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Enhanced surface water flood forecasts: User-led development and testing

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Abstract
The risk of surface water flooding (SWF) in England is already high and its frequency and severity is projected to increase in the future. SWF generally occurs due to intense, highly localised rainfall, which is challenging to forecast with sufficient accuracy to take proactive action ahead of flood events. Being able to manage the risk effectively lies in improved rainfall and flood forecast products, better communication of uncertainty and building the capacity of local responders. This study utilises state-of-the-art high-resolution ensemble rainfall forecasts and hydraulic modelling tools alongside a novel post-processing method to develop and trial new SWF forecast products within an incident workshop attended by forecast producers and regional forecast users. Twenty-two of 24 workshop participants reported that the new information would be useful to their organisation but more product development and training in its interpretation is required. Specific recommendations to improve SWF forecast provision include increased support for local government through a single government organisation responsible for SWF, making more use of existing static SWF mapping in a real-time context and employing the process of user-based consultation, as outlined in this study, to guide the future development of future SWF forecast information and processes.

KEYWORDS
convective rainfall, engagement, ensemble forecasting, flood forecasting, intense rainfall, pluvial flooding, surface water flooding, user-led testing

1 | INTRODUCTION

It is estimated that over 3 million properties in England are at risk of surface water flooding (SWF), even more than the 2.4 million at risk from rivers and the sea (Environment Agency, 2009). The majority of SWF events occur due to intense, highly localised convective summertime rainfall, which is extremely challenging to forecast (Houston et al., 2011). Rapid urban development that is reliant on aging drainage systems and increasingly intense rainfall as a result of climate change (Blenkinsop, Chan, Kendon, Roberts, & Fowler, 2015) means that the problem is worsening and will continue to do so according to climate projections (Kendon et al., 2014; Met Office, 2019).

A recent UK government review into multi-agency SWF planning uncovered many systemic challenges, such as the need to: improve risk mapping, ensure infrastructure is resilient, clarify roles and responsibilities, and notably—improve forecast and warning systems (UK Government, 2018a). Alongside this, the need for better communication of storm forecasts has been identified. Specifically, the question of whether and how real time flood mapping should be developed was considered in a recent study (Environment Agency, 2019). The Pitt Review (Pitt 2008), which followed the widespread UK flooding of summer 2007, also recommended 'flood visualisation tools that are designed to meet the needs of flood risk managers, emergency planners and responders' (Recommendation 37), and that flood visualisation data should be: 'held in electronic map format' (Recommendation 36).

The impact of intense rainfall on SWF is greatly dependent on highly localised storm characteristics. When considering a specific location, storms displaced just a few kilometres apart could have a very different impact. This is in contrast to fluvial flooding, where the impact is more related to the amount of rainfall integrated over the entire catchment. A major practical difficulty associated with forecasting SWF is that it is generally not possible to determine where heavy rain will fall with the necessary levels of confidence, precision, and lead time (Clark, Roberts, Lean, Ballard, & Charlton-Perez, 2016). There are methods to address this issue by using probabilistic forecasting and by post-processing raw forecast information. For example, using neighbourhood processing methods to search for storms within a defined radius and communicate the degree of probability of occurrence within a given area (Golding, Roberts, Leonicini, Mylne, & Swinbank, 2016; Olsson et al., 2017; Yussouf & Knofmeier, 2019).

The increased availability of operational convection-permitting forecast models, including ensembles, over the last decade has improved convective rainfall forecasts (Hagelin et al., 2017). Convection-permitting ensemble rainfall forecasts for SWF forecasting were trialled at the 2014 Glasgow Commonwealth Games, where maps and forecasts of risk at the city scale were provided (Speight et al., 2018). The ensemble forecasts were blended with shorter-term nowcasting information, which allows rainfall observations from radar to be advected forward to provide short-term predictions up to several hours in advance. Rainfall nowcasts have also been applied to hydrological models to provide live inundation maps during heavy rainfall events through trials in the English cities of Leicester and York (Coles, Yu, Wilby, Green, & Herring, 2017).

There is recent and ongoing research to develop flood forecast systems that effectively combine radar observations, weather forecasts and hydraulic modelling, and improve understanding of the propagation of uncertainty through the forecast chain (Flack et al., 2019; Speight, Cranston, Kelly, & White, 2019). A key recommendation from Flack et al. (2019) is that scientists should 'build closer relationships with and between users throughout the chain to better understand their requirements from an end-to-end system to inform their response to flood events'. Ochoa-Rodriguez, Wang, Thraves, Johnston, and Onof (2018) report that flood management professionals would welcome a two-tier approach where current national flood forecast information is complemented by finer-resolution local forecasts. However, providing reliable, user-centric localised SWF forecasts presents a range of issues relating to uncertainty and risk communication.

There are a number of previous studies that assess the added-value of new tools and information for flood forecasting and risk management. The methodologies can be broadly categorised into four types: surveys, interviews, group activities and 'real life' observations. Ochoa-Rodriguez et al. (2018) surveyed and held workshops with a range of flood professionals to understand the benefits, limitations and ways to improve the UK SWF warning service. Frick and Hegg (2011) assessed the benefits to users of a new flood data visualisation platform for the European Alpine region using surveys before and after the introduction of the new system. Interviews with flood forecasting duty officers were conducted by Arnal et al. (2019) to understand the transition to using probabilistic fluvial flood forecasts in England, which resulted in ten key recommendations to support the uptake of the forecasts. Recommendations included focused communication and training and the co-design of new products with both forecast producers and users. Nobert, Demeritt, and Cloke (2010) used a combination of interviews and participant observation in flood forecast centres and governmental agencies in 16 European states to understand the challenges of using probabilistic flood forecasts for decision-making.

Group activities are a particularly effective way of engaging with flood professionals and assessing their confidence in and understanding of new tools. These activities can involve realistic scenarios or 'games', where participants 'role-play' flood professionals (McEwen, Stokes, Crowley, & Roberts, 2014), such as for decision-making around managing a reservoir (Crochemore, Ramos, Pappenberger, Andel, & Wood, 2016) or play themselves in an 'in-the-moment' decision-making activity for a flood event (Neumann et al., 2018; Ramos, van Andel, & Pappenberger, 2013). Pappenberger et al. (2012) used interactive exercises to improve communication of probabilistic flood forecasts by understanding perceptions of different methods of data visualisation. Arnal et al. (2016) assessed the likelihood that participants would take certain actions by asking questions about, for example, the 'willingness to pay for forecast information'. Simple group discussions can also be effective (Borga, Anagnostou, Blöschl, & Creutine, 2011).

This study aims to understand how, or even if, the latest advances in probabilistic rainfall forecasting and high-resolution hydrodynamic modelling could be combined into real-time, sub-regional forecasts that are useful for making decisions and that complement existing national forecast provision. The study was designed as an end-to-end (weather to actions) study to address a common disconnect between scientists that develop products and the individuals and organisations that use them. The overarching aim has three associated objectives:

- Understand current and potential future SWF forecasting and incident management processes through literature review and user engagement through semi-structured interviews.
- By reflecting on user needs, develop enhanced SWF forecasts based on the latest available tools and research from the international literature.
- Test the enhanced forecasts with users in an incident response workshop through participation in a simulated real-time SWF emergency.

This study combines multiple methods to elicit user needs and perspectives, including semi structured-interviews, a participatory scenario group workshop, combining elements of serious games, and a subsequent debriefing survey. Semi-structured interviews were chosen to gather information on current flood forecast practice and gauge interest in new products. They allowed open-ended responses, two-way communication and provided the opportunity to build relationships between the project researchers and flood forecast users. The enhanced forecasts were tested within a simulated flood incident workshop and participants filled out a debrief survey that reflected on the added-value of the new products in decision-making and the challenges around communication. This type of group activity was chosen to reflect a realistic decision-making setting across a variety of flood forecast users. It provides a good forum for them become familiar with the new forecast material and builds capacity to respond to it in the future. The debrief survey provides quantitative evidence for the issues related to the workshop activity.

2 | CURRENT SWF FORECASTING IN ENGLAND

Semi-structured interviews were conducted with seven forecast 'users' and three forecast 'producers'. The aim of the interviews was to understand the processes and tools currently used in SWF forecasting and warning, the capacities and needs of those involved, and the roles and responsibilities of information 'producers' and 'users' in the forecast–warning–response process.

The forecast 'users' serve the Yorkshire region in England and included Flood Risk Officers, Flood Risk Engineers and Emergency Planning Managers from five Local Authorities. Other forecast 'users' that were interviewed included representatives from Yorkshire Water, the regional water utility company and the Environment Agency. The Environment Agency is a public body responsible for protecting and improving the environment in England, and has primary responsibility for main river and coastal flooding. Local Authorities (unitary authorities or county councils that is, local government) have primary responsibility for SWF risk management in their geographic region, however, the Environment Agency does provide ad hoc support for SWF to some local communities, including advice and information preceding and during events (UK Government, 2018b). The three forecast 'provider' interviews included representatives from a UK-based university, the Met Office (National Weather Service) and the Flood Forecasting Centre.

The Flood Forecasting Centre is run jointly by the Met Office and the Environment Agency and produces Flood Guidance Statements for England and Wales, which provide general guidance at county or regional scale (Figure 1). Until May 2020, these statements were informed using the SWF decision support tool (SWFDST), which was introduced in 2010 and combines ensemble rainfall forecasts with soil moisture and urbanisation/population information to produce a weighed score for each county in England and Wales (Speight et al., 2019). The ensemble rainfall forecasts are provided by the UK Met Office Global and Regional Ensemble Prediction System (MOGREPS-UK, Hagelin et al., 2017), which uses a national-scale, convection-permitting model with 2.2 km horizontal grid spacing and that is designed, in part, to account for the uncertainty inherent in predicting convective rainfall events at the local scale.

A new SWF hazard impact model has since been developed, tested through convective seasons (Speight et al., 2019) and went into operational use in time for summer 2020 (Flood Forecasting Centre, personal comm.). This approach takes rainfall fields from MOGREPS-UK 24 ensemble members and uses them to

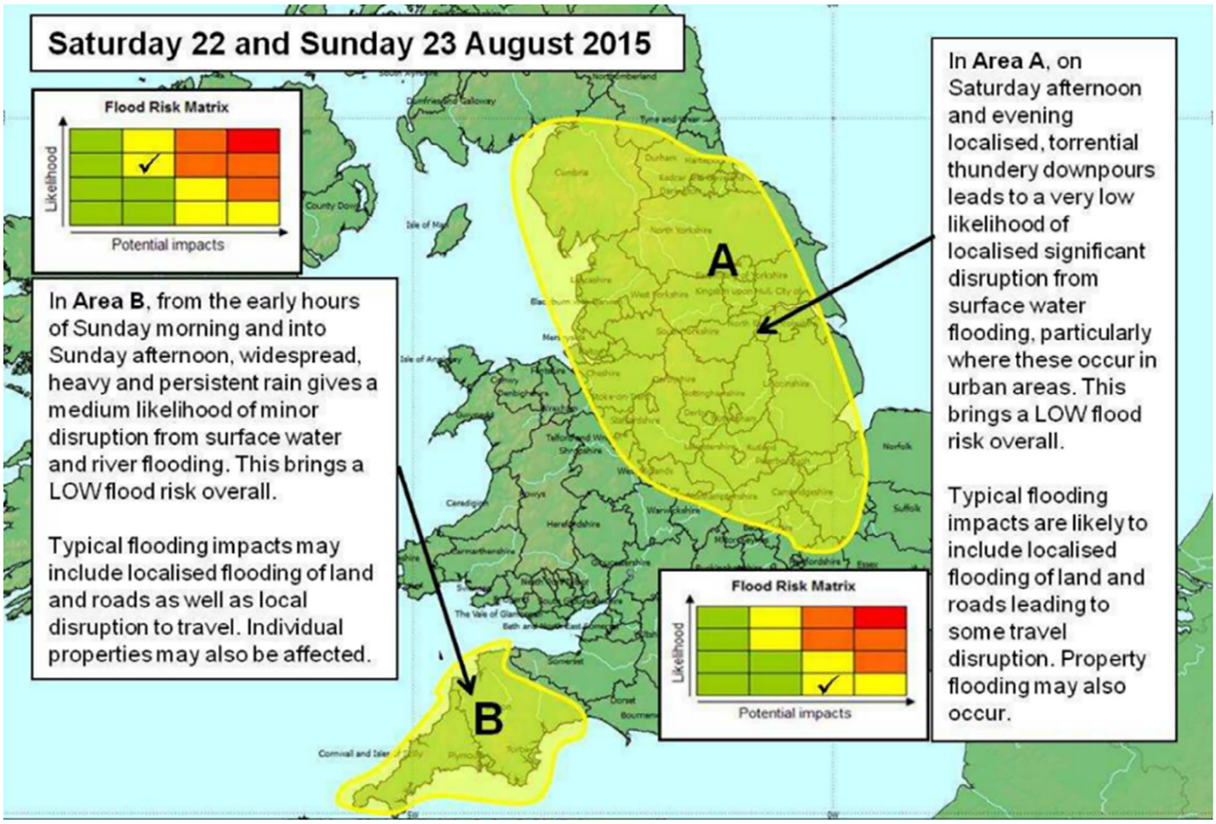

FIGURE 1 'Specific areas of concern' section of the Flood Guidance Statement, issued 1030 BST Saturday 22 August 2015 (provided by the Flood Forecasting Centre, Exeter, UK)

drive a national Grid-to-Grid (G2G) rainfall-runoff model at 1 km horizontal resolution (Bell et al., 2007; Price et al., 2012). G2G computes surface runoff and tracks where accumulations exceed predefined thresholds. The 24 member ensemble of G2G outputs is used to select the most appropriate pre-calculated impact map on a 1 km × 1 km grid basis. The pre-calculated impact maps are made up of a combination of data sources, including the Updated Flood Map for Surface Water (uFMfSW), Environment Agency National Receptor Database and National Population Database and are developed for 9 scenarios that is, 1 in 30, 100, 1,000 year and 1, 3, 6 hr rainfall duration design storms (Aldridge, Gunawan, Moore, Cole, & Price, 2016). The selected impact maps are then converted into county-level red/amber/yellow/green risk areas (on the basis of risk = probability x impact) and delivered to a range of users including Local Authorities and emergency responders via the Flood Guidance Statement (Pilling et al., 2016).

During the semi-structured interviews, the users highlighted that they typically receive information on impending heavy rain and SWF warnings from three sources: firstly, the Flood Forecast Centre's Flood Guidance Statement (Figure 1); secondly, from monitoring rainfall radar observations via the Met Office's premium forecast service—Hazard Manager or a commercial provider, and thirdly, from the Met Office's regional weather advisor, who provides detailed forecast descriptions via email and Local Resilience Forum teleconferences. Local Resilience Forums are multi-agency partnerships made up of representatives from local public services, including the emergency services, Local Authorities, the National Health Service, the Environment Agency and others, who plan and prepare for localised incidents and catastrophic emergencies. Responses to this information can include three main practical and proactive actions: (a) cleaning gullies, drains and trash-screens in known flooding hot-spots; (b) having clean-up crews on standby to respond to calls of flooding when needed, and (c) monitoring the status of pumping stations. Table 1 includes some indicative interview quotes regarding these proactive actions and shows how many of the interviewed organisations highlighted each action.

Although some proactive action can be taken, most actions tend to be responsive following reports of flooding incidents. This is due in some instances to the large geographic regions covered by both the forecasts and operational areas, for example, the county of North Yorkshire is the largest in England, covering 8,654 km^2. The uncertainty of forecasts and the short lead time in

TABLE 1 Examples of proactive actions taken in response to information on impending heavy rain and surface water flood warnings

Examples of proactive responses to flooding	Number of organisations who mentioned measure during interview	Example quotes
Cleaning trash screens	4	'A typical response would be to direct highways staff to proactively clear gullies, trash screens and distribute sandbags'.
Having 'street scene' crews on standby to clear up and provide sand bags	1	Prior to an event, practical action is limited to prescriptive actions based on known flooding 'hot spots' for example, cleaning trash screens, having 'street scene' crews on standby to clear up and confirming the status of pumping stations'.
Monitoring the status of pumping stations	2	'These protocols could include proactive drain flushing and installing temporary flood barriers at vulnerable infrastructure sites, for example, pumping stations'.

which they are sufficiently reliable to take action are also major factors. Example actions in response to incident reports include public information broadcasts, deployment of temporary flood defences, road closures, closure of other public locations susceptible to pluvial flooding such as underground passages, and activation of control elements such as pumps and water storage (Dale et al., 2013; Ochoa-Rodriguez et al., 2018).

3 | YORKSHIRE CASE STUDY

The development and user-led testing of example enhanced flood forecast products discussed in the following two sections focuses on a single, but significant and typical, SWF case study that took place in the Garforth area of Leeds, United Kingdom on 22 August 2015 (a region of ~2 by 2 km in scale, Figure 2). Approximately 70 mm of rain fell over the region in 4 hr (Figure 3, 1 in 150 year event), leading to 45 flooding incidents being recorded by Leeds City Council. The level of flooding resulting from this event was similar in nature to a previous event that occurred in the same region in August 2014 (Leeds City Council, personal communication), for which Leeds City Council produced a flood investigation report (Leeds City Council, 2015).

4 | ENHANCED FORECAST PRODUCTS

Two types of enhanced forecast products were developed for testing during the workshop. The first was probabilistic rainfall maps, produced by assigning thresholds to ensemble rainfall forecasts. Likelihood of rain over a given threshold is a statistic that is both relevant to extremes and relatively easy to explain. The second was reasonable worst-case scenario (as defined later) SWF forecasts, produced by driving a 2D hydraulic model with a post-processed version of the ensemble rainfall forecasts. The rainfall post-processing implements a neighbourhood method on the 95th percentile of rainfall, which is more representative than using the unprocessed rainfall or the neighbourhood maximum (100th percentile).

Both products use rainfall information from the MOGREPS-UK forecast system, which at the time of the event consisted of 12 members operating at 2.2 km horizontal resolution, initialised from a global ensemble (Hagelin et al., 2017). The forecast lead time is 36-hr and forecasts are issued every 6 hr. Six forecast initialisation times were used to cover the period of the event in Garforth: 1000, 1600, and 2200 British Summer Time, BST (0900, 1500 and 2100, Coordinated Universal Time, UTC) on 21 August 2015 and 0400, 1000 and 1600 BST (0300,

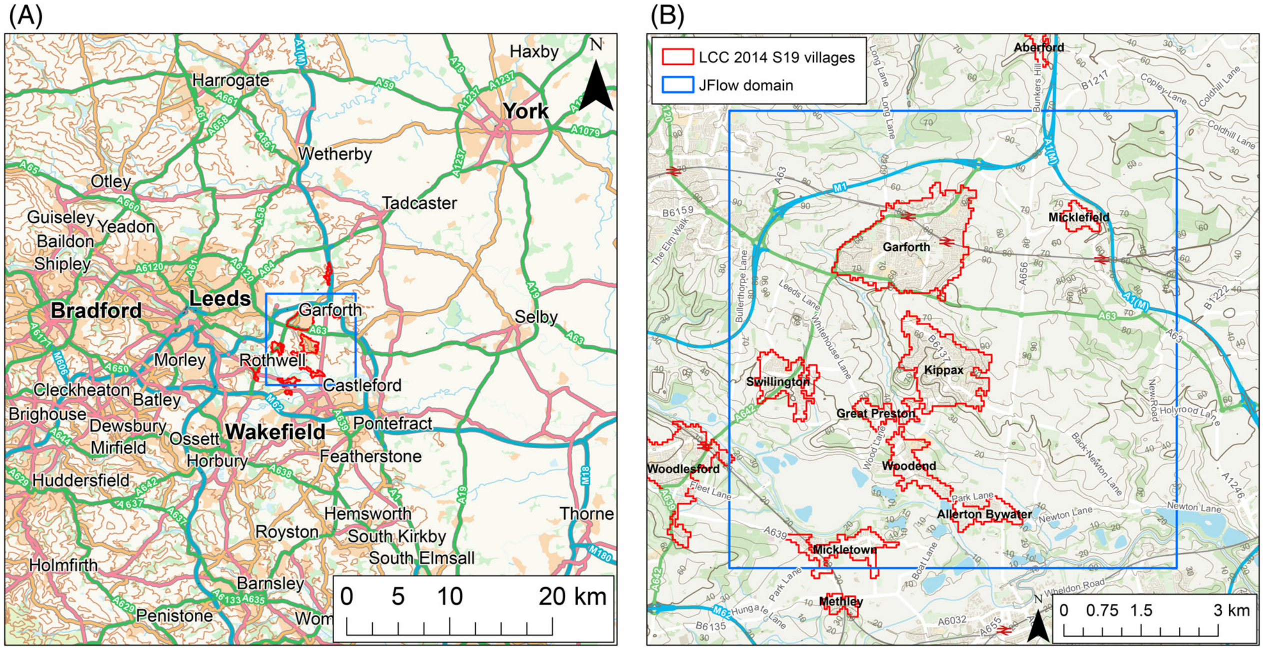

FIGURE 2 Left panel: Location of study domain within the broader area. Right panel: Towns and villages that suffered significant SWF damage during the 2014 event (as reported in the Leeds City Council 2014 Section 19 Report). The JFlow® hydraulic model domain used in this study is shown by the blue box in both panels. Contains OS data © Crown copyright and database right 2019

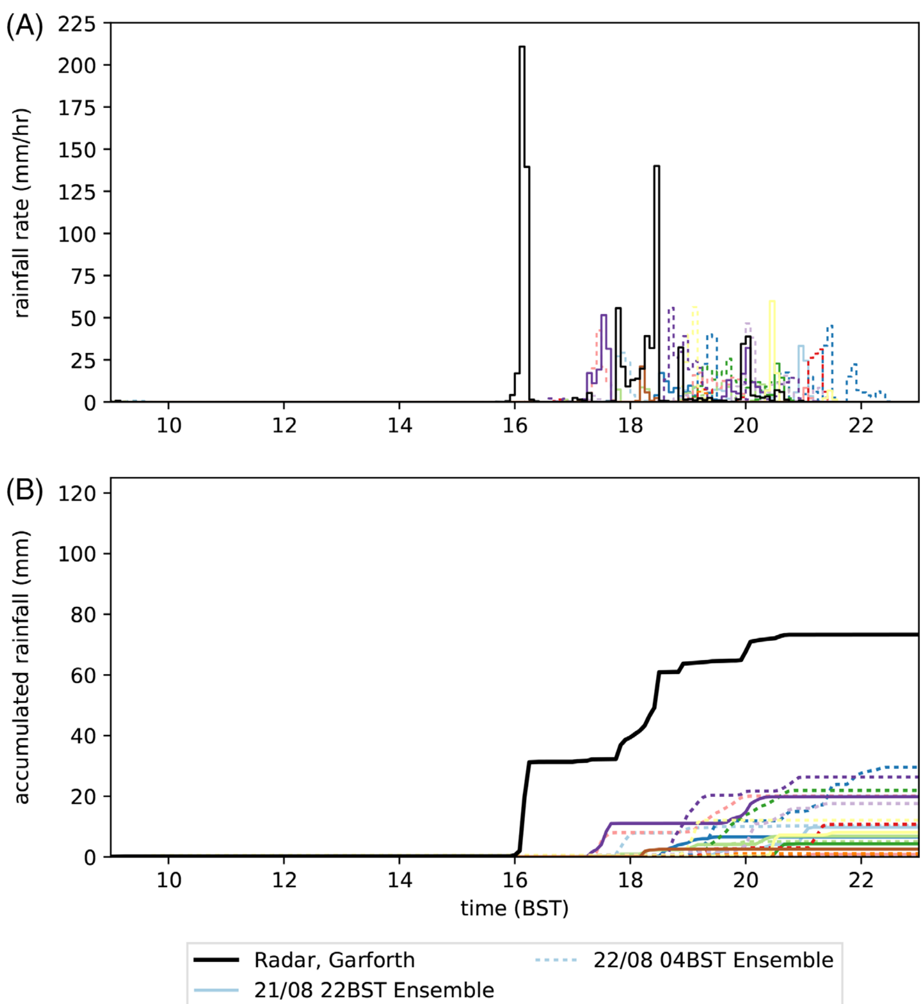

FIGURE 3 Unprocessed observed and forecast rainfall (a) hyetograph and (b) accumulation for the 22 August 2015 event. Observations are from radar (thick black line) and the forecasts are from a 24-member staggered ensemble, from the model grid point containing the location of Garforth (coloured lines). Forecast initialisation times for the staggered ensemble are 2200 BST (2100 UTC), 21 August 2015 and 0400 BST (0300 UTC), 22 August 2015

0900 and 1500 UTC) on 22 August 2015. Following operational practice, the MOGREPS-UK 12-member 36-hr forecasts are combined to form a 24-member time-lagged ensemble forecast using the overlapping 30-hr periods from 2 consecutive forecast runs (Figure 3). None of the ensemble members produce rainfall accumulations above 30 mm over Garforth, compared to the radar accumulation of above 70 mm, although some members produced higher accumulations at nearby locations (not shown), which motivates the use of a neighbourhood search methodology, introduced later in this section.

4.1 | Probabilistic rainfall maps

The forecasts are presented as the likelihood of heavy or very heavy rainfall occurring for at least 1 hr, based on the proportion of the ensemble members exceeding defined thresholds (see the example for heavy rainfall in Figure 4). The 30-hr lagged-ensemble forecasts are divided into five 6-hr blocks. The rainfall forecast information across all ensemble members is summarised for each block based on the exceedance of two rainfall rate thresholds (rates of 4 and 16 mm/hr occurring for at least 1 hr within the 6-hr period for heavy and very heavy rainfall, respectively). The calculation is performed independently for each grid point, allowing the probabilistic information to be presented spatially. Note: no neighbourhood processing methods are used for this stage.

Where the likelihood is relatively high (e.g., >55%), this can be interpreted as the majority of forecast members having heavy or very heavy rainfall that persists for at least 1 hr (i.e., it could persist for longer) in the 6-hr period. This product is designed to allow the user to identify areas where persistent heavy or very heavy rainfall may lead to SWF, and provide an indication of when, over the next day and a half, this might occur.

The format of the probabilistic rainfall products is designed to present the required information in a readily accessible and understandable way. The selection of the probability ranges and the plain English description of these categories are based on WMO guidelines (WMO, 2008). The shading selected for the probability scale uses shades of blue as it has been demonstrated that users prefer to have colour scales that are physically meaningful (e.g., blues for rainfall or shades of orange and reds for positive temperatures).

The products are based on fixed rainfall thresholds. This is consistent with current Flood Forecasting Centre approaches that followed research to develop the Extreme Rainfall Alert Service (Dale, 2008), in which nationally consistent rainfall thresholds were proposed. The use of fixed thresholds makes these products relatively easy to explain to users, however, due to variations in antecedent conditions, geology, land use, topography, drainage system capacity and climatological rainfall, fixed rainfall thresholds may be more appropriate in some areas than others.

4.2 | SWF inundation maps

To produce the SWF inundation maps, the ensemble forecasts were post-processed to take into account nearby storm cells that are not forecast by the model to pass directly over Garforth, but given spatial uncertainty in the forecasts, may do so in reality. This is known as a neighbourhood processing method (Schwartz & Sobash, 2017) and is achieved in five steps:

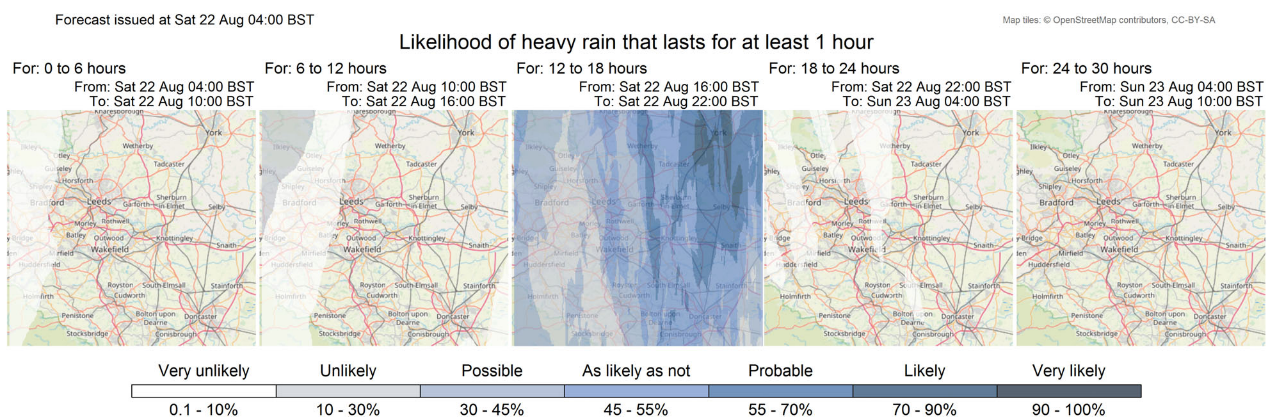

FIGURE 4 Probabilistic rainfall product showing the likelihood of heavy rainfall (>4 mm/hr) lasting for at least 1 hr. The forecast was made using the 24-member time-lagged ensemble and shows forecast summary maps for the consecutive 6-hr periods between 0400 BST (0300 UTC) on Saturday 22 August and 1000 BST (0900 UTC) on Sunday 23 August. Darker shading indicates higher likelihood

1. For each model grid box and ensemble member, compute hourly rainfall accumulations using a 5-min rolling time interval over the entire 36 hr forecast. This produces 421 hourly rainfall accumulations per ensemble member.
2. For each grid box and ensemble member, identify the maximum hourly rainfall accumulation out of the 421 available values.
3. For each ensemble member, find the 95th percentile of the maximum hourly rainfall accumulations within a 30 km radius of each grid box (Figure 5).
4. For each ensemble member, extract the hyetograph that corresponds to the 95th percentile of maximum hourly rainfall accumulations over Garforth (Figure 6a).
5. Select the one hyetograph from the 24 ensemble members that exhibits the greatest accumulation of rainfall (solid purple line in Figure 6, showing 55 mm of rainfall accumulated by end of 22 August 2015). Use this hyetograph to drive the 2D hydraulic flood model.

The procedure generates a predicted 'reasonable worst-case scenario' for this particular storm event. The method is somewhat similar to that of Olsson et al. (2017), in that it is based on a hyetograph that is retrieved within a search neighbourhood. However, rather than using the most extreme worst-case scenario within this neighbourhood, our method uses a percentile-based approach, which is less sensitive to extreme that may occur in a single grid box (which could be the result of model or radar error), and has the additional advantage that the results will be less sensitive to the search radius, as they do not depend as strongly on single points being located inside or outside the search radius. Another advantage of this method is that the same approach can also be applied to the radar data for evaluation purposes (Figure 5a).

In the example in Figure 6b, the 'reasonable worst-case scenario' rainfall accumulation (purple coloured line) is within 15 mm of the ∼70 mm accumulated rainfall observed by the radar (Met Office, 2003). The value of the post-processing step can be seen by comparing the unprocessed data in Figure 3b, where no ensemble member predicts an accumulation of more than 40 mm, with the processed data in Figure 6b, where the highest member accumulation is 55 mm. Whilst the final post-processed accumulation of 55 mm remains well below the observed value of 70 mm, this is a much improved prediction on the unprocessed value of 40 mm. Böing, Birch, Rabb, and Kay (2020) describe the neighbourhood processing methodology in more detail and evaluate the

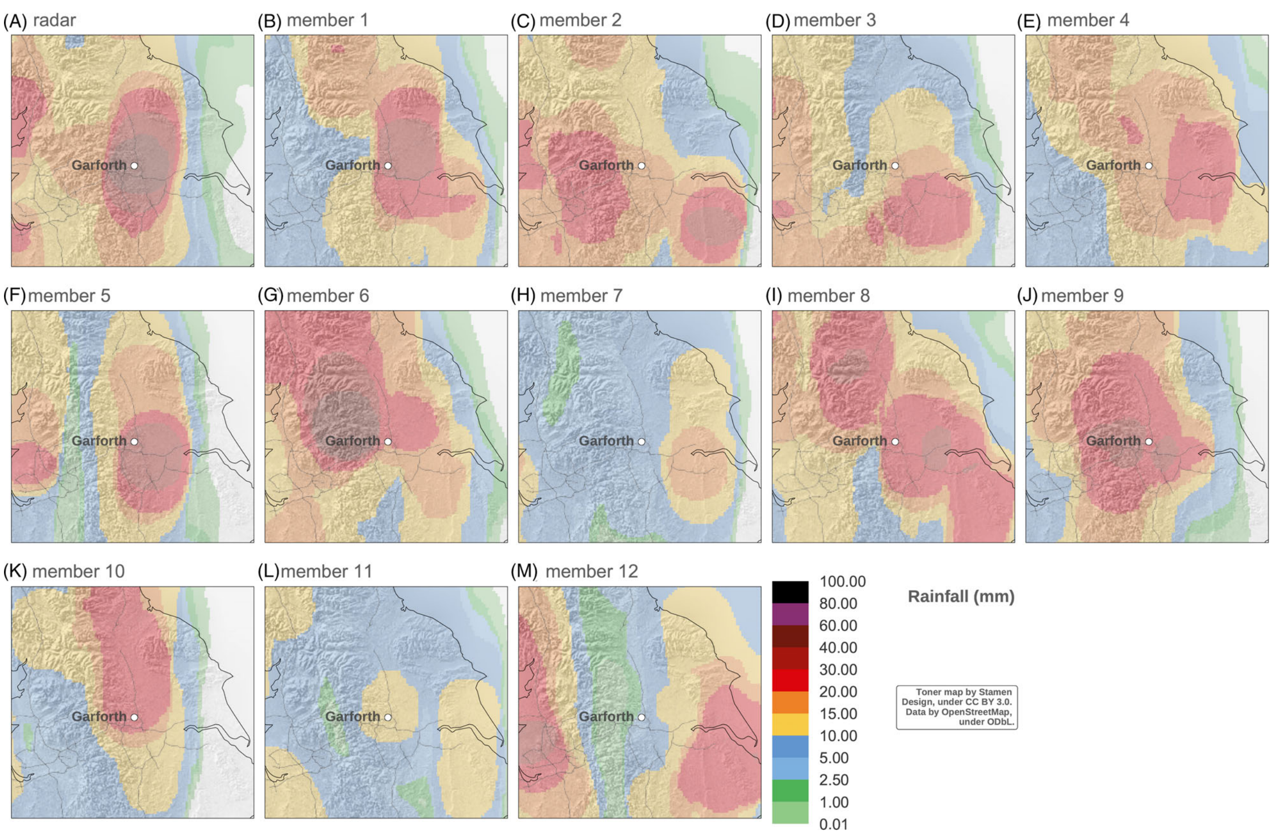

FIGURE 5 Map of 95th percentile hourly rainfall accumulations (mm) in each ensemble member over the 36 hr forecast, initialised at 0400 BST (0300 UTC) 22 August 2015

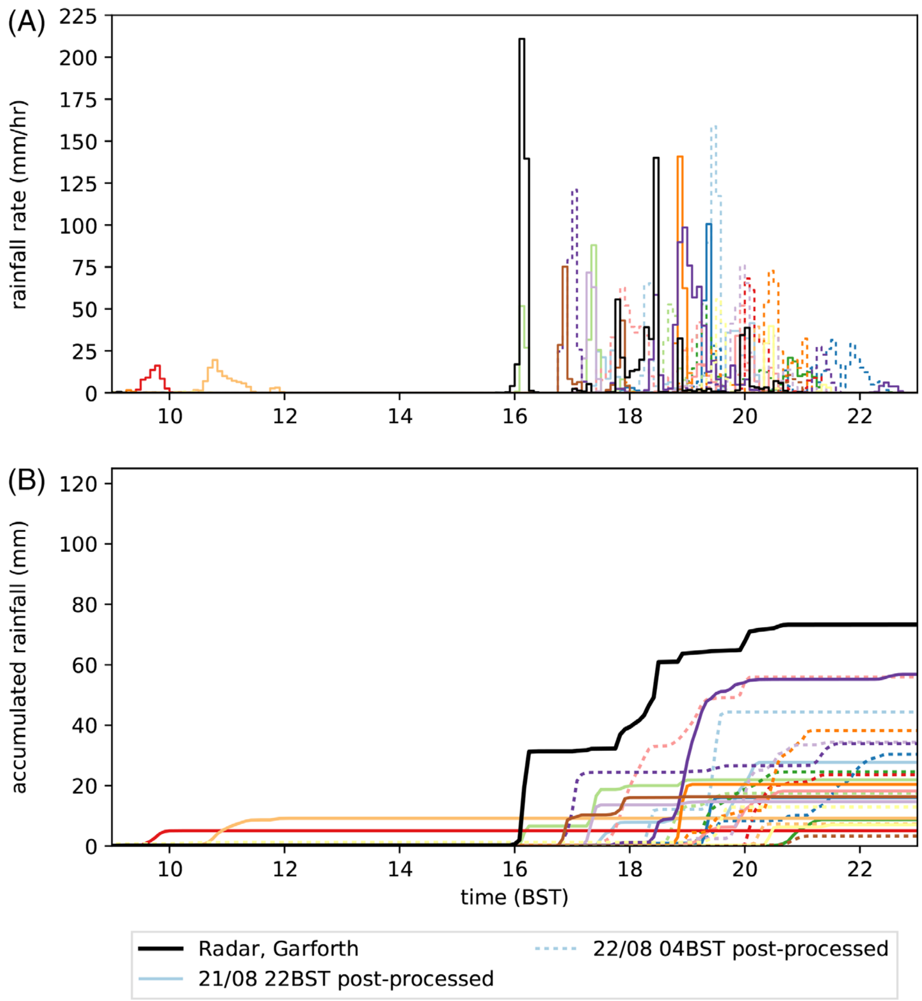

FIGURE 6 Post-processed rainfall (a) hyetograph and (b) accumulation for the 22 August 2015 event for the model grid point closest to Garforth. Radar observations (thick black line) and the 24 post-processed ensemble member forecasts (coloured lines). Forecast initialisation times for the staggered ensemble are 2200 BST (2100 UTC), 21 August 2015 and 0400 BST (0300 UTC), 22 August 2015. The 'reasonable worst-case scenario' rainfall accumulation, that is, the post-processed ensemble member with the highest accumulated rainfall, is shown by the purple line

method for two additional storm cases, although a systematic evaluation over a large number cases is still required. The Böing et al. (2020) study also shows that other time periods, percentile thresholds and search radius sizes can be used and could be optimised for other regions of the UK and elsewhere.

The 2D hydraulic model, JFlow®, is used for the SWF modelling by applying gross rainfall onto gridded topography. The version of the model used is the 'JFlow+' scheme, introduced in 2010, which solves the Shallow Water Equations using an explicit, shock-capturing, finite volume scheme as described in Crossley et al. (2010,b) and Environment Agency (2013) to simulate the movement and accumulation of this water on the landscape. The domain used in the flood modelling was selected to ensure that the villages affected in a similar SWF incident in August 2014, for which a Section 19 Flood Investigation Report was completed (Leeds City Council, 2015), were included (Figure 2). Note that due to the lack of a Section 19 report, detailed flood location information is not available for the 2015 case.

JFlow® is run using the spatially uniform direct-rainfall approach, whereby a single rainfall hyetograph is applied over the entire domain on a 2 m regular grid topography. Following Step 4 in the method above, the purple coloured line in Figure 6a is used to drive the model.

For each 36-hr forecast period, hourly flood depth maps are combined into 6-hr forecast blocks by determining the maximum flood depth in each 2 m hydraulic model grid cell. In addition to flood depths, JFlow® also produces an output parameter called the hazard rating index, which also includes flow velocity and is based on the level of danger the water poses to people, from 'Very low hazard—Caution' to 'Danger for all—including the emergency services' (Defra, 2006). The 6-hr depth and hazard maps are presented at street-level (Figure 7). These flood forecast products allow users to identify specific areas of concern, for example, impassable roads or possible property flooding, and provide an indication of when, over the next day and a half, this might occur.

The spatial extent of the flooding at the local scale (e.g., within Garforth) is physically plausible for an intense rainfall event associated with the scale of typical

FIGURE 7 Reasonable worst case forecasts of (left) maximum flood depth and (right) maximum flood hazard for the 6 hr period 1600 to 2200 BST (1500 to 2100 UTC) 22 August 2016

intense rainfall-producing weather features, such as thunderstorm clouds and complexes. However, due to the uniform rainfall intensity applied to the hydraulic model, the spatial extent of the flooding at the wider regional scale (right panel, Figure 2) is not plausible for a single event. On the regional scale, the flooding can be viewed as a composite of several local reasonable worst-case scenarios.

5 | USER-LED TESTING IN AN INCIDENT WORKSHOP

The utility of the newly developed forecast products for decision-making was tested in a simulated incident workshop in April 2019, based on the 22 August 2015 Garforth flood event. A total of 38 individuals were present at the workshop. Ten of the 38 were individuals were associated with this project and acted as facilitators and organisers. The remaining 28 were the workshop participants, consisting of 24 forecast users and 4 forecast providers (Table S1).

The aims of the workshop were to:

- Introduce the technical background to current SWF forecast information provided by the Flood Forecasting Centre and Met Office.
- Explore how Local Authorities and others currently act on SWF forecast information.
- Participate in a SWF forecast incident exercise based on the enhanced forecasts.
- Reflect on whether the new, enhanced forecast information is available at an appropriate lead time and the products and their limitations are sufficiently understandable to users to make a difference to decision-making during SWF events.
- Determine how the new information, if deemed useful, would be best implemented into the decision-making process.

The workshop was based around a version of the JBA Exercise Management System (JEMS, JBA Consulting, 2020). The system was used to step through a series of chronological events between 1030 BST 21 August 2015 and 2330 BST 22 August 2015. The participants were periodically shown a variety of information (called 'injects') that were either available to decision-makers at the time, such as the Flood Forecast Centre's Flood Guidance Statements (Figure 1), Met Office advisory emails, rainfall radar, or the newly developed forecast products (Figures 4 and 7). After each inject the participants were asked to report what action should take place at this point, why and by whom. Actions could include, for example: continue to monitor the forecasts/radar observations, call a teleconference, put staff on alert, clear drains of obstructions, deploy staff and/or equipment or do nothing.

After the exercise, 24 of the 28 workshop participants filled out a debrief survey to explore a number of issues regarding the enhanced forecasts:

- Did the enhanced forecasts make a difference to your decisions?
- Are there communication challenges relating to the enhanced forecasts?
- How could the enhanced forecasts be integrated into existing SWF forecasting processes and are there any general recommendations for future development?

Table S2 presents the questions asked, Table S1 summarises the response rate to each question and Table S3 presents the transcribed detailed responses of each anonymised participant to each question. Note that not all those surveyed responded to every question and some responses were not sufficiently clear to interpret. In the survey, results section below the individual questions in Table S2 are referred to by number for example, Q1.

5.1 | Debrief survey results

5.1.1 | Making a difference to decisions

There was a mixed response to the question of whether the enhanced forecast information made an overall difference to decision-making during the exercise (Q1). Thirteen of 24 respondents reported 'yes' the information did have an impact on their actions. The remainder either explicitly reported 'no' (eight respondents) or were undecided (three respondents). Note that making a difference to decision-making did not necessarily equate to taking action. It was emphasised that inaction was an equally valid response.

There was also no clear indication of a single enhanced forecast product that participants found particularly useful (Q2). Of the 10 participants that responded to the question, half indicated the rainfall forecasts were most useful whilst the others suggested the flood depth and extents were. There was no clear pattern of preference based on type of organisation.

Conversely, there were two pieces of information in particular which were found to be 'not useful' (Q3). Of the respondents offering a clear preference (16 out of 24), 4 respondents identified the flood hazard maps and 5 respondents the heavy rainfall (>4 mm/hr) maps as not useful. Based on the comments associated with this question (Table S5), the hazard scores would benefit from a clearer explanation, whilst it was noted that a 4 mm/hr rainfall rate threshold is relatively low intensity and was deemed unlikely to have much of an impact in terms of surface water inundation.

In summary, there was a degree of caution over how useful the enhanced information was during the exercise. This was the first time participants had come into contact with it, so it is unsurprising there were calls for further experience, training and assistance with interpretation. Some participants found the new information a useful companion to the currently issued Flood Guidance Statement and weather warnings, but even they commented on the need for forecasts over a wider geographical area for context and to enable Local Authority-wide response decisions.

5.1.2 | Communications challenges

When asked to name an example piece of information that was difficult to understand or interpret (Q4), 5 of 14 respondents reported problems understanding the flood hazard forecasts. Individuals also commented that the rainfall forecasts still need expertise to interpret and, along with the flood forecasts, still require local knowledge to interpret the foreseeable impacts in the context of the wider region. It was also noted that high uncertainty about where the rainfall will fall remains, which would hinder targeting proactive response resources, particularly for those with responsibility for a large geographical region such as Yorkshire Water.

In suggesting ideas to overcome the above challenges (Q5), respondents identified linking the information more explicitly with the thresholds used in the Flood Guidance Statement risk levels. Generally, the information (specifically the hazard rating scoring system) would benefit from greater explanation through, for example; training, a glossary of terms and the clarification of map legends. The shift in the forecasts over time should be made clearer that is, has the probability of rainfall >16 mm/hr increased since the last forecast? The level of confidence and uncertainty should also be made more explicit.

When asked to identify a piece of information that they found easy to understand (Q6), 9 of 17 respondents chose information that is currently issued that is, Food Guidance Statement, Met Office advisory emails or rainfall radar animation. The remaining chose either the new flood forecast maps (six respondents) or the new rainfall forecasts (two respondents).

When the participants were asked if they understood the probabilistic rainfall information (Q7), 18 of 23 respondents said yes and, 4 respondents said yes but with the caveat that they would like to see greater clarity in the explanation of how they are produced.

In summary, there is a need to align the enhanced forecasts with existing information such as the Flood Guidance Statement, which does a good job of clearly communicating the level of risk, likelihood and impact over the wider geographical regions. More information is not necessarily required by all Local Resilience Fora member organisations, but some feel it would complement the existing information—especially if appropriate training is provided. There is also a need to clearly convey the level of uncertainty (e.g., high, medium or low) associated with the enhanced forecasts, which, being a qualitative measure, would benefit from verbal or written advice for example, via the Met Office advisory service. There is also a need to tailor the information to the local/regional context—a rainfall threshold for one location may not be as relevant in another. Overlaying critical infrastructure and vulnerable populations would help in this localisation.

5.1.3 | Integrating the new information into existing processes

Twenty-two of 24 respondents said the enhanced forecast information would be useful to their organisation (Q8). However, 10 respondents caveated this positive response with a variety of comments. For example, the information should cover larger areas for shorter time periods (i.e., <6 hr windows) and there is a need for expert operational interpretation of uncertainty and confidence in each forecast, such as that provided by Met Office advisors.

Fifteen of 21 respondents suggested the information should be delivered via web portal, with some adding that this should be supplemented with either text or email notifications (Q10). The remaining six respondents suggested the information should be delivered only via text and/or email, perhaps tied to alerts of local rainfall accumulations observed or forecast to be over a certain threshold. Of those advocating a web portal, three respondents made reference to leveraging existing online facilities such as the Met Office Hazard Manager, possibly implementing a tiered system whereby the enhanced forecasts are only available to 'super-users' that have an understanding of ensemble forecasting and its uncertainties.

When asked what the minimum lead time required would be to take proactive/preventative measures (Q12), there were a variety of responses, ranging from 1 to 36 hr depending on the type of organisation. Local Authorities, water utility and community flood action groups generally reported the need for a longer lead times (6–36 hr), whilst the Environment Agency and emergency services typically only need 1–2 hr to take action. Some Local Authority respondents expanded further by explaining that the time of day and the day of the week would have an impact, with more time needed prior to weekends and public holidays to ensure sufficient staff cover.

6 | CONCLUSIONS AND RECOMMENDATIONS

The frequency, severity and impact of SWF in England is projected to increase in the future. The UK Government Department for Food, Environment, Agriculture and Rural Affairs (Defra) have clearly stated that managing the risk effectively, in part, relies on improved flood risk mapping, better communication of storm forecasts and building the capacity of local responders—notably of Local Authorities (Defra, 2018). This study has developed new probabilistic rainfall maps and novel SWF forecast products based on neighbourhood-processed ensemble rainfall forecasts and hydraulic inundation modelling. The products were trialled with a range of stakeholders in Yorkshire, England through an incident workshop to gain feedback from practitioners on how useful the new forecast products are and if/how they should be integrated into existing operational practises.

Even with advances in meteorology and hydrology, it is unlikely that over the next decade or more, forecasters will be able to provide accurate local forecasts with a lead-time beyond a few hours due to uncertainty inherent in the modelling of convective rainfall. The accuracy of the rainfall forecasts remain the main limiting factor for the real-time, dynamic, spatially-detailed hydraulic modelling. The SWF maps trialled in this study will only add significant value to decision-making with much improved rainfall forecasts. Therefore, the main focus in the medium term should be placed on responders being able to make practical decisions in spite of the uncertainty. There needs to be strong emphasis on the need for capacity building to understand the potential and limitations of ensemble rainfall forecasts.

Due to the forecast uncertainty in convective storms and the necessary neighbourhood processing, a single hyetograph was applied over the entire JFlow® model domain to produce the SWF forecast maps. This lack of spatial variability in the rainfall means the resulting flood forecast products are very similar to the design rainfall events used in the existing static Risk of Flooding from Surface Water (RoFSW) maps (Environment Agency, 2020). Therefore, it might be more worthwhile to simply evaluate the reasonable worst-case rainfall hyetograph against the design rainfall hyetographs used to generate the RoFSW maps, identify the most similar one and use the flood map with the associated level of risk. This would avoid the need to run a computationally demanding hydraulic model in real time.

The idea of using RoFSW maps is very close to the 'simulation library' concept that was tested, and recommended as a viable method, in research in England on delivering real-time forecast maps of flood impacts for river flooding (Environment Agency, 2019). The approach also aligns with that referred to as 'Hydrological forecasts linked to pre-simulated impact scenarios' by Speight et al. (2019). An example of such an approach was proposed (but has yet to be implemented) as part of work carried out under the Flooding From Intense Rainfall research programme, in which modelling approaches were developed that allowed pre-simulated flood maps to be used in real time with probabilistic forecast rainfall data.

Encouraging users to simply view the static RoFSW maps in the run up to an incident could be facilitated by including them as an overlay in Hazard Manager and referring to them in the event of flood risk communicated through the Flood Guidance Statement. Indeed, practitioners strongly recommended a 'one stop shop' point of access, which Hazard Manager offers. Whatever the mode of delivery, it is the opinion of the authors of this study that there needs to be a centralised organisation responsible for updating and advising on how the information should be interpreted at the local level.

In summary, our five specific recommendations for future SWF forecast provision are:

1. ***Improve support for Local Authorities***. A single government agency should take a central role in the provision of SWF forecasting, particularly to monitor the ongoing weather situation and forecasts over weekends and holiday periods, when Local Authorities (i.e., local government) have limited or no staff cover. This is particularly the case for SWF forecasts (as opposed to fluvial flooding), where lead times corresponding to a relatively high likelihood of flooding can be short.
2. ***Use existing risk maps more***. Encourage users to make better use of the existing static Risk of Flooding from Surface Water (RoFSW) maps. This information could be added to the Met Office's Hazard Manager online portal to provide less experienced staff within Local Authorities with information on locations prone to flooding in their region.
3. ***Try a simpler 'look up approach'***. Rather than run hydraulic model flood forecasts in real time, the reasonable worst-case rainfall hyetographs should be evaluated against the design rainfall hyetographs used to generate the static RoFSW maps. The most similar magnitude event should be identified and the flood map used with the associated level of risk.
4. ***Evaluate new forecasts***. A quantitative evaluation of the accuracy and reliability of any new rain and flood forecast products over a prolonged period of time and multiple locations is necessary, with particular emphasis on determining the limits of meaningful lead time and spatial resolution. An in-depth analysis is required to establish what level of forecast accuracy is required for the information to be useful for decision-making.
5. ***Continue the co-design process***. The Met Office and Flood Forecasting Centre regularly verify SWF forecasts and improve the functionality of their SWF hazard impact model. User requirements are at the heart of these developments, as are new initiatives in machine learning and improved nowcasting techniques. The process of user-based consultation and testing put in place through this project demonstrates a powerful mechanism to guide the development of user-centric SWF forecast information.

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DATA AVAILABILITY STATEMENT

The interview and workshop survey response data that support the findings of this study are available in the supplementary material of this article. The rainfall forecast data used in the study are available from the Met Office. Restrictions apply to the availability of these data, which were used under license for this study. Data are available from the authors with the permission of the Met Office.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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