOs' roles in an incident response context, using the interviewees' responses to the question: "Could you please walk me through what you would do ahead of a potential flood event?" It is worth noting that all interviewed pairs suggested the MFDO answer that question before the FWDO, indicating that the decision-making process starts with the MFDO.

> *"My role's an MFDO so generally if there's a flood event coming I should know before the FWDO, in theory" [MFDO2]*

4.1.1 The role of Monitoring and Forecasting Duty Officers

"Ramping up to a flood event, the MFDO gathers that information, processes it and filters it, and passes that along to the area staff [FWDO]." [MFDO2]

What information do they use?

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The MFDOs regularly receive FFC (Flood Forecasting Centre) national and county scale (i.e. area sub-divisions) flood risk forecasts and produce catchment/local scale flood forecasts, which they communicate with the FWDOs (see Fig. 3). The FFC generates three types of products:

- **Outlook products –** annual, seasonal and monthly assessments of flood risk;
- **Flood Guidance Statement (FGS)* –** a five-day forecast of flood risk for all sources of flooding, for England and Wales, at a county scale (see Appendix B, Fig. (a) for an example);
- **Hydro-Meteorological Services* –** detailed products communicating flood forecast data, currently comprising Hydro-Meteorological Guidance, Forecast Meteorological Data and Heavy Rainfall Alerts (see Appendix B, Fig. (b), (c) and (d), respectively, for examples).

How do they use this information?

Based on this suite of information, the MFDOs decide whether they want to run the hydrological forecasting model, which sits in a separate system called the National Flood Forecasting System (NFFS; see Appendix B, Fig. (e) for an example). The decision can be triggered by the colours shown on the FGS (which communicates flood risk as a combination of likelihood and impact; e.g. high flood risk values on the FGS are more likely to lead to the MFDOs running the hydrological model). The NFFS allows users to explore the observed data (i.e. river levels and rainfall) and run hydrological and hydraulic models*. These models, forced with the FFC's deterministic weather forecast, provide a single trace of past and future (i.e. for the next five days) river level for specific areas. This initial forecast scenario is usually referred to as the 'Best Estimate' scenario, showing what 'should' happen. What 'could' happen (i.e. the 'Reasonable Worst Case' scenario) may not always be run.

> *"If there's uncertainty in the forecast like if there's showers […] especially when they're thundery and they can give you really high totals in a very short space of time that's when you start to run 'What If' scenarios" [MFDO1]*

'What If' scenarios (i.e. 'Reasonable Worst Case' scenarios) are additional forecasts run by the MFDOs by manually modifying the FFC's deterministic weather forecast (usually through the use of predefined factors applied over an entire catchment; e.g. 200% of catchment rainfall totals in the next 6 hours). They then run this 'modified weather forecast' through the hydrological/hydraulic models to obtain a new river level forecast scenario, often referred to as the 'Reasonable Worst Case' scenario. The MFDOs choose which What If scenario to run based on the FFC Hydrometeorological Guidance and their own expert knowledge, to estimate the likelihood of both scenarios (the 'Best Estimate' and the 'Reasonable Worst Case').

> *"[The FFC] might give us a number of different scenarios and we tend to pick the worst one and then see what that does" [MFDO1]*

A critical part of the MFDOs' role is to interpret the different forecasting products, which might sometimes be inconsistent (e.g. differences between the national and local scale pictures). The MFDOs usually do this by applying expert judgement based on knowledge of model performance and catchment response* to make a coherent story and put the information into context for the FWDOs.

The MFDOs decide when to pass the information on to the FWDOs, generally waiting for the forecast to be confident* before flagging a situation. The exact content of the communication depends on each pair, but usually contains information about the scale of the event and their confidence in the forecast.

> *"Which scenario is going through which threshold [and] how likely that is to happen" [MFDO1]. "Approximate […] scale of the event […] are we talking just a bit of water out of bank? Or is it Armageddon?" [MFDO2]*

The conversation can sometimes be bilateral, and the MFDOs might ask questions to the FWDOs.

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> *"Can they provide information […] in terms of local sensitivity […] and are works going on in that catchment? Is there a gauge out of play?" [MFDO2]*

4.1.2 The role of Flood Warning Duty Officers

> **"The role of the FWDO is to make sense of all that forecasting information and try and work out potentially what the impacts could be of that on the ground and then make decisions as to whether or not [they] issue flood alerts, flood warnings or severe flood warnings." [FWDO1]**

What information do they use?

The FWDOs' role is to combine several different types of information to decide whether to issue a flood alert or warning (see Fig. 3). The information available to them includes:

- **The processed hydro-meteorological forecast and interpretation from the MFDOs**
- **Factors within the catchment** that could influence river levels (e.g. blockage from a tree fallen down). This is ad-hoc information and comes from a variety of sources, including: information gathered from community contacts (flood wardens*, flood action groups*, etc.), from EA staff and duty officers, hydrometric data/CCTV images, details of consented works (i.e. work going on in a channel);
- **The situation on nowcasting meteorological products** (e.g. rainfall radar);
- **Information about the communities that might be affected** (e.g. have they been affected by many floods in the past);
- **Expert knowledge about catchment response.**

How do they use this information?

The FWDOs assess these various sources of information (e.g. in terms of their accuracy) to make a decision, knowing that they do not necessarily have all the information to make a judgement call.

> *"I look at the river level forecasts and then what I want to know from the MFDO is, does this account for the rain we've had? So, do you think this is likely to change? Is the forecast I'm seeing on my screen a good river level forecast? Or do we think it's not picked something up properly?"* [FWDO2]

According to an internal document on using the two flood scenarios in practice, the *Best Estimate* should be used as a basis to issue flood alerts or warnings. However, both scenarios are currently used for incident planning activities (e.g. resources needed for response) and communication with responders and communities, while flood alerts and warnings are mostly issued based on nowcasting products. This discrepancy could be due to the challenges associated with forecast accuracy* and lead time, specifically for surface water flooding* and rapid-response catchments*. This document does however encourage the use of the two scenarios for planning and flood warning activities whenever possible, in combination with expert judgement.

> *"The scenarios are planning scenarios and at some point […] we move into operational now type forecasting. So normally we'd issue a flood warning with anywhere between 30 minutes to […] six hours lead time, whereas these scenarios are generally two to five days ahead. So you wouldn't normally […] come up with a simple statement that will issue flood warnings based on the best estimate […] and at some point we transition into something that's more now that we use for operational decision making" [I1]*

4.1.3 Communication between MFDOs and FWDOs

"The FWDO shouldn't even really be thinking about anything until they've had a phone call from the MFDO […]. Some FWDOs do go a bit more proactive than that, I think particularly the ones with the forecasting backgrounds almost can't help themselves looking into it. And it depends on personality as well, some people hate the idea of being surprised by anything. But it does also depend on the MFDO." [FWDO2]

There is usually a constant exchange of information between MFDOs and FWDOs, even when no major event is on the horizon. However, more recently, the level of activity in preparation for a potential event has increased. Since 2007 (this corresponds vaguely with the summer 2007 floods), the lead time for which forecasts are shown and on which MFDOs and FWDOs can take action has increased from a few days to a few months ahead (based on the FFC's outlook products mentioned in Sect. 4.1.1). This is consistent with findings from Neumann et al. (2018), who report that the EA currently uses long-range* (i.e. seasonal) hydrological forecasts mainly as supporting information, while relying on the shorter-range forecasts* for action.

"So even from a month out now we're starting to become aware of potential situations […], but […] because […] most of our products […] are […] based on that five-day forecast […] that's when the activity really starts to build" [MFDO1]

The communication between MFDOs and FWDOs varies across people and EA centres. Factors that might influence communication – in terms of its trigger, frequency and content – include the duty officers' personality, day-to-day job and level of experience. Some FWDOs are more proactive than others in obtaining the information needed to make a decision; some might wait to be contacted by the MFDOs with a processed forecast, and others monitor the situation on a daily basis (see quote from FWDO2 above). In some cases, the FWDO might contact the MFDO first to get more details about an area of concern to them.

"[…] and […] then it's […] liaising with regional forecasting [the MFDOs] so they can give us any more detail or certainty or if we're concerned about an area they can watch it a bit more for us [the FWDOs]" [FWDO3]

Duty officers' level of experience can also influence the content and interpretation of the conversation. Knowing each other helps interpret and gauge the confidence from each other's language, which MFDO2 refers to as 'nuanced communication'. Working with new duty officers can lead to misinterpretations and you might have to justify your position further and prompt them to obtain the information you need.

"I've known [FWDO1] for quite a while so when I'm on duty with [them] […] I can sense […] what sort of questions [they] want to ask, where [they're] coming from. I think with less experienced duty officers it's often more tricky to do that. So […] the verbal communication that you go into with [FWDO1] for example might be a bit brief probably because I know that [they've] understood the message and interpreted the message well, whereas a new duty officer you might be spelling out […] your position more, spending more time explaining why the uncertainty is such and how that may impact on the ground" [MFDO1]

"Knowing each other is really important because if I know it's [MFDO2] on duty [they've] probably put that interpretation on already. If I get someone who's reading off the screen, I put the interpretation on and if we misjudge that and we both put it on we could end up getting it too low" [FWDO2]

Other factors that influence communication include the context of the event, duty officers' geographical proximities and a centre's practice. In some areas, the FWDOs will make the final call of warning the public or not, while in other areas, the MFDOs will tell the FWDOs when they need to issue a warning. In addition, MFDOs and FWDOs do not always sit in the

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same building or town. MFDOs work from forecasting centres, while FWDOs are based in Area offices or Area incident rooms, which influences their (mode of) communication (in person vs via phone or emails).

"If these people [the FWDOs] were sitting geographically with these other people [the MFDOs], I think you'd get a better service" [I1]

4.2 The forecast, a small cog in a much bigger wheel

"Forecasting's really important. It is, it should be really central to what we do […] but actually it's a small cog in the middle of a much bigger wheel." [I1]

Forecasting supports incident response by providing a critical piece of information. However, duty officers have to consider a range of other sources of information and factors when making risk-based decisions.

"We always implore people to try and look at different sources of information" [I2]

These additional sources of information include river level correlations*, model performance*, local knowledge (i.e. knowledge of how a certain catchment behaves), personal experience, and internal and external considerations (see Fig. 4). This section gives a more detailed overview of these factors and their relevance for decision-making.

4.2.1 River level correlations and model performance

"The MFDO will be looking at how much rain is falling compared to what was forecast. You can check the river levels on the telemetry sites*, so you can see how fast they're responding compared to the model and you can start to gauge how that catchment's responding compared to what you thought it would do" [MFDO1]

MFDOs might use several products to gain an understanding of model and forecast performance while the event unravels. More basic forecasting methods, like river level correlation tables, complement forecast information and aid the decision-making process. These correlations are based on a linear regression between peak levels upstream and downstream of a station. However, discrepancies between the forecasts and correlations can call into question the forecast accuracy.

"If the model says you're going to get flooding, the correlation says we're going to get flooding, we've had more rainfall than any previous event, you know that that decision's […] a clear one. If the model says flooding, the correlation says no you're fine, and we've had somewhere in the middle in terms of rainfall, that's when it gets difficult, because those borderline calls are really tricky to make" [I2]

The MFDOs' knowledge of the hydraulic/hydrological model performances, for certain types of events and catchments, is also key in interpreting the forecast. This is based on performance measures*, local feedback from real time river gauges*, experience and target lead times (i.e. the theoretical maximum lead time you have to send out a flood warning for a catchment before it floods, based on catchment size, gauge location and flood risk in that catchment). For certain types of events, such as convective rainfall events*, for which the duty officers know models are still limited, they might decide to issue a warning based on the 'Reasonable Worst Case', although it is *"technically against procedure" [MFDO2]*.
The FFC meteorological products also communicate some sort of confidence, which the MFDOs can use to complement the hydrological models' performance information.

4.2.2 Local knowledge and personal experience

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"Whilst we are very data reliant on the information coming through, there's also that experience that you know that certain watercourses are very slow responding and […] no matter how much money we spend on your forecast, it's always not very good, you always delay it by a day and drop the peak by a bit. […] Data is very important but that local experience is as important if not more so in certain circumstances" [MFDO2]

Local knowledge and personal experience are key ingredients for judgement, an important component of the decision-making process. This means duty officers can react appropriately to an event and add confidence to the forecast. As MFDO2 put it, *"experience is the unwritten part of the value that each role has"*.

Local knowledge is so important to decision-making that the interviewees believe it cannot be replaced by training, written material or fully automated systems.

"Some areas have very set triggers for a severe flood warning whereas other areas may just take it on a feel. […] And each area has done it for a good reason, it's the local reasons for doing that but it isn't nationally consistent" [MFDO2]

"We have in the past looked at automated warnings […], we can't automate them […], there's a lot of personal interpretation and judgement [that] goes into it, and if a computer just hits a level and issues a warning, it's going to go wrong" [FWDO2]

This also manifests itself in perceptions about how successfully duty officers can transfer to other centres or areas to help during an important flood event.

"One of the things we're trying to do at the moment is to get mutual aid sorted out so that if a flood event happens in [some of the Northern areas] and their MFDOs […] or the FWDOs are very […] stretched […] we can go […] there, use their tools, their systems and do the same job. But whenever we've tried it the local knowledge is the key thing. Like knowing that this river responds particularly quickly and that we need to deal with it first before we move on to other ones that's the sort of thing that even if you're picking it up whilst you're working in a different centre it's affecting your ability to deliver the role at the time" [MFDO1]

Duty officers have access to tangible information about past flood events that can be useful for placing model information into context. The 'Flood Intelligence Files' compile information (e.g. highest events on record, what rainfall led to them, what the catchment state was at the time and any known impacts) for every gauge the EA is providing forecasts for.

How information is interpreted, risk appetite and past experience, can all affect decisions taken. There is the danger of following instincts too much and becoming biased towards issuing too many (i.e. risk-averse) or not enough warnings (i.e. risk-hungry), while in some cases decisions might never be forecast-led.

"Since the Boxing Day floods I think the next level of flooding after that there was some discrepancies amongst the area responses […] they were a bit […] jumpy […] to not be caught out again which is understandable" [MFDO2]

"these kind of decisions about do we need to draw up a roster, do we need to be in the office overnight, a lot of that has probably been done on gut feel, probably this FWDO being the advisor. […] Do we need to do whatever based on judgement, experience, feel for it. […] I wouldn't expect these people to actually be looking at any forecast and saying, based on this I will do" [I1]

4.2.3 Internal and external considerations

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"There are lots of external pressures as well, particularly as FWDO you can come under pressure from all different types of sources to make decisions and perhaps not based on the evidence that you've got for political reasons, […] reputational reasons, organisation, in terms of being seen to be active, seen to […] act early" [FWDO1]

Decisions are not only dictated by the science, local knowledge or personal experience and differences, but might have to respond to internal and external considerations, especially during major events.

At an internal level, some areas and duty officers might be more forecast-led while others are more reliant on a nowcasting type approach. Discrepancies amongst the area responses are partially due to historical differences across the different areas and EA centres.

"There are definite differences between areas and […] between individual staff, so [town X] are far more likely to issue flood alerts […] purely on rainfall than [town Y] is, [town Y] will generally wait for a river level to rise and that develops I suppose out of slight historical differences and personalities involved" [FWDO2]

"Some other areas will issue messages based on forecast whereas, we were always told to base it on what's happening, so we kind of wait to see if the rain comes in and then if anything happens issue. And we get marked on messages that we send out, so one of the things is the timeliness and if you've issued one, did it actually flood afterwards? So if you're obviously issuing on a forecast, then you're probably going to get scored low because it doesn't always happen, so it's difficult" [FWDO3]

There are exceptions to these procedures and FWDO3 mentions the possibility of issuing flood alerts based on the forecast when the impact is expected to occur overnight or if the forecast displays *"rarely high confidence"* of rainfall and *"if it's a more prolonged event"* and *"you know the catchment's already wet"*.

The EA's principle, 'think big, act early, be visible', is an example of an internal consideration, which might influence the duty officers' decision-making (EA, 2018). In what ways does the EA's statutory warning responsibilities and principle influence decision-making? Does 'act early' put the forecast in first place while 'think big' and 'be visible' move it to a secondary position?

"Our mantra to incident response is think big, act early so sometimes […] there is a danger that you're over responding. Somewhere you're issuing alerts and warnings when actually the risk is low. So I think the role of the FWDO is to assimilate all that information, forecasting information and using it to help inform the instant response but also manage expectations" [FWDO1]

There is usually a political element (external consideration) to the response immediately following a very major flood, as the EA puts a greater focus on demonstrating to communities and the government that they are being proactive in warning, informing, etc. There is also the need for the EA to align its message with actions of lead local flood authorities and responders and to think about public response.

"It's managing expectations internally in terms of operational response and how this is going to potentially play out which […] can still be quite hard to do but it's even harder to do it externally with [the] mood of the public or even some of our professional partners, so local authorities are also obviously geared up to respond to flooding" [FWDO1]

To conclude this section, it is evident that the duty officers have to take different sources of information, besides the forecast, into consideration to make a decision. However, the forecast helps determine the timing of warning and response activities. Because the forecast plays a seemingly small part in a much bigger system, could that mean that the transition to a different

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type of forecast will have very minor impacts on the duty officers? Or on the contrary, could it unsettle this very complex machine?

4.3 What could a transition to probabilistic forecasting mean in practice?

4.3.1 Current practice: communicating confidence for decision-making at the EA

"Uncertainty is present in everything that we do and every bit of communication, […] I don't think I've ever been able to say something with 100% confidence, ever." [MFDO2]

We have previously touched on the factors and uncertainties duty officers have to work with, including uncertainties in: the weather (and how it cascades down to hydrological response), model performance, the different spatial scales of response (local vs national), the situation on the ground (e.g. soil conditions prior to an event and river blockages), EA staff decisions and actions, and the public's reaction to warnings.

Duty officers currently adapt the language they use to communicate these uncertainties internally and externally, based on their confidence level. According to internal EA guidelines, the language used should change according to the scenario used so that duty officers *"get used to the [..] way they're working around scenarios and probabilistic forecasting" [I1]*.

> *"If messages around a 'Reasonable Worst Case' use, could or […] is possible; if it's a 'Best Estimate' use, we expect, it's probable" [I1]*

Between the MFDOs and the FWDOs, confidence and uncertainty appears to always be (based on these interviews) communicated, usually using the two flood forecast scenarios.

> *"I don't think we can withhold uncertainty. One, the key role for MFDO is providing the forecast. So it's getting the forecast as accurate as you can and then communicating it in the clearest way possible. So that's often about interpreting the uncertainty and communicating it. So we often use the 'Reasonable Worst Case' and the 'Best Estimate' to do that" [MFDO1]*

Messages to the public are also worded with care to communicate the appropriate level of risk and prompt appropriate response and also contain some information about confidence and uncertainty. These messages are usually free-text messages and will therefore vary from across FWDOs.

> *"The message starts off with this flood warning has been issued for this place then it runs on after a while into detail which is where you can communicate those shades of grey" [FWDO2]*

However, not all uncertainties are critical, and local knowledge and experience are key for the *"interpretation of the uncertainties" [FWDO2]* and their impact on the ground.

> *"Uncertainty from the forecasting point of view is always prevalent but understanding how it will impact the […] area's reaction is kind of the key thing" [MFDO2]*

There is currently space for the communication of confidence at the EA and externally. This is a step towards probabilistic forecasting. But how big of a step is it? And how big of a step is still needed to reach that full transition to probabilistic flood forecasts?

4.3.2 The duty officers' perceived opportunities and challenges

"Whether it creates as many problems as it solves, maybe" [I2]

The transition to probabilistic forecasts is a significant evolution, which generates mixed feelings amongst the duty officers. It is undeniable that this transition will bring changes at the EA; as *FWDO2* put it, *"probabilistic forecasting is kind of a fresh start for everyone"*. This section presents the interviewees' perspectives on the changes that will ensue from this transition, in terms of perceived opportunities (left wordcloud on Fig. 5), challenges (right wordcloud on Fig. 5) and neutral changes. Table 1 outlines these perspectives, split into six main topics and supported by quotes reported in Appendix C.

Some of quotes reported in Appendix C might sound very extreme, which could be partly due to the way the questions that prompted them were phrased. However, it could also reflect personal resistance and should be explored further.

5 Discussion and recommendations

5.1 Considerations for a successful transition to probabilistic forecasts

Probabilistic forecasts have a great potential to capture extreme events (Stephens and Cloke, 2014), and their benefits (compared to deterministic forecasts) for flood warning are evident (Verkade and Werner, 2011; Pappenberger et al., 2015). However, despite the increasing lead times at which we can confidently predict floods, the uncertainty inherent in the chaotic natural system being modelled grows with increasing lead times, posing new problems. As science and decision-making are both individually progressing, adapting to their respective internal and external changes, there still lacks an ideal framework for the incorporation of new and 'uncertain' science in decision-making practices, and, respectively, the uptake of decision-makers' perspectives in the design of scientific practice. Here, results from this study and relevant literature are joined to put forward elements that should be considered for a successful transition to probabilistic forecasts for flood warning in England.

From these interviews and previous EA studies, it is apparent that forecasts are one element in the complex decision-making landscape within which EA duty officers operate (Orr and Twigger-Ross, 2009; Dale et al., 2014). This landscape includes alternative 'hard scientific facts' (e.g. correlations, model performance and local knowledge to an extent), and 'soft values' (dependent on culture and context, personal experience and internal and external considerations) (Morss et al., 2005; Cloke et al., 2009; Arnal et al., 2016; Neumann et al., 2018). Morss et al. (2005) found that "although flood management practitioners might appreciate more certain hydro-meteorological information, scientific uncertainty is often swamped by other factors [e.g. community perception, time, money and resource constraints] and thus is not a high priority." When uncertainties are evident and decision stakes are high, as is the case for the uncertainty communicated by probabilistic forecasts for flood incident management, traditional decision-making pathways could become ineffective and soft values might become more important than hard scientific facts (Funtowicz and Ravetz, 1993). In this specific study for example, an uncertain probabilistic forecast could lead to some duty officers reverting to the 'Best Estimate' and the river level correlations to make a decision, ignoring low probabilities of extreme events which could have ultimately led to an earlier flood warning.

Facing constantly evolving soft values, some decision-makers may find familiarity with the scientific methods they use reassuring, reducing their personal willingness to adopt new scientific methods (Morss et al., 2005; Ishikawa et al., 2011). This personal willingness was captured in the range of responses (perceived challenges and opportunities) obtained during the interviews. An institute's operating practice should reflect the complex landscape in which decision-makers operate, where the forecast plays an integral role in decision-making. To this end, the co-design of forecasting systems by both forecasters and users is necessary.

To do that, clear communication between forecasters and users is needed. However, language is perhaps one of the biggest barriers between scientists and decision-makers. It has been observed that "the way scientists referred to and discussed uncertainty sometimes confused practitioners" (Morss et al., 2005). Similarly, there is a lot of research done on the impacts of graphical representation of uncertainty in hazard forecasts on decision-making. These have shown that great care has to be taken when designing and communicating uncertain information, as it can impact the nature of the actions taken (Bruen et al., 2010; Joslyn and Savelli, 2010; Stephens et al., 2012; Pappenberger et al., 2013; Sivle et al., 2014).

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There is the common misconception amongst the scientific community that decision-makers want 100% certain information (Demeritt et al., 2013; Michaels, 2014). In reality, as shown in this paper, decision-makers appreciate that scientific information is uncertain, not unlike other types of information they use. Decision-makers want to see that uncertainty, which they do not necessarily perceive as a barrier to use (Morss et al., 2005; Bruen et al., 2010; Neumann et al., 2018). One reason for this misconception might be the different ways scientists and decision-makers approach forecast uncertainty. Scientists see (the reduction of) forecast uncertainty as an end goal and "often deal with uncertainty by attempting to reduce, quantify, analyze, and/or assess it". Decision-makers "view uncertainty as an unavoidable factor […,] all information about the future is uncertain [and] they must make decisions under uncertainty every day, in a complex, evolving social, institutional, and political environment" (Morss et al. 2005).

In this complex evolving landscape, decision-makers deal with forecast uncertainty similarly to other uncertainties they might face: under time and resources constraints. They assess the total uncertainty there is (the forecast uncertainty might sometimes be negligible compared to all the other factors at stake) in terms of its potential effect on the decision-making process and outcome (Morss et al., 2005). As mentioned by a few EA duty officers, uncertainty is prevalent in everything that they do, and the key is understanding what the impact of these uncertainties will be on the ground. It is crucial to develop a methodology for decision-makers to be able to use (forecast) uncertainty information optimally. A solution that does not require any additional time- and resource-consuming complex analyses, given the high stakes and strict deadlines decision-makers have to work with. Smith et al. (2018) argue that if there was a "greater involvement of decision-makers in the design and execution of uncertainty analyses", "more purposeful evaluation and communication of uncertainty would certainly result". This remains an open challenge to be tackled.

By design, probabilistic forecasts might contain some realisations that capture scenarios which do not always realise. This may lead to false alarms. Institutions can have specific risk perceptions and flood management priorities: seeking to avoid false alarms, or on the contrary, seeking to avoid missed flood events*, and the minimum/maximum lead time at which they (have to) issue flood warnings. This cultural landscape within which decision-makers operate may have an impact on the decision-making outcome (as discussed in Sect. 4.2.3) and an institution's uptake of probabilistic flood forecasts in practice (Nobert et al., 2010; Ishikawa et al., 2011; McEwen et al., 2012; Demeritt et al., 2013; Michaels, 2014). A transition to probabilistic flood forecasts should be reflected in an institution's wider flood management priorities. This could be done, for example, by changing their internal communication pathways or their warning procedures (e.g. lead times at which they operate).

Very often however, the ability of an institution to pick up new information and methods is not only down to them, but could be influenced by the wider socio-political context and other key actors in the decision-making web (e.g. the government, local authorities, regulations and guidelines), additionally to the populations at risk and the way they respond to flood warnings (Dessai and Hulme, 2004; Morss et al., 2005; Parker et al., 2009). This is reflected in the interviewed EA duty officers' perceived challenges regarding 'Language & communication' and 'Binary decision-making' (Sect. 4.3.2). In the face of a socio-political context that is demanding ever more precise information and with the rise of a post-factual society, the general trust in science might be a limiting factor to the uptake of new science and institutions should trust their capacity to use uncertain probabilistic information (Soares and Dessai, 2015; Golding et al., 2017; Knudsen and de Bolsée, 2019).

It is also important to note that "moving to probabilistic forecasting from deterministic forecasting may trigger an institutional shift in who is responsible for decision making under uncertainty" (Michaels, 2014). Because making a decision based on probabilistic information is more nuanced than using deterministic information, the outcome will determine who will be 'blamed' and this ownership of the uncertainty judgment might have implications on the forecasters-users relationships (Michaels, 2014). This relates to some of the interviewed duty officers' fears of a transition to probabilistic forecasts at the EA, as it might move "the burden of making a decision further down the tree" (Sect. 4.3.2). In this context, a framework to engage with all key actors of the decision-making web ahead of and during a transition to probabilistic forecasts appears crucial. Ramos et al. (2010) advocated the use of integrated platforms to allow a continuous exchange between scientists and

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decision-makers in real-time. Similar studies on the provision of climate services have identified the lack of user engagement as a great limiting factor of the uptake of climate information in practice (Golding et al. 2017). It is evident that a transition to probabilistic forecasts is not only a scientific endeavour and feasibility studies should include other disciplines, such as social-science.

5.2 Recommendations to the EA

In light of the findings of this study, and other relevant studies, we make a list of recommendations to support the uptake of probabilistic forecasts at the EA. These ten recommendations are high priority actions for the EA as an institution. The service, role owners and those responsible for ensuring a quality service delivery should ensure that these recommendations are pursued, alongside technical work around the transition. Please note that these recommendations are not ranked in priority order for the EA, as some of these will be quicker and easier to implement and to demonstrate progress on.

1) Communicate (via engagement campaigns, videos, email newsletters, social media updates and webinars, etc.) with all key players in the decision-making chain (as well as external players such as the emergency responders and the public) to ensure that they are all aware that the transition to probabilistic forecasts will become operational practice.

2) Give appropriate and custom designed internal training to all key players (Nobert et al., 2010). Duty officers must receive training on how to make decisions based on probabilistic forecasts (for example in the form of decision-making activities and serious games - see the HEPEX[1] and the Red Cross Climate Centre[2] resources for inspiration).

3) Expand existing EA communication structures to allow the co-design of the new products between forecast producers and users (Morss et al., 2005; Smith et al., 2018). Everyone using the forecasting products and systems at the EA should have the chance to have a say in how the system will look and function through a mutual design strategy. If the new system does not reflect the complex landscape in which duty officers operate (a mix of 'hard scientific facts' and 'soft values'), probabilistic forecasts might end up being under- or misused.

4) Reach out to the community of practice in hydrological probabilistic forecasting, such as HEPEX[3] (community of international experts in the field of probabilistic hydrological forecasting and decision-making) and connect with institutes which have already gone through such a transition to gain insights and share best practice, as some elements might be transferrable (Nobert et al., 2010; Dale et al., 2014). This could be done through organised workshops, webinars and the establishment of an advisory group.

5) The way probabilistic information will be translated into meaningful content and communicated to the emergency responders and the public requires careful thought and design (Bruen et al., 2010; Joslyn and Savelli, 2010; Stephens et al., 2012; Pappenberger et al., 2013; Sivle et al., 2014). To this end, an interdisciplinary approach between forecasters and social-scientists would be greatly valuable as social-science can offer insights into the human response to warning messages. A tailored and inter-disciplinary study of the forecasting products using probabilistic information and used in the decision-making process is urgently required.

[1] hepex.irstea.fr/resources/hepex-games
[2] www.climatecentre.org/resources-games/games
[3] hepex.irstea.fr

6) a) The EA's heterogeneity at the national level should be accounted for and addressed. Given the heterogeneity of the EA at a national level and the areas' diversity in terms of history and catchment response, we do not expect probabilistic forecasts to be welcomed similarly in all the EA centres. Efforts will therefore have to be made by the EA to achieve a simultaneous and homogeneous transition in all its centres.

b) Furthermore, the design of the new forecasting system should be homogenised at the national level (to allow for staff movement during major flood events), while accounting for the heterogeneity of local conditions, existing dynamics and institutional practices. This could be achieved through the co-design of the forecasting system with local duty officers (see recommendation 3).

7) Be prepared to move towards lead times that reflect the probabilistic forecast predictability. The optimal lead time to trigger action depends on both the probabilistic flood forecast quality and the actions' operational implementation time (Bischiniotis et al., 2019). While the EA operates with pre-defined lead times for each specific activity (e.g. it takes x hours/days to move equipment from A to B, or to deploy temporary defences), probabilistic forecasts could in theory provide earlier indications of potential future floods, giving the EA more time to prepare ahead of a flood event. To utilise probabilistic forecasts to their full potential, tailored studies should be performed during the EA system's co-design to adjust lead times (for planning and warning) on the probabilistic products and event types, with ample time for testing by the EA duty officers.

8) Under no circumstances should the old system be switched off as soon as the probabilistic system is operational. There should be a reasonable period of overlap between the two systems in order to give everyone some time to gradually adapt (Funtowicz and Ravetz, 1993). During that time of overlap, end-user feedback should be collected (Thielen et al., 2006). To avoid situations where the probabilistic forecast and the two scenarios show contrasting results, the new operating procedures need to specify that the probabilistic forecasts should be looked at first.

9) Update the duty officers' operating procedures. Clear guidelines should be provided to the duty officers on how to make a decision based on the new probabilistic products. These guidelines should include information such as: the various sources of information available to them for making a decision, how to interpret a probabilistic forecast, the forecast confidence at which certain decisions and actions should be made and the language that should be used.

10) Document this transition (in writing or through documentary-style interviews, etc.) to help other institutes and future transitions at the EA (Pielke, 1997). While this paper investigates how things might change, post-transition evaluation should seek to answer the question: "How did we do?"

Many of these recommendations are however general and could be applicable to other institutes and types of information.

6 Conclusions

The Environment Agency (EA) is in the process of a transition to probabilistic fluvial flood forecasts, from the two flood scenarios they currently use operationally for flood warning and incident management activities in England. State-of-the-art probabilistic forecasts can give an earlier indication of potential future extreme events, such as floods, increasing the amount of time decision-makers have to prepare. A series of interviews were carried out with EA 'Monitoring and Forecasting Duty Officers' (MFDOs) and 'Flood Warning Duty Officers' (FWDOs), two roles at the heart of the EA's flood risk management

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decision-making chain. The aim was to understand how an operational transition to probabilistic flood forecasts might affect their decision-making activities. Overall, none of the interviewed duty officers mentioned concerns about impacts of this transition on their two roles' interaction. Perceived challenges lie mostly outside of their roles and relate to: communication with emergency responders and the public, translating uncertain information into a binary decision and the speed of the transition. Ten high priority recommendations were made to the EA to ensure a successful transition. They include: i) communicating with all key players in the decision-making chain (as well as emergency responders and the public) to ensure that they are all aware that this transition will become operational practice, ii) facilitating the co-design of the new products by forecasters and users and collecting end-user feedback during a reasonable period of overlap between the two systems, iii) employing an inter-disciplinary approach to translate probabilistic information into meaningful content for communication with emergency responders and the public, and iv) being prepared to adapt the EA's overarching warning and incident planning strategy to reflect this transition. It is vital for these recommendations to be followed to ensure that state-of-the-art science is used to its fullest potential for risk management practice and is not being under- or misused.

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Disclaimer. The information and findings in this paper are based on interviewees with six EA duty officers. They should not be taken as representing the views or practice of the EA as a whole.

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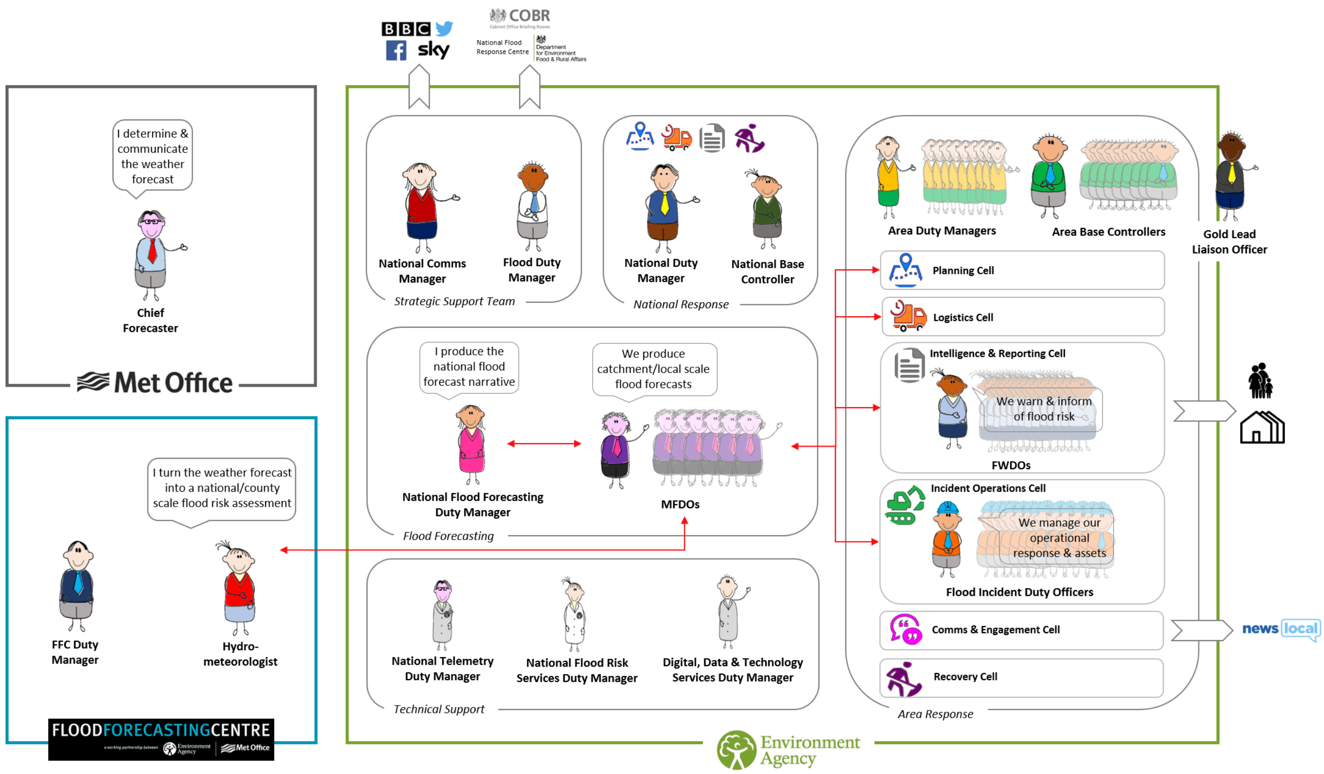

Figure 1: Schematic of the EA's institutional landscape and the FIM information flow between MFDOs, FWDOs and first-degree contact points (red arrows) (source: EA).

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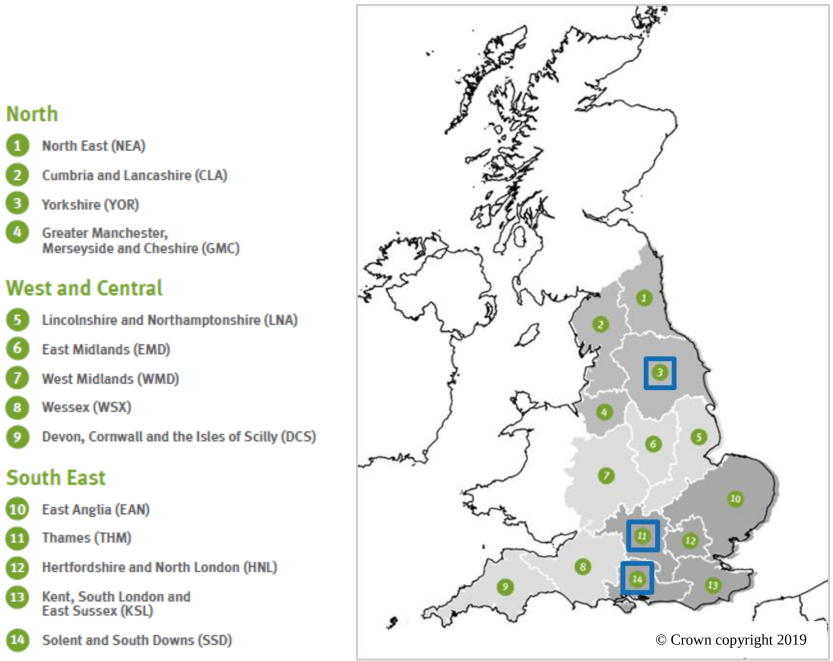

Figure 2: Map showing the geographical areas of the EA's operations (green numbered areas), highlighting the three areas which the centres where interviews were carried out are responsible for (blue boxes) (source: EA). The works published in this journal are distributed under the Creative Commons Attribution 4.0 License. This licence does not affect the Crown copyright work, which is re-usable under the Open Government Licence (OGL). The Creative Commons Attribution 4.0 License and the OGL are interoperable and do not conflict with, reduce or limit each other.

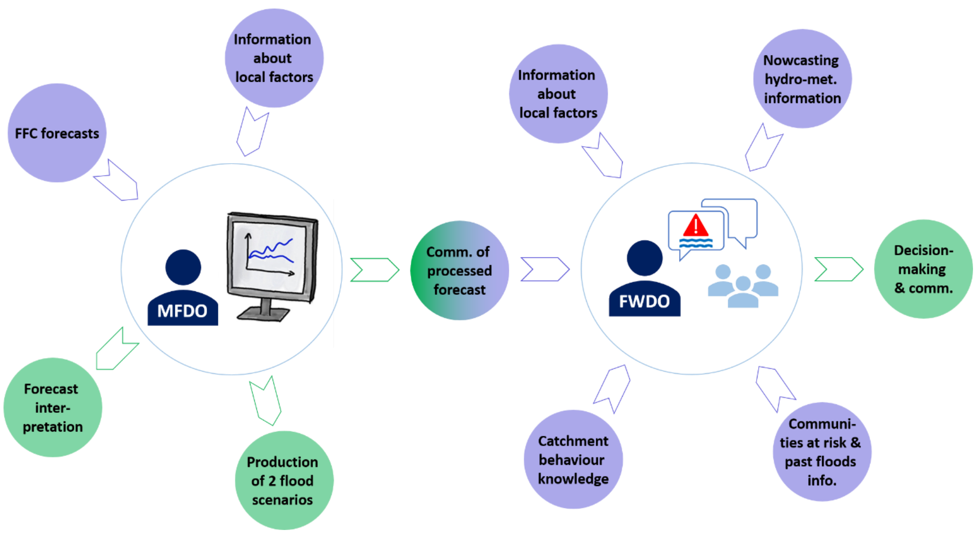

Figure 3: Roles and interactions between EA duty officers. Blue arrows and circles are for incoming information and green arrows and circles relate to outputs from either of the duty officers.

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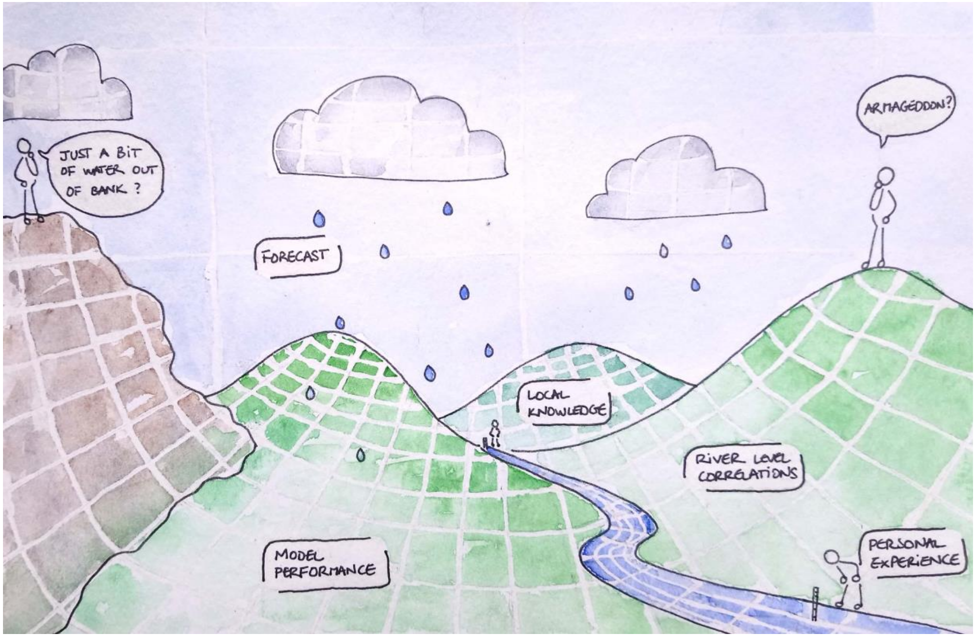

Figure 4: Complex decision-making landscape in which EA duty officers operate.

Figure 5: Wordclouds of perceived opportunities (left) and challenges (right), based on the interview transcripts.

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Table 1: Interviewees' perceived opportunities, challenges and neutral changes associated with a transition to probabilistic forecasts. Perspectives are split into six main topics (rows). Supporting quotes can be found in Appendix C.

Language and communication	Most interviewees agreed that this will probably be the biggest change. Some said they thought it might improve long-term communication and increase the MFDOs' credibility and confidence (quote O1) This was also found by Thielen et al. (2006). Others believe that there is a potential for misunderstanding and that a lot more work is still needed on this topic (quotes C1 and C2).
Uncertainty	Probabilistic forecasts contain uncertainty which they openly display. Some interviewees thought that this would materialise the forecast uncertainty, otherwise sometimes hidden with the two scenarios (quote O2). This is in line with the EA's 2009 science report (Sene et al., 2009). Many interviewees however questioned whether probabilistic forecasts would really help tackle the uncertainty they deal with while on duty (quotes N1 and C3).
The forecasting system	Some interviewees mentioned that the two scenarios, and the What If scenarios used to produce them, were sometimes challenging to play with and required a lot of expert judgment, thus making them inconsistent nation-wide. There were hints that a few MFDOs thought probabilistic forecasts might lead to more consistency across the EA centres (quote O3). It was however clear from the interviews that things will need to change slowly to give duty officers time to build confidence in the new system (quote C4).
Decision-making	A few interviewees mentioned the fact that probabilistic forecasts will not solve the fundamental need of decision-making to be binary and saw this as a challenge (quotes C5 and C6). Others saw this as an opportunity for early warning and long-term planning (quotes O4 and O5)
Duty officers' roles	This transition was seen neither as an opportunity nor as a challenge by and for the MFDOs. They simply stated how things might change for them (quotes N2 and N3). A few of the FWDOs however thought that this might push more of the interpretation on to them (quotes C7 and C8). It is worth noting is that none of the interviewees mentioned worries concerning potential impacts of this future transition on the communication and interaction between duty officers. The worries seem to mostly lie outside of their interaction (quote O6).
New staff training	An interviewee mentioned that probabilistic forecasts could help with new staff training, by increasing their understanding of catchment response (quote O7).

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Appendix A. Glossary of terms.

Best Estimate	A forecaster's assessment of the most likely rainfall, river and groundwater levels, and coastal conditions, and their impacts.
Catchment characteristics and response	Catchment characteristics are the features that describe a river basin (i.e. the area of land drained by a river), such as its location, size, vegetation cover, soil type and topography. They partially define the catchment response, the catchment's reaction when subjected to a rainfall event (e.g. how fast the water level increases after a rainfall event).
Chaos	The property of a complex system, like the weather, whose behaviour is so unpredictable that it appears random. This is due to the system's sensitivity to small changes in conditions.
Confident	A forecaster's expert judgement of how certain they are that the forecast is right.
Convective rainfall events	The sun heats the ground, warming up the air above it. This causes the air to rise. As the air rises it cools and condenses, forming water droplets that organise into clouds and lead to rainfall. Convective rainfall events can lead to thunderstorms.
Department for Environment, Food and Rural Affairs (Defra)	UK government department responsible for safeguarding the UK's natural environment and supported by 33 agencies and public bodies, including the Environment Agency (EA). www.gov.uk/government/organisations/department-for-environment-food-rural-affairs
Deterministic forecasts	Refers to a forecast which gives a single possible outcome of the future rainfall, river and groundwater levels and coastal conditions.
Ensemble	Instead of running a single deterministic forecast, computer models can run a forecast several times, using slightly different inputs to account for uncertainties in the forecasting process. The complete set of forecasts is called an 'ensemble', and each individual forecast within it are 'ensemble members'. Each ensemble member represents a different possible scenario of future rainfall, river and groundwater levels and coastal conditions. Each scenario is equally likely to occur.
Environment Agency (EA)	An executive non-departmental public body sponsored by Defra. The EA has an operational responsibility to manage risks of flooding from rivers and the sea in England, by warning and informing the public and businesses about impending floods. www.gov.uk/government/organisations/environment-agency
False alarms	A warning given ahead of an event (e.g. flood) that does not ultimately occur.
Flood action groups	Cores of local people who act as representative voices for their wider community. They work alongside agencies and authorities and meet on a regular basis with the aim of reducing their community's flood risk and improving its resilience to flooding.
Flood Forecasting Centre (FFC)	A partnership between the Environment Agency and the UK Met Office. It provides a UK-wide 24/7 hydro-meteorological service to emergency responders to better prepare for flooding (river, surface water, tidal/coastal and groundwater). www.ffc-environment-agency.metoffice.gov.uk
Flood Guidance Statement (FGS)	A daily flood risk forecast for the UK, produced by the FFC (in collaboration with the EA and Natural Resources Wales) to assist with strategic, tactical and operational planning decisions. It gives a flood risk assessment shown by county and unitary authority across England and Wales over the next five days for all types of natural flooding (coastal/tidal, river, groundwater and surface water). The FGS is issued by the FFC every day at 10:30am and at other times, day or night, if the flood risk assessment changes.

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	www.ffc-environment-agency.metoffice.gov.uk/services/FGS_User_Guide.pdf
Flood incident management strategy	An institute's priorities for preparing for and responding to flood events.
Flood management measures	Solutions to reduce the impacts that floods pose to humans and the environment. They can be natural (e.g. planting vegetation to retain extra water in the ground) or engineered (e.g. flood barriers).
Flood preparedness	Measures taken to prepare for and reduce the effects of a flood event.
Flood scenarios	Possible future development of a flood event and its associated likelihood.
Flood wardens	Volunteers from local communities who have the responsibility to monitor watercourses in the area they cover and contact local authorities with up to date information.
Forcing	The action of inputting information into a computer model to produce a forecast.
Forecast accuracy	The level of agreement between the forecast and the truth (i.e. what is observed in reality).
Forecasting product	A comprehensive and tailored overview (i.e. in the form of text, graphics and/or tables, etc.) of the forecast.
Hydraulic model	Mathematical model of the movement of water in a system (e.g. a river).
Hydrological model	Simplified model of a real-world system that describes the water cycle.
Hydro-meteorological observations and forecasts	Hydro-meteorology is a branch of meteorology and hydrology that studies the transfer of water and energy between the land surface and the lower atmosphere. Hydro-meteorological observations include observations of meteorological (e.g. temperature and rainfall) and hydrological variables (e.g. river and groundwater levels). Hydro-meteorological forecasts are forecasts that predict the evolution of meteorological and hydrological variables in time.
Hydro-Meteorological Services	Hydro-meteorological forecasting* products* produced by the FFC and issued daily (Hydro-Meteorological Guidance), twice daily (Forecast Meteorological Data) or whenever required (Heavy Rainfall Alerts).
Lead time	The length of time between when the forecast is made and the occurrence of the event (e.g. flood) being predicted.
Long-range forecasts	Forecasts which cover a period of time from a month to more than a season.
Missed flood events	A flood for which no warning was given ahead of it happening.
Model performance	The level of agreement between the model's outputs and their observations in reality. The difference between a model output and its respective observation is the error. The lower the error, the greater the model performance.
Nowcasting	Extrapolating from the latest observations (e.g. radar rainfall) to forecast the evolution of, for example the weather, in the next couple of hours.
Operational decision-making	Decision-making based on real-time information to resolve imminent situations.
Outlook	Refers to a forecasting product* based on long-range forecasts* (i.e. monthly to seasonal).
Performance measures	Metrics that characterise the quality of a forecast or a model compared to observations.
Probabilistic forecasts	While a deterministic model gives a single possible outcome for an event, a probabilistic model gives a probability distribution as a solution, indicating the likelihood of each scenario to occur. Probabilistic and ensemble forecasts are sometimes used interchangeably (see 'Ensemble').

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Rapid-response catchments	Catchments and rivers that respond quickly to rainfall events.
Real-time river gauges	Instruments that measure a river's characteristics (e.g. flow or water level) and communicate these data in real-time remotely.
Reasonable Worst Case	A forecaster's assessment of the potential upper range of rainfall, river and groundwater levels, and coastal conditions, and their impacts.
Risk	A combination of likelihood and impact of an event.
River level correlations	Mathematical characterisation of the river level at one point of the river with respect to another point on the river. This can be used to estimate the river level at a point on the river if the river level upstream is known.
Short-range forecasts	Forecasts which cover a period of time from a couple of a hours to a couple of weeks.
Surface water flooding	Flooding caused when the volume of rainwater falling does not drain away through the river network and other drainage systems, or infiltrate into the ground, but lies on or flows over the ground.
Surge forecasts	Forecasts of the rise of water along coastlines.
Telemetry sites	Sites where instruments collect measurements automatically and transmit it remotely (see 'Real-time river gauges')
Uncertainty	Having limited knowledge or understanding of our environment, it is impossible to characterise and predict its evolution with 100% certainty. All forecasts are uncertain, and that uncertainty amplifies with lead time*. Ensemble* or probabilistic forecasting* can be used to represent the forecast uncertainty.

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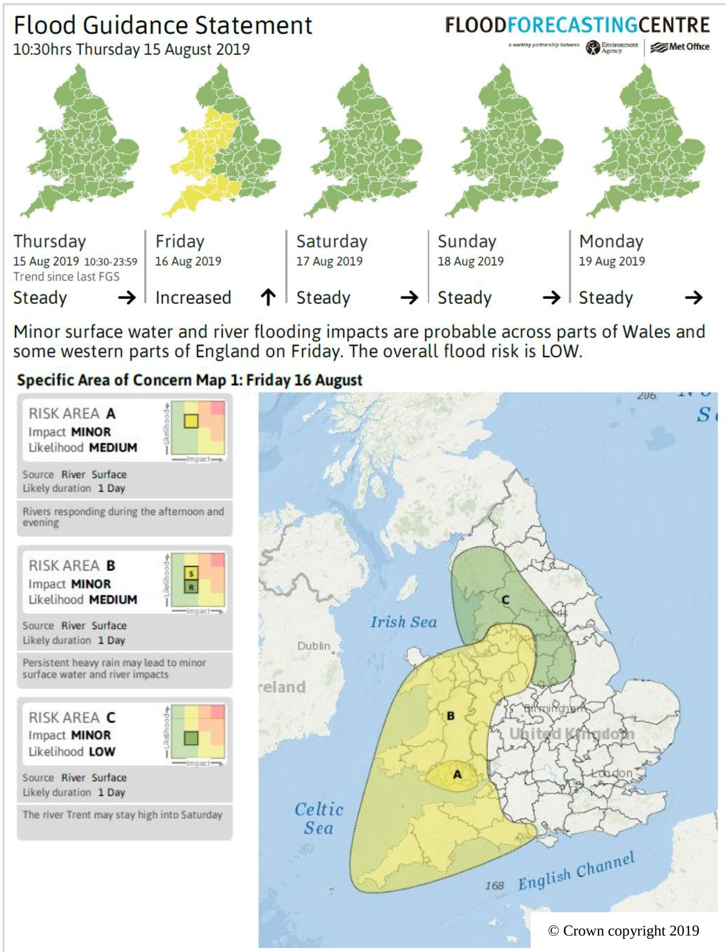
Appendix B. Visual examples of operational products used by EA MFDOs and FWDOs: (a) Flood Guidance Statement, (b) Hydro-Meteorological Guidance, (c) Forecast Meteorological Data, (d) Heavy Rainfall Alert, and (e) National Flood Forecasting System (source: EA). The works published in this journal are distributed under the Creative Commons Attribution 4.0 License. This licence does not affect the Crown copyright work, which is re-usable under the Open Government Licence (OGL). The Creative Commons Attribution 4.0 License and the OGL are interoperable and do not conflict with, reduce or limit each other.

(a)



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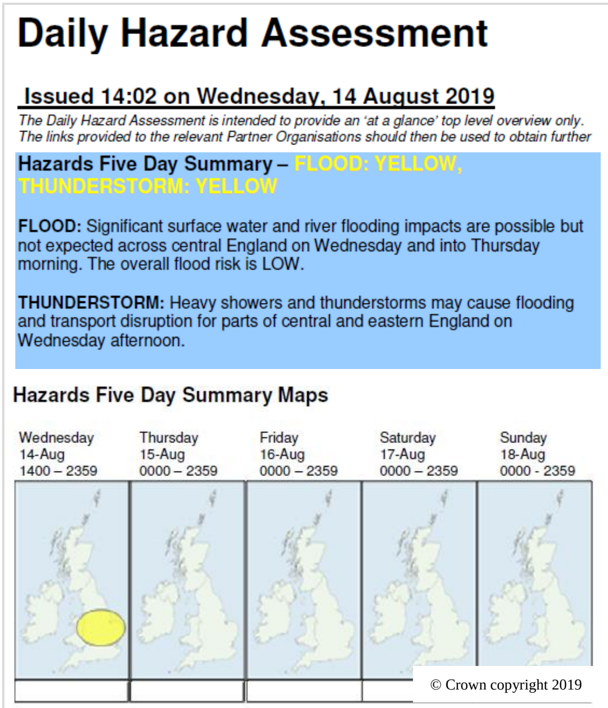

Daily Hazard Assessment

Issued 14:02 on Wednesday, 14 August 2019

The Daily Hazard Assessment is intended to provide an 'at a glance' top level overview only. The links provided to the relevant Partner Organisations should then be used to obtain further

Hazards Five Day Summary – FLOOD: YELLOW, THUNDERSTORM: YELLOW

FLOOD: Significant surface water and river flooding impacts are possible but not expected across central England on Wednesday and into Thursday morning. The overall flood risk is LOW.

THUNDERSTORM: Heavy showers and thunderstorms may cause flooding and transport disruption for parts of central and eastern England on Wednesday afternoon.

Hazards Five Day Summary Maps

https://doi.org/10.5194/gc-2019-18
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Geoscience Communication
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Discussions

(c)

Forecast Meteorological Data
EA South East Region

FLOODFORECASTINGCENTRE
a working partnership between Environment Agency | Met Office

Issued by the Flood Forecasting Centre on 15/08/19 at 05:11 GMT (06:11 local time)
Unique Reference No. 5766 Version 1 Morning Issue

Precipitation Forecast Days 1 and 2

		Thursday 15/08/19					Friday 16/08/19			
		00-06 (GMT)	06-12	12-18	18-24	Day 1 Total (06-24)	00-06	06-12	12-24	Day 2 Total (00-24)
WT(N)	Ave (mm)		0	0	0	0	0	1	18	19
	Max (mm)		1	0	0	1	0	2	22	23
WT(S)	Ave (mm)		0	0	0	0	0	0	13	13
	Max (mm)		1	0	0	1	0	2	23	24
NET	Ave (mm)		0	0	0	0	0	1	11	12
	Max (mm)		1	0	0	1	0	2	16	16
HIOW	Ave (mm)		0	0	0	0	0	0	17	17
	Max (mm)		0	0	0	0	0	1	24	25
Sussex	Ave (mm)		0	0	0	0	0	0	11	11
	Max (mm)		1	0	0	1	0	1	18	18
KSL	Ave (mm)		0	0	0	0	0	0	8	8
	Max (mm)		1	0	0	1	0	1	12	12

WT(N)	West Thames (North)	WT(S)	West Thames (South)
NET	North East Thames	HIOW	Hampshire & IOW
KSL	Kent and South London		

Notes: All precipitation values are given as rainfall equivalents
***Ave:** Best estimate of mean rainfall depth over the Area during the period.*
***Max:** Best estimate of maximum rainfall depth at any one location in this time period, this is not an extreme value.*
***Model Output:** A number in brackets shows the original model output value. The number below this, is the FFC's Hydrometeorologists modification.*

Daily Summary Days 1 – 5

		Thursday 15/08/19	Friday 16/08/19	Saturday 17/08/19	Sunday 18/08/19	Monday 19/08/19
Precipitation	Ave(mm)	See table above		1	1	0
	Max(mm)			3	4	2

		Thursday 15/08/19	Friday 16/08/19	Saturday 17/08/19	Sunday 18/08/19	Monday 19/08/19
Temperature	Min(degC)	10	8	12	11	11
	Max(degC)	22	20	23		

https://doi.org/10.5194/gc-2019-18
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Geoscience Communication
Discussions
Open Access
EGU

(d)

Heavy Rainfall Alert
EA South East Region (Summer)

FLOODFORECASTINGCENTRE
a working partnership between Environment Agency | Met Office

Issued by the Flood Forecasting Centre on 19/07/19 at 16:51 GMT (17:51 local time)
Unique Alert Reference No. 2817_SOUTHEAST_795 Version 1

ORIGINAL

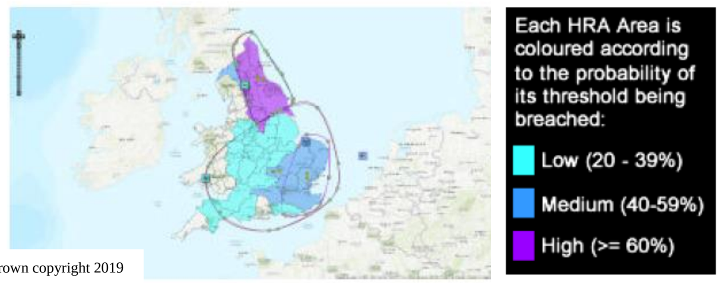
Start of meteorological event: 0800 GMT on 20/07/19

End of meteorological event: 2100 GMT on 20/07/19

Summary of Alert Criteria Met

Alert Criteria	HRA Areas covered	Confidence
10 mm (or more) in 1 hours (or less)	West Thames (North)	L
	West Thames (South), North East Thames, Kent and South London	M
30 mm (or more) in 6 hours (or less)	Sussex, Kent and South London	L
30 mm (or more) in 12 hours (or less)	West Thames (South), North East Thames	L

Notes:
- ***Confidence:*** *The probability of this threshold being achieved anywhere in the specific HRA Area within the time periods outlined by the Heavy Rainfall Alert. H = more than 60%; M = 40 – 60%; and L = 20 – 40%*
- *Issue of a Heavy Rainfall Alert means the probability of rainfall thresholds being met or exceeded during the meteorological event is within the bands indicated by the confidence levels above.*
- *All Alert criteria should be defined in this table. If it is predicted that some criteria will not be exceeded, these boxes should be greyed out*



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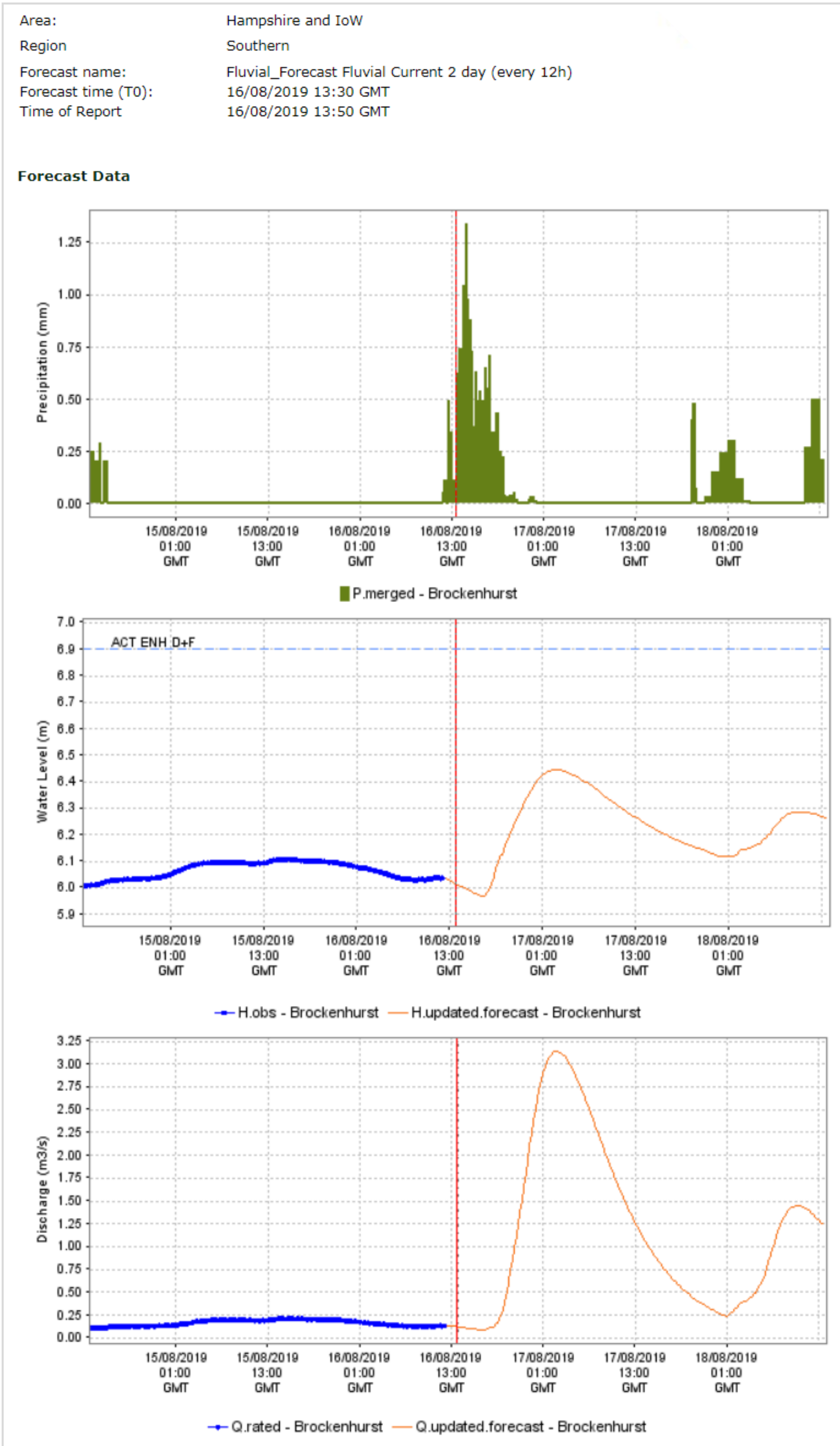

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Appendix C. Interviewees' quotes in relation to their perceptions (opportunities, neutral and challenges) associated with a transition to probabilistic forecasts.

Opportunities

O1: *"If you've got a huge spread then you know that there's a very wide range of impact potentially, but if [...] everything's within a couple of centimetres of each other, it gives you a lot more confidence in saying, no I think we're going, we're not going to see a threshold crossing. So [...] it will help decision making I think" [MFDO3]*

O2: *"I think in a good way [...] it will [...] reveal the uncertainty that's hidden by apparent simplicity" [I1]*

O3: *"The new flood forecasting system is being developed at the moment so it's going to replace the NFFS. [The] benefits to that I suppose [...] are that if we can look to be more consistent across the country in even simple things like what displays look like [...] we're more interoperable if we need to" [MFDO1]*

O4: *"I think in an incident I'm happy that that's [...] a useful range of things to know, like you said, you probably warn for the lowest one and plan for the highest one and we can interpret between them" [FWDO2]*

O5: *"We're talking about some of these decisions that have got a long lead time, we're going to move people around the country, we're going to move equipment. It takes a long time to do that" [I1]*

O6: *"Between us [duty officers], it's probably OK because we've got that understanding of the roles" [FWDO3]*

O7: *"I can see some benefits to it, especially when you've got less experienced staff [...], you're almost [...] showing them the breadth of what a catchment could do given a range of responses" [MFDO2]*

Neutral

N1: *"Uncertainties are very tricky to deal with, whether probabilistic forecasting and a switch to that is going to help?" [MFDO2]*

N2: *"I think the MFDO role won't change, it will still be to communicate a forecast but the [...] wording of the forecast may change slightly" [MFDO1]*

N3: *"I think from our point of view it will just mean a bit more interpretation of forecasts and then [...] just a slightly different way of passing it on [...]. But I don't think it will change the process" [MFDO3]*

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Challenges

C1: *"All the comms research we hear about generally says […] the public message has to be as simple as possible, so that is working the opposite way to any proposal for probabilistic forecasting" [FWDO2]*

C2: *"A lot of local authorities standing their staff up, putting them on standby for a weekend is quite a big budget thing […]. So […] if we say, it is going to flood, they can justify the spend on it […]. If we pass it on as shades of grey, a lot of them, they'll appreciate the information but some of them would actually resent having the decision forced on them because they will struggle to then justify doing something or they'll be blamed, either way, blamed for spending money if it doesn't happen and blamed for not spending enough if it does happen." [FWDO2]*

C3: *"That would be my concern that it's even more information and more uncertainty and it's kind of like, well what do you do with this information? And which bit do you communicate to who?" [FWDO3]*

C4: *"It is something to bear in mind with that if probabilistic forecasting put too much pressure and stress on decision making on the people in these roles, the system probably would just collapse, people would walk away" [FWDO2]*

C5: *"You're still going to have this overriding issue with fast responding catchment where one scenario says we might need to issue a flood warning but 99 of them say no. Someone has to make a decision" [MFDO1]*

C6: *"I think still for a lot of people the question they […] want answered is am I going to flood?" [I2]*

C7: *"I think my role is going to be the one where it has to stop and it can't be probabilistic because it […] does come to a yes or no, issue it, don't issue it. So to some extent, probabilistic forecasting does feel like everyone else just pushing things down the line saying you make the decision, […], we have to make the decision because we're the last ones on the line" [FWDO2]*

C8: *"Having probabilistic forecasting just moves the burden of making a decision further down the tree" [MFDO2]*