Hydrology Research

NHF British Hydrological Society IWA PUBLISHING

Hydrology Research Vol 54 No 12, 1477 doi: 10.2166/nh.2023.023

2021 UK floods: improvements and recommendations from the flood forecasting centre

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ABSTRACT

In recognition of the increased risk to national resilience from flooding, we provide an overview of recent and future improvements to flood risk forecasting and communication at the Flood Forecasting Centre (FFC). We draw on the analysis of fluvial and surface water flooding across England and Wales in 2021 to highlight these areas of improvement. Already implemented improvements in both the underpinning science and our long lead-time product are described in the context of high-magnitude, high-impact floods. In addition, we consider more substantial developments from improved modelling of convection to translating this to surface water flood risk and to the essential communication and service provision. Finally, recognising that many of the challenges are shared internationally, we distil our key recommendations for future improvement. These improvements rely on collaboration for them to be successful.

Key words: climate change, extremes, flood, surface water

HIGHLIGHTS

- We consider the most noteworthy floods that affected England and Wales in 2021 and suggest developments and further improvements to both our services and the underpinning science.
- We describe where service improvements have already been implemented in our longer lead time service, the 30 day Flood Outlook.
- We highlight underlying improvements to our science, drawing on the evolution of weather types from multi-model Decider, the Surface Water Flooding Hazard Impact Model (SWFHIM), and improvements from high resolution modelling.
- Future recommendations for improvement are then highlighted, illustrating the need for international collaboration, the co-design and co-creation of future services with users.

INTRODUCTION

Trend analysis, the assessment of rainfall event profiles, and attribution studies provide emerging evidence that rainfall events are becoming more intense and more frequent (e.g. Davies *et al.* 2021; Kreienkamp *et al.* 2021). Evidence is also indicating that an increase in the intensity of short-duration, sub-hourly rainfall is occurring earlier than the projected climate change would have suggested (Davies 2023, personal communication). This reinforces the increased risk to national resilience from flooding even under the current, baseline, climate. In addition, there is increasing evidence that a more extreme future climate is to be expected (e.g. Kendon *et al.* 2021; Kent *et al.* 2022). Therefore, considering the (rainfall) hazard alone, surface water flood risk would be expected to increase. However, it is more complicated and potentially more serious than this. Impacts from more intense rainfall and surface water are likely to be nonlinear, given increased vulnerability and exposure also. Indeed, the images of flooding across the London underground network highlight this and the tragic loss of life in underground networks in China and New York (e.g. Greater London Authority 2022; Zurich Insurance Group 2022).

Currently, the Environment Agency (2023) estimates that approximately 3.2 million properties are at risk from surface water flooding in England alone. Given the underlying changes to our climate, this is likely to increase in the future. It is by better understanding observations and reconciling these with impacts from the projected changes in climate that we can better understand the risk landscape and introduce improvements for better preparedness.

The FFC is the national flood forecasting centre for England and Wales (Flood Forecasting Centre 2022a, 2022b). This 24/7 operational centre brings together expertise in hydrology and meteorology to assess and communicate flood risk for England

and Wales. An overview of the centre and the key approaches are provided by Pilling *et al.* (2016). The centre produces daily assessments of the river, coastal, surface water and groundwater flood risk, which are communicated to emergency responders via the 5-day Flood Guidance Statement (FGS). A longer-range Flood Outlook service is issued twice a month covering the next 6–30 days.

The main floods that affected England and Wales in 2021 are summarised by Pilling *et al.* (2023). In summary, Storm Christoph affected large parts of England and Wales between 18 and 20 January, then flooding affected west and south-west of England and Wales between 19 and 21 February. The most impactful flooding through the summer and the autumn was from short-duration, intense rainfall across London causing surface water impacts on 12 July, 25 July, and 5 October.

We now consider areas where the FFC can further improve its services and underlying capabilities. We focus on the FGS and the Flood Outlook. First, we explain the service improvements that have already been implemented. Next, we consider improvements in the underpinning science that have been capitalised on. Then we explain advances in training and outreach that benefits our users. Building on this further, we consider more substantial areas that warrant investigation and improvement. Since many of these challenges are shared internationally, we frame developments within our strategic plan and look to collaborators to explore more fully.

SERVICE IMPROVEMENTS ALREADY IMPLEMENTED

Flood Outlook refresh

A generational refresh of the 30-day Flood Outlook was delivered in Spring 2022. The Flood Outlook is designed to communicate broader signals of elevated or reduced flood risk from the rivers, surface water, the coast and groundwater. The previous version is shown in Pilling *et al.* (2023: Figure 4), with the updated version shown in Figures 1 and 2.

User research was undertaken to identify what was valued in the existing product (the second generation introduced in 2015) and also the main areas for improvement (FFC 2021). Feedback from users revealed the requirement for more forecast information around 'more typical' floods, other than just when a significant or severe flood event was indicated. Also, that the forecast flood risk was 'low' too frequently – 'when it shows low so often it's difficult to take decisions based on it' (FFC 2021). Users also suggested that confidence in the forecast was low too often, and they were uncertain what the low/medium/high risk referred to. This tied in with a request for 'access to further training and support to understand how the Flood Outlook might be more useful to me' from responders (FFC 2021). In addition, there was a desire for a clearer product with less technical information, which could be shared more easily, larger maps and an improved colour palette (FFC 2021).

The improvements made to the new style Flood Outlook (Figure 1), which was first issued in May 2022 and has a refreshed, clear presentation, and all the key information is on the new Flood Outlook dashboard appearing on the first page. This is designed to enable users to share that page. The new product also defines weeks 3 and 4 in less granularity than previously (as weeks rather than by day), giving a more realistic representation of the forecast precision at such a range.

Another key difference is in what is being forecast. The new Flood Outlook shares whether the likelihood of flooding is increased, neutral or reduced in the table and the text, as well as continuing to highlight whether any significant (or severe) flood events are signalled within the text of the forecast.

This change to forecasting the likelihood of flooding should enable FFC hydrometeorologists to share more of the information they gather when preparing the forecast with users. More subtle signals in the forecast data can now be shared, giving users better insight into when possible localised or less severe flooding could occur. Previously, FFC hydrometeorologists would wait for a signal for a major flood event before raising the risk on the Flood Outlook. Therefore, an improvement with the updated Flood Outlook is the ability to communicate signals of lower magnitude floods proportionately using the key detailing the 'likelihood of flooding'.

In the context of learning from 2021 events, well-forecast frontal events with wet antecedent conditions will still be clearly highlighted as possible periods of major flooding on the new Flood Outlook. However, there is now more scope to bring users' attention to spells in the summer half of the year when convective weather regimes are signalled as seen in the summer 2021. These periods can be highlighted as having an increased likelihood of flooding, possibly resulting in surface water flooding issues, even when there is no confidence that a significant or severe event will occur. Less well-signalled winter events, or wet periods with drier antecedent conditions, can also now be highlighted to users more clearly.

Finally, to support responders in making decisions with confidence, FFC ran three well-received training webinars in the autumn 2021 to help responders interpret the Flood Outlook product before the upcoming winter.

Figure 1 | First page of the new Flood Outlook: dashboard illustrating the likelihood of flooding from each source for the next 4 weeks along with headlines and situational awareness.

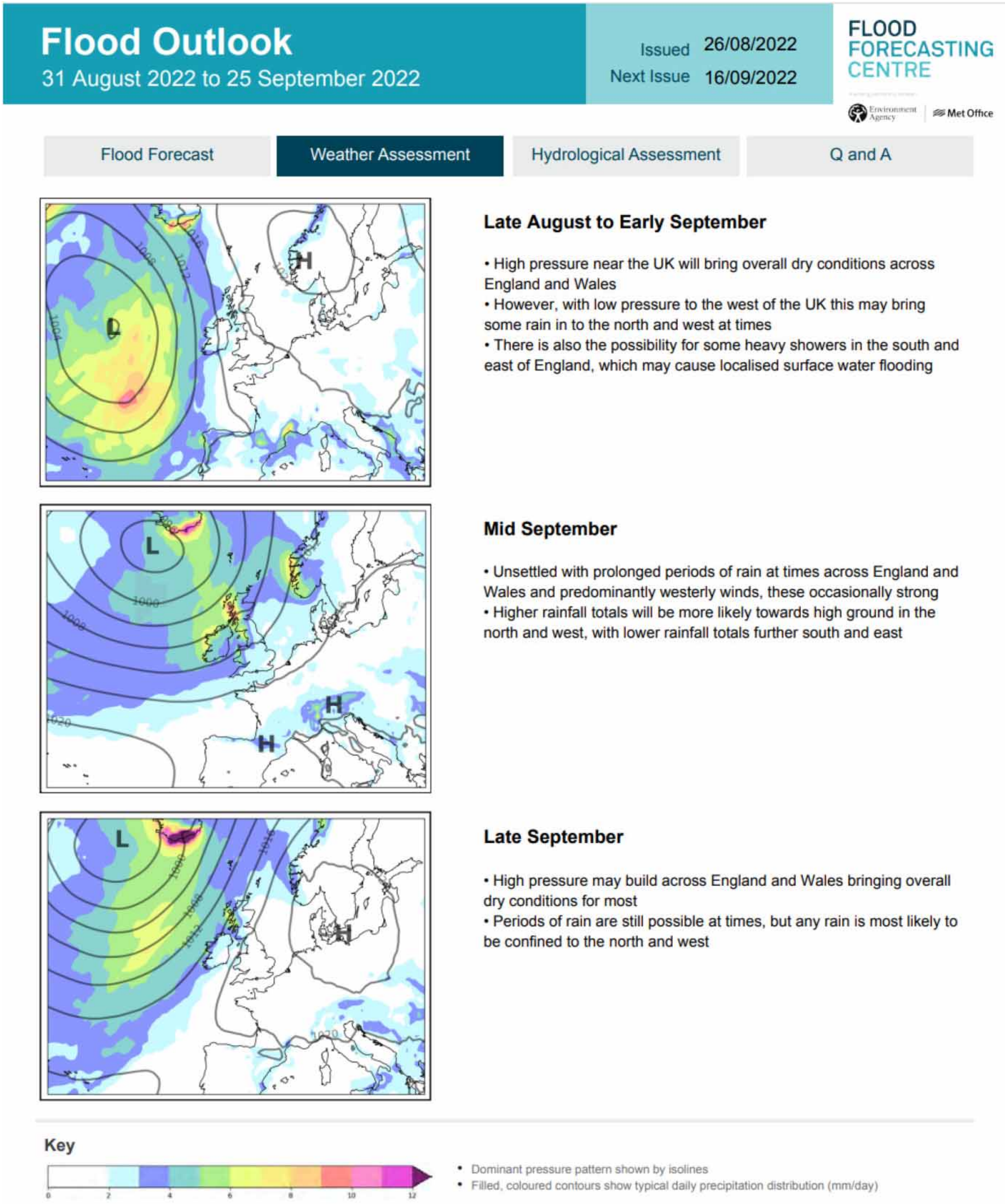

Figure 2 | Second page of the new Flood Outlook: example of most likely Decider regimes and weather summaries.

IMPROVEMENTS IN UNDERPINNING SCIENCE HAVE ALREADY IMPLEMENTED

Given our reflections and learnings from the 2021 floods (Pilling *et al.* 2023) and recent previous floods, combined with findings from our biennial responder surveys, the FFC progressed several activities to improve our forecast capabilities. While feedback from users is extremely positive, for example, 92% satisfaction with the FGS (Met Office 2022), there is the desire for increased lead time, especially for surface water flooding, increased granularity of forecasts, and also increased accuracy. Improvements to our forecasting capabilities will provide enhanced services to our users and key stakeholders. Two examples now follow: multi-model Decider where the likelihood of weather regimes is generated by combining ensemble forecasts from a range of Numerical Weather Prediction (NWP) models, and improvements in the surface water forecasting model run for the FFC.

Multi-model Decider

Decider is a medium- to long-range forecasting tool based on several predefined weather regimes (Neal *et al.* 2016). If the weather regime characteristics are understood, in this case for England and Wales, then ensemble members from probabilistic weather forecasting systems can be assigned to a particular weather regime. By clustering these into the most likely forecast scenarios, large volumes of ensemble data can be analysed quickly to describe the likely hazards and assess uncertainty. While the benefits of Decider were well recognised and indeed used during 2021, a limiting factor was that each of the ensemble forecasting systems, for example MOGREPS-G, ECMWF, and GloSea6, were treated independently. Consequently, judgement had to be used to favour one suite of the ensemble forecasting system over the other. In practice, there would be a value in each ensemble forecasting system, and some of this was being dismissed in the forecaster selection process. To overcome this, and also increase forecaster efficiency, the FFC commissioned a project with the Met Office Applied Science to create a multi-model seamless version of Decider combining these ensemble forecasting systems and to provide weather regimes from lead times of 1–51 days (Neal 2023). Furthermore, the multi-model Decider also benefited from the ECMWF upgrade in June 2023 by incorporating the 46-day ECMWF extended range forecast, now runs daily (instead of twice a week), with 101 ensemble members (up from 51 members). Decider output is used routinely in the Flood Outlook (Figure 2), and this enhanced capability offers the benefits of a super-ensemble.

Surface Water Flooding Hazard Impact Model

The Surface Water Flooding Hazard Impact Model (SWFHIM) is a tool that provides a first objective assessment of surface water flood risk. An example of the output is shown in Figure 3. It draws on Met Office ensemble precipitation and surface-runoff forecasts from the Grid-to-Grid (G2G) hydrological model (Cole *et al.* 2015), and a library of impacts that map to the hazard footprint (Cole *et al.* 2017). Output is the probability of the severity of flood impact (very low, low, medium, and high) for each county or unitary authority across England and Wales. During debriefs on the surface water floods of 2021, it was evident that the SWFHIM performed to varying levels of reliability across its England and Wales domains. In addition, it emerged that there were inconsistent levels of confidence in the output across the operational team.

Consequently, several activities have been implemented to improve our operational interpretation more consistently across the team, these include:

- pre-season training for FFC hydrometeorologists, rolled out in Spring 2022 and repeated annually
- routine post-event reviews to help understand SWFHIM performance
- improved visualisation to aid operational decision-making
- commissioning of science development work to upscale approaches used by the SWFHIM and address the issue of over- and under-sensitive counties

Enhanced training and user support

Even with the best forecasts and products, there is still a need for users to understand and correctly interpret the information they receive before they can take appropriate and proportionate action. Results from the biannual Met Office survey revealed that 'Three fifths (60%) of responders who receive the FFC FGS say they are unaware of a range of training and resources' (Met Office 2022). In addition, Flood Outlook users requested further training (FFC 2021).

Over the last 2 years, the FFC has expanded the training and support available to responders. Webinars for FGS users and also for Flood Outlook users have been run, and bitesize training videos are now accessible from the FFC website (FFC 2023). The training videos introduce the products and step through them, explain the flood risk matrix that underpins the FGS, and also shows how the products fit with other Met Office, Environment Agency (EA) and Natural Resources Wales (NRW) alerts and warnings. All (100%) of the responders who accessed this training found it useful (Met Office 2022).

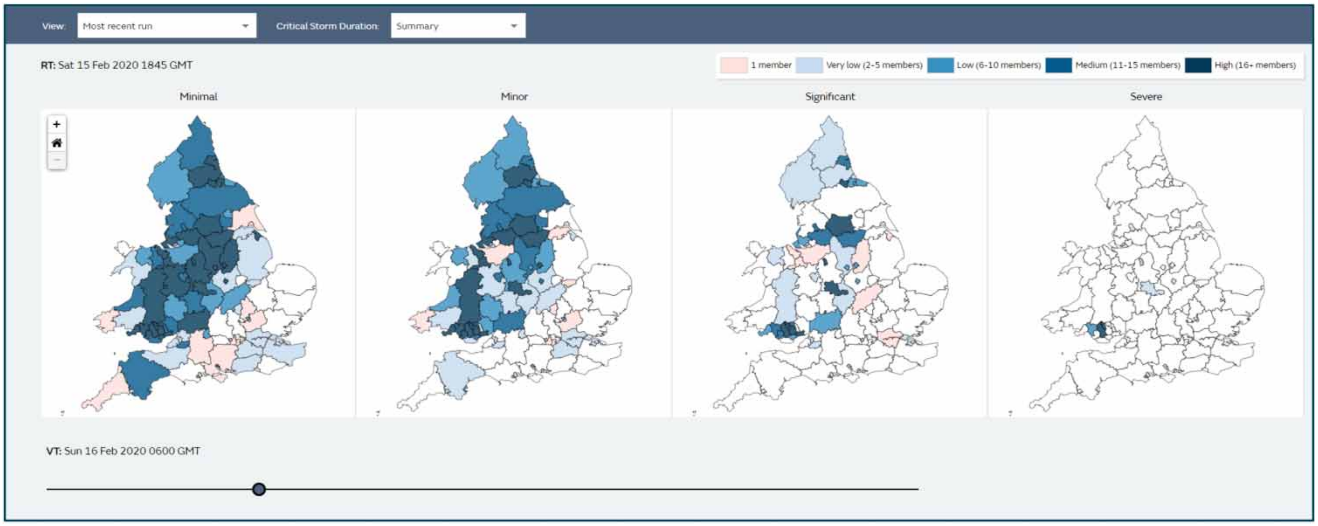

Figure 3 | Example of probabilistic objective output from the SWFHIM illustrating the number of ensemble members reaching thresholds of 'Minimal', 'Minor', 'Significant' or 'Severe'. The slider bar at the bottom allows the user to scroll through the forecast period.

RECOMMENDATIONS FOR FUTURE IMPROVEMENTS

We now consider further developments to improve flood risk assessment and communication and better enable decision-making. While the focus is primarily on England and Wales, it is appreciated that many challenges are shared internationally. Specifically, considering the 2021 floods and feedback from users, we suggest improvements to better identify and warn for extreme events now and in the future.

The FFC's Strategic Plan (FFC 2022a) was developed alongside our users and partners with many of the flood forecasting challenges in mind. This plan sets out our strategy till 2024, with key elements illustrated in Figure 4. The plan recognises the value of collaboration and our partnerships, right the way through from co-creating services to delivering these services through partnerships themselves. It puts users at the heart of all that we do. While maintaining our high technical standards, we want to ensure that our users trust, understand and have the confidence to act on our guidance. Finally, we recognise that we are in a world that is rapidly changing. We must remain flexible, agile and adapt, so that we can meet future needs. Indeed, just as we are doing in response to the 2021 floods.

Improvements in surface water flooding

In terms of properties at risk from surface water flooding, the risk is greater than that from rivers and the sea combined (Environment Agency 2023). Furthermore, given the typically highly localised nature of surface water, flooding can impact any neighbourhood, and at shorter lead times, our preparedness is tested. This is the situation under our current climate, even before future climate change further exacerbates the hazard. Indeed, there are views that our national resilience and warnings will not be fit for the more extreme and hazardous climate that the UK may experience over the next 10–30 years.

In 2021, the Government provided an update on the policy, progress and challenges of surface water management (Defra 2021). While appreciating the complexity and challenges of surface water management, the Central Government has an increasing expectation of our flood forecasting and response capability, which ultimately resides with Defra. As such, Defra (2021) is looking for ways to improve surface water flood forecasting to enable: better incident planning and response in built-up areas, actions to be taken to protect infrastructure and better safeguarding of the public. Partly in response to this, the FFC has developed two proposals. The first considers forecasting capability and warning under our current climate; the second is more focussed on extremes and surface water flooding, particularly under a future climate.

Forecasting capability, communication and action for floods under our current climate

For perspective, this is very much focused on events similar to the London floods of 12 and 25 July and 5 October 2021, as described in Pilling *et al.* (2023). The main aim is to draw on applied research to improve the forecasting of surface water flooding and the translation of the risk to decision-making and timely action by users.

Figure 4 | Summary of FFC's Strategic Plan highlighting objectives and success criteria (FFC 2022a).

More specifically, and in an operational sense, this would involve

- capitalising on advances in social science and social sensing to improve rapid data assimilation and faster translation of surface water flood risk to users,
- further our understanding of our users' requirements and explore a pilot automated warning capability in fast-developing situations,
- with other risk management authorities, explore and pilot real-time impacts from surface water flood inundation, extent and velocity modelling, and translation into potential services,
- better understanding of our current capabilities by baselining our current and new capabilities through verification, and
- close the current 'gaps' in the warning systems and communication to emergency responders (and the public) to incite the appropriate action to be taken.

Tangible benefits would include piloting modelling systems for surface water flooding applications, proposals for optimising operational decision-making, improved guidance we can provide in the FGS and improved warning of surface water flood events. This would enable users to take more informed actions at longer lead times, ultimately reducing the risk to life from surface water flooding.

The current FGS service identifies broad geographic areas of concern with little certainty for responders to put plans into effect. We are looking to improve lead times and geographical accuracy and to carry out specific engagement with customers to identify their detailed needs for surface water events. Alongside this, the FFC should develop a clear link from the FGS to wider alerting/nowcasting capabilities to help responders identify and react to rapidly changing situations.

Identifying and warning for extreme events and future climates

A second approach is to identify and warn for extreme events now, and those more frequently experienced under our future climate in 10–30 years. The main aim of this applied research would be to better understand the scale, impacts and potential timescale that extreme surface water flood events may be realised. This would help ensure that services from the Met Office and our partner organisations are fit for the future. More specifically, this would involve

- identifying dynamic flood models that are suited to modelling surface water flooding impacts under future climates and use the model to
- simulate and document how extreme surface water flooding impacts may be at decadal intervals to 2100,
- identify when typical drainage capacity will be routinely overwhelmed in urban areas (typically 30 mm/h capacity),
- map possible scenarios that could exceed Reasonable Worst Case (RWC) scenarios in the National Strategic Risk Assessment (NSRA), which are characterised by the number of fatalities, and
- share knowledge and co-create mitigation and emergency response plans with key infrastructure providers and operators (e.g. Transport for London).

Tangible outputs include piloting a hydrodynamic flood model that is well suited to modelling extreme surface water flooding impacts. This would provide benefits for our future climate research but also for modelling the impacts of extreme events in our 'current' climate. This could inform NSRA submissions to the Cabinet Office as well as provide an outline of potential impacts from extreme events in the forecast production process. Research findings would be shared with the Government and our strategic partners, such as the Environment Agency. In addition, there is potential to work with key infrastructure operators and owners to co-create mitigation and emergency response plans. Adaptation and mitigation work could provide growing sources of revenue in the future.

Improvements in the SWFHIM

As introduced by Pilling *et al.* (2023), the SWFHIM (Aldridge *et al.* 2020) is one of only a handful of operational hazard impact models (Schroeter *et al.* 2021). As a relatively new model, the FFC is still learning about performance and operational best practices. Knowledge gained from the 2021 floods and other work has already been pulled through into training and model development. Future work is planned as part of a lifecycle approach to development. This aims not only to ensure the currency of underlying vulnerability and exposure datasets but also to advance operational interpretation and incrementally improve forecast accuracy.

A thorough understanding of forecast performance should be the basis for SWFHIM life cycling, providing evidence-based forecaster guidance and informing a targeted value for money, scientific and technological developments. Subjective event-based verification is well established. While importantly, this approach is laborious, does not provide continuous or consistent results over time (Robbins & Titley 2018) and cannot assess false alarms or baseline performance statistics. Objective verification is required but is almost completely novel for hazard impact models, mainly due to a lack of observed impact data (Robbins & Titley 2018; Schroeter *et al.* 2021).

The FFC has collected surface water impact observations at a county scale since 2014, giving a unique opportunity to objectively verify the SWFHIM. A pilot study covering April 2020–November 2022 has demonstrated the utility of the approach for guiding future development. Figure 5 provides a good illustration of this from which individual events can then be objectively reviewed in detail (as demonstrated in Pilling *et al.* 2023). Work will soon begin to build on this by implementing a new verification system, which will run continuously and produce additional statistics, and to investigate how different components of the model contribute to overall performance.

The results will be relevant to the use of hazard impact models more widely. International effort is focussed on moving towards impact-based forecasting and warning (United Nations 2015; WMO 2015), and objective impact models such as the SWFHIM are a key part of this. However, only a minority of European Meteorological and Hydrological Services currently use these operationally (Kaltenberger *et al.* 2020), which Schroeter *et al.* (2021) suggest may in part be due to a lack of impact and verification data.

Alongside verification, operational guidance and model development, there should be a future focus on extracting the maximum value from the existing model. Kaltenberger *et al.* (2020) found that low utilisation of objective impact models in Europe may indeed be due to cost. The FFC currently uses only a fraction of the available forecast data, which includes four impact types (risk to life, communities, transport and utilities; Aldridge *et al.* 2020), all available on a 1 km grid. There is valid

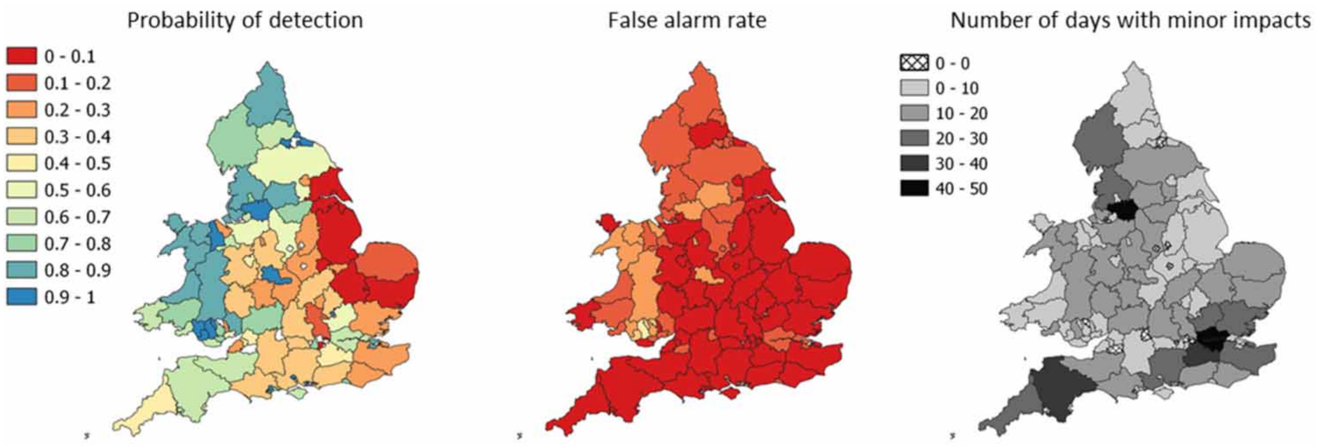

Figure 5 | Probability of detection, false alarm rate and number of days with impacts for the SWFHIM minor impact category and 3-h critical storm duration between April 2020 and November 2022. Contingency data underlying these statistics consider any probability of impacts (i.e. only one or more ensemble members need to forecast minor impacts to score a hit or a false alarm). Counties with high false alarm rates (e.g. in Wales) and conversely with low probability of detection (e.g. in the East of England) are clearly picked out. High false alarm rates are a distraction from genuine signals when hydrometeorologists use the SWFHIM operationally, and understanding and resolving this issue will be a focus for future work.

apprehension around the use and provision of such detailed data due to uncertainty in underlying precipitation forecasts and the potential to give a false sense of forecast accuracy. Developing and implementing different SWFHIM configurations, alternative input data, training, or future NWP prediction model development may all be routes to alleviate these problems and enable more complete utilisation of the SWFHIM. Looking further into the future, it may be that the SWFHIM could be used to better understand the impacts of climate change by coupling to relevant input data.

Improvements in the sub-km-scale NWP models

Increasing the resolution of NWP to represent convection allows smaller-scale processes to be modelled explicitly with less dependency on parameterisations. It follows that improved representation of convection, which is directly linked to the generation of surface water flooding, is likely to result in improved forecasting of surface water events.

Hanley (2022) investigated the benefits of running sub-km models, considering the horizontal and vertical grid length, the domain size, and the benefits of running in ensemble mode. Indeed, the benefits of 300 m grid length ensembles were assessed compared with 1.5 km grid length ensembles for the convection that resulted in the London flooding on 25 July 2021. While limitations in the 300 m grid length ensemble were acknowledged by Hanley (2022), these were attributed to limitations in the driving 1.5 km grid length ensemble and the relative small ensemble size of 18 members. Importantly, there were promising indications of the 300 m grid length ensembles better capturing higher rainfall intensities.

Another key finding was that the model domain had to be large enough to allow convection to fully spin up from the lateral boundaries. While this could be overcome for the Greater London region by enlarging the size of the domain to roughly the size of England, this would be prohibitively expensive. One approach to overcome this is to adopt a variable model domain. Indeed, during the summer 2022, Hanley & Lean (2023) trialled an inner fixed 300 m grid length part of the domain, which is surrounded by a stretching zone where the grid length is gradually inflated outwards, so that it reaches 1.5×1.5 km.

For this trial, the 300 m grid length variable was run in the ensemble mode that was nested inside the operational MOGREPS-UK 1.5 km ensemble. Results were analysed by scientists and users, indicating that this high-resolution approach 'looks promising for high-impact convective events as it is better able to represent the organisation of convection into lines or larger storms' and that it provided 'more reliable probabilities of heavy rainfall' (Hanley & Lean 2023, p. 29). Given the encouraging results, the approach will be explored and refined further during the Wessex Summertime Convection (WesCon) observation campaign in 2023 and the WMO 2024 Paris Olympics Research Demonstration Project (Hanley & Lean 2023).

Best Estimate and RWC FGS

Our findings revealed that different responders take different actions to mitigate flood impacts and have different levels of risk tolerance. Some customers of the FGS may need to act on a RWC basis implementing measures to prevent any impacts whenever at all possible. The current FGS is designed for these users. Other recipients of the FGS may have more tolerance to risk, and it makes sense for them to only act when flooding is considered quite likely (medium or high likelihood) or just be ready to respond rather than act ahead of time. '*Around a quarter (27%) of survey responders say that the FGS provides sufficient information … to take appropriate action all the time … Additional communications may be necessary to ensure responders are receiving the information they require from … the FFC*' (Met Office 2022).

There is a possibility to provide a Best Estimate (BE) FGS, in addition, if users would benefit from that. This could bring several advantages. Firstly, it would enable the FFC to share information about what is most likely to occur rather than just the most pessimistic forecast. Secondly, it allows users to understand what should happen rather than what could happen. Thirdly, it makes clear what outcome is more likely in an all-or-nothing situation. Finally, it reduces the number of false alarms.

So, for example, in the build-up to Storm Christoph flooding (Pilling *et al.* 2023), when the FGS forecasts a low likelihood of significant impacts with 3 days' lead time, the BE forecast could have been a high likelihood of minor impacts. This information is not currently shared through the FGS service (either through the current online offering or email version) but could be useful to some responders to help them take proportionate actions according to their requirements.

Fully probabilistic forecasting and verification of ensembles

Rather than simplifying or aggregating scenarios, more information and valuable details are available from viewing fully probabilistic data. While meteorologists have been working with probabilistic forecasts for many years, it is only more recently that operational flood forecasting in England has been capable of producing local probabilistic hydrological forecasts. Developing this more widely and operationalising probabilistic flood forecasts would enable operational teams to share the whole range of possible flood impacts and their likelihoods with responders.

Related to this is the requirement to verify ensembles of rainfall and river flow. The FFC in collaboration with partners is looking to address a capability gap concerning the lack of readily available quantitative data for the verification of rainfall and river flow ensembles for use in real-time flood forecasting. The second phase of this project delivered a proof-of-concept 'Ensemble Verification Framework' for both the rainfall and river flow ensemble data and provided evidence that this approach is both possible and useful for operational forecasting (Anderson *et al.* 2021). The next step is to progress to the implementation of an end-to-end interactive forecast visualisation and a verification platform as shown in Figure 6.

For a forecast selected to cover a specific time, the ensemble member hydrographs are plotted with one colour per ensemble member. In the case of a post-event analysis, the observed flows are plotted in black to allow the ensemble performance to be visually assessed. Each flow threshold of Q(2)/2, Q(2), Q(5) and also Q(50) appears as a horizontal black dashed line only

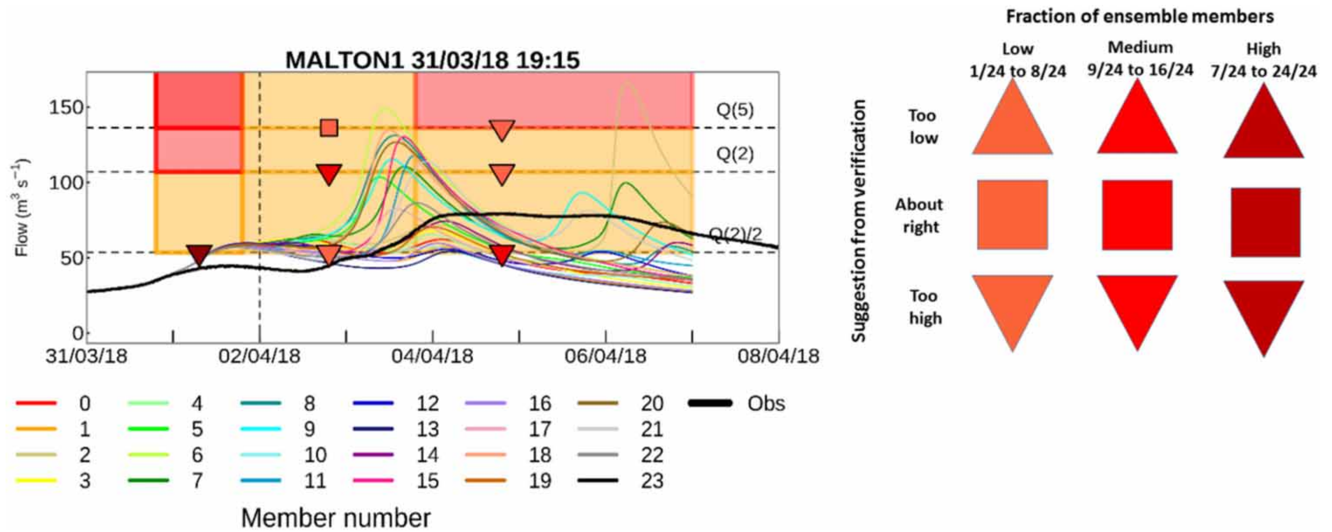

Figure 6 | Example hydrograph display is used to place the ensemble river flow threshold exceedance in the context of the ensemble verification information. The catchment shown is Derwent at Malton, NE England, for a forecast time origin of 19:15 31 March 2018. Q(2)/2, Q(2), and Q(5) represent return periods. The red triangles and squares indicate if the ensemble forecast is too high, about right, or too low for different flow thresholds and lead times compared to historical ensemble verification data.

when it is exceeded by at least one ensemble member or by the observations of river flow. Where forecasts have been selected to analyse performance at a specific time of interest, this time is shown by a vertical black dashed line.

Ensemble probabilities of upward threshold-crossings are calculated for Day 1, Days 2–3 and Days 4–6 of the forecast. These are plotted at the relevant flow threshold, and the centre point of the lead-time range is considered with a coloured symbol indicating the probability of crossing each threshold. The background of the hydrograph is coloured according to the overall skill of the ensemble. The approach aims to give a quick impression of the ensemble performance at the site of interest, and how this varies with threshold and lead time.

Grid-to-Grid

The G2G hydrological model has been used successfully by the FFC in both deterministic and ensemble modes for over a decade. The configuration and rainfall hierarchy are described by Price *et al.* (2012). Successive improvements in the driving precipitation data result in improvements to the national hydrological output.

A further area for the development of the fluvial modelling capabilities in the FFC are improvements in the medium-range ensemble precipitation NWP used to drive the ensemble configuration of G2G. Indeed, this was a recommendation from the Rainfall and River Flow Ensemble Verification project (Anderson *et al.* 2021). Currently, the ensemble rainfall data are from the high-resolution (~2 km) MOGREPS-UK precipitation data for the first 3 days of the forecast with the remainder of the 6-day period driven by downscaled lower-resolution (~20 km) MOGREPS-G data. The new Met Office post-processing system IMPROVER (Roberts *et al.* 2023) is designed to exploit high-resolution km-scale ensembles. Coupling IMPROVER precipitation with G2G would optimise the use of high-resolution precipitation ensembles out to 5 or 6 days. This approach would improve the modelled fluvial flood risk to a much more representative local hydrological scale through the medium-range period.

Real-time inundation

The 2021 flood events show that river models are useful tools for forecasting relatively large, longer-period flood events, and it is also clear that there is still a huge challenge in forecasting surface water flooding with any degree of accuracy or precision. This is a challenge through the flood forecasting chain, but especially so in identifying and simulating the driving meteorology, i.e., the actual rainfall location and intensity. While the SWFHIM uses a library of nine different idealised storms to produce a flood hazard footprint from a background library (Pilling *et al.* 2023), these are static datasets with limited flexibility.

The capability already exists to take recent or nowcast rainfall data and runs this through inundation models in a research environment. So, when intense rainfall is forecasted as a possibility near large urban areas, these forecast storms could be input into inundation models in an operational environment to determine a forecast hazard footprint and possible impacts. Such a method should run in a probabilistic manner and be introduced for specific urban areas, such as Greater London or West Midlands, at least initially to reduce demands on computer power and focus on locations where the greatest impacts are likely. The outputs would be assessed for impact levels by hydrometeorologists with the likelihood aligned with the probability values and feeding directly into the FGS flood risk matrix. Such progress would provide a more accurate assessment of the possible impacts of a surface water hazard.

Customised services by the sector/user

The current one-size-fits-all FGS has proved its value over the last 10 years, especially in larger, longer flood events (both river and coastal floods), but was designed for government responders. Nowadays, the FGS is also shared with numerous other responders, sector partners and bodies responsible for national infrastructure. These have different roles, capabilities and resources with various aims, resulting in different levels of risk aversion and triggers for flood-mitigating actions. Consequently, it would be sensible to undertake user (and potential user) research to understand future requirements.

Ultimately, the FFC wish to provide a service that is user-driven and provides the most useful intelligence about flood risk to drive appropriate actions. There is an opportunity to develop a service where recipients of the FGS, who understand their own role and capabilities best, can determine their own thresholds. User-defined thresholds trigger users' actions. Individual users could customise their FGS to their needs, or different FGSs could be produced for responders in different sectors. These could use BE and/or RWC or fully probabilistic FGSs, taking the whole probabilistic distribution of flood risk into account.

CONCLUSIONS

The floods that affected England and Wales in 2021 have provided the FFC with an opportunity to make improvements in underpinning capabilities, our 6- to 30-day lead time Flood Outlook, as well as improved training and support for users. While this is considered good progress, it is evident that many other opportunities remain in flood forecasting and flood risk assessment. In addition, we make the distinction between forecasting impactful events such as those experienced in England and Wales in 2021 and the more extreme events that are likely under an even warmer climate.

We highlight key areas for further development in the UK context but also appreciate that many challenges are shared internationally. We suggest that it is in our collective interests to work with others. The FFC's Strategic Plan has been developed with this approach at the core. Perhaps, the most challenging future floods for the UK will be from surface water. With this in mind, we have focussed on possible improvements in surface water flooding, notably the SWFHIM which is one of only a few operational hazard impact models globally. We highlight how we continue to refine the modelling approach and how we continue to learn and further develop our operational interpretation and understanding. We emphasise that a lifecycle approach and objective verification are key aspects and examples are included.

Improvements in precipitation forecasting models will, in turn, improve flood forecasts. Examples cited include shorter-range 1- to 2-day sub-km-scale NWP models and medium-range 3- to 6-day improvements. Such improved precipitation forecasts can then be used to drive detailed impact models such as SWFHIM or larger-scale national fluvial models such as G2G. We also highlight the role that ensembles and probabilistic flood forecasting are likely to play in the future, integrated into national flood forecasting to aid decision-making and potentially drive much more detailed inundation models. We have also identified several areas where our customers and users can expect improvements; some of this may be from tailoring products and services to their requirements, in addition to the improvements in underpinning capabilities.

To conclude, we highlight the challenges that surface water flooding presents given the less predictable nature of intense and localised rainfall, broader geographical areas which can be affected, more complex covered drainage systems and less well-developed warning and communication methods. Despite increases in computer power and higher resolution modelling, and indeed SWFHIM, surface water flooding remains a challenge under current climate conditions.

Our future climate will consist of more extreme weather events. To meaningfully assess the risk faced by our national resilience, we need to consider the increase in hazard footprint but also the increase in exposure and our vulnerability. To cope with this, we need to improve our capabilities in terms of data, models, expert interpretation, capacity of our customers, more rapid communication and decision-making. These improvements need to be made during 'peacetime', so that we can collectively be in the best position possible ahead of the more extreme and record-breaking floods that will undoubtedly unfold.

ACKNOWLEDGEMENTS

The authors would like to thank the two anonymous reviewers for their constructive suggestions and Dave Cox for proofreading and further suggestions that have led to an improved paper.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 5 February 2023; accepted in revised form 30 October 2023. Available online 13 November 2023