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2021 UK floods: event summaries and reflections from the Flood Forecasting Centre

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ABSTRACT

Flooding in 2021 has highlighted the increased risk to national resilience. This is against a backdrop of the UK climate projected to become more extreme over the next few decades. This paper considers the notable river and surface water flood events within England and Wales during 2021 and examines the performance of the Flood Forecasting Centre in highlighting the flood risk to our customers. We reflect on team debriefs as well as feedback and surveys from our customers. We distil our learnings and make connections with improvements in our underpinning science, forecasting tools, products and services. Finally, we highlight challenges associated with surface water flooding and suggest how we may collectively start to overcome these.

Key words: extremes, flood, forecasting, river, surface water

HIGHLIGHTS

- We provide an overview of the most noteworthy floods that affected England and Wales in 2021 and outline key products and services provided by the Flood Forecasting Centre (FFC).
- Our post flood event reviews are summarised and our reflections on these 2021 events are highlighted.
- Key findings from our customer reviews are provided.
- Future recommendations for improvements are then highlighted, illustrating the need for international collaboration and the co-design and co-creation of future services with users.

INTRODUCTION

Flood risk across England and Wales

Flooding that affected England and Wales in 2021 has demonstrated the increasing risks to national resilience. While there have been greater flood-affected years across the UK in recent decades, 2021 was notable given that the Met Office (MO) first named a storm for rain impacts (rather than solely for wind; Kendon 2021) and three surface water floods affected London. In addition, 2021 was unique given the complications of warning of, and responding to, widespread river flooding during the COVID pandemic when it was a priority to maintain the operation of COVID test and vaccination centres. Furthermore, 2021 was a year of widespread and impactful flooding across the globe, as documented in this special issue.

This is the situation experienced under our current climate. There is mounting evidence of a more extreme climate over the next few decades in terms of rainfall (Kent *et al.* 2022) and temperature (Murphy *et al.* 2020; Kendon *et al.* 2021). Indeed, attribution studies are now able to link specific events to climate change (e.g. McCarthy *et al.* 2019; Davies *et al.* 2021). This was not possible 5–10 years ago.

For England, the Environment Agency (EA) estimates there to be approximately 5.2 million properties at risk of river, surface water or coastal flooding (Environment Agency 2023) Of these, 3.2 million properties are at risk from surface water flooding. In addition, the British Geological Survey and the EA estimate the number of properties at risk of groundwater flooding in England is between 122,000 and 290,000 (McKenzie & Ward 2015). For Wales, Natural Resources Wales (NRW) estimates some 245, 000 properties are at risk of flooding with 100,000 of these at risk of surface water flooding.

Here, we consider two different types of flooding that affected the UK in 2021, namely fluvial or river flooding, and pluvial or surface water flooding. The risk associated with surface water flooding has increased in the recently published National Risk Register (HM Government 2023) to now be similar to that of river flooding. Projections suggest that both of these flood sources will become more extreme in a changing climate (e.g. Sayers *et al.* 2020).

River floods tend to be more predictable, partly due to the more mature forecasting, warning and communication systems, even for smaller catchments; and also because of the lag between rainfall and river response as water is stored. The greater challenges tend to relate to surface water flooding given the less predictable nature of intense and localised rainfall, complex covered and impermeable drainage systems and less well-developed warning and communication methods. This is compounded by the complex 'ownership' of flooding from surface water across England and Wales.

Figure 1 illustrates that for England and Wales, the flood agencies, namely the EA and NRW, are responsible for issuing flood warnings to communities for river and sea floods. Guidance and warnings for heavy rainfall that can lead to surface water flooding impacts are provided by the MO.

The Flood and Water Management Act 2010 established Lead Local Flood Authorities, as the local government authority responsible for warning communities ahead of surface water floods. However, few have technically or financially been able to provide a local service that can mirror the community service provided for rivers and the coast. For this reason, and as the national centre for hydrometeorology, the Flood Forecasting Centre (FFC) delivers the national strategic surface water flood risk service for the Department for Environment, Food and Rural Affairs (DEFRA) via the EA and MO partnership.

The FFC

The FFC is the National Flood Forecasting Centre for England and Wales (Figure 1, Flood Forecasting Centre 2022a, 2022b). It was established with DEFRA funding in response to the 2007 floods as a working partnership between the EA and MO, combining the organisations' hydrology and meteorology expertise to create a hydrometeorological centre.

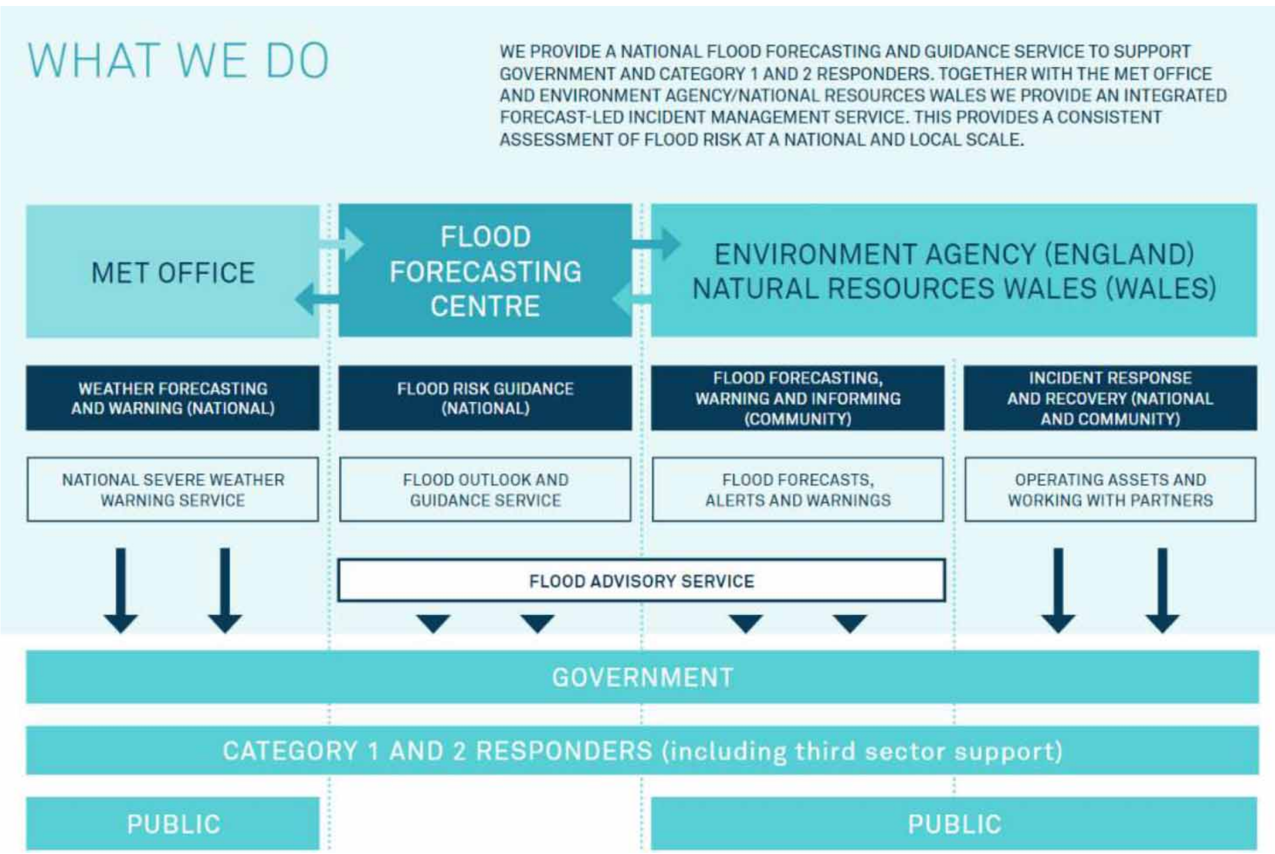


Figure 1 | FFC's role in the integrated forecast-led incident management service and the organisational responsibilities for England and Wales (FFC 2022a).

Following the severe, widespread and prolonged floods of summer 2007, the Government commissioned the Pitt Report (Pitt 2008), a comprehensive review of the event and performance of all agencies and organisations involved. Two key recommendations from the Pitt Review resulted in the FFC being established:

- The EA and the MO should work together, through a joint centre to improve their technical capability to forecast, model and warn against all sources of flooding (Recommendation 6).
- The MO and the EA should issue warnings against a lower threshold of probability to increase preparation lead times for emergency responders (Recommendation 34).

The 24/7 joint operational centre combining EA and MO expertise now operates out of the MO headquarters in Exeter where FFC hydrometeorologists issue longer lead time guidance. The role of the FFC was cemented in the first National Flood Emergency Framework in 2013, itself another Pitt Review recommendation (Pitt 2008). Pilling *et al.* (2016) provide an overview of forecasting river, surface water, coastal and groundwater flood risk in an operational setting for emergency responders. While the array of models has been upgraded and improved, the operational process remains very similar. Two key products and consultancy services referred to in this paper are the 5-day Flood Guidance Statement (FGS) and the 30-day ahead Flood Outlook. Both provide an assessment of flood risk from rivers and surface water, as well as coastal and groundwater. The FGS communicates the risk using a matrix assessing level of impact and likelihood, while the Flood Outlook provides a broad signal of elevated or reduced flood risk. Details of both of these along with a detailed explanation of the flood risk matrix are available on the FFC website (FFC 2022b).

2021 in summary

Figure 2 illustrates the flood risk across England and Wales during 2021. The green, yellow, amber and red categories are defined as very low, low, medium and high flood risk, respectively, and were communicated as the overall flood risk on the FFC's FGS. The purpose here is to summarise the 2021 floods visually, with the higher risk corresponding to events with more impacts on communities, infrastructure, transport and risk to life.

It was a busy start to the year with a major storm, Storm Christoph, affecting large parts of England and Wales between 18 and 20 January 2021. Storm Christoph was also notable for being the first ever storm named by the MO for its expected impacts from rainfall rather than wind alone (Kendon 2021).

On 19–21 February, widespread and heavy frontal rain affected the west and south-west of England and Wales. Continued wet weather through February meant that by the afternoon of the 19th catchments were primed and rivers rose quickly leading to precautionary evacuations. Although river levels stopped just short of the highest predicted levels, there were widespread minor river and surface water flood impacts recorded.

The most impactful flooding through the summer and autumn took the form of short duration intense rainfall totals which fell across London causing surface water impacts on 12 July, 25 July and 5 October. There was also a period of heavy rainfall and modest fluvial flooding that affected Cumbria between 27 and 29 October which is not discussed further in this paper.

In this paper, we focus on the national guidance and longer lead time communications provided by the FFC for the fluvial and surface water floods that affected England and Wales in 2021. We consider the forecasting and communication through the 5-day FGS and the 30-day ahead Flood Outlook. Comparisons are made between river and surface water events. We consider our post-event reviews, learnings and insights from customers. Finally, we suggest areas for future improvements which we capture in our continued service improvement programme. These feed into operational improvements, some of which have already been delivered as described in our accompanying paper (Pilling *et al.* 2023).

2021 Floods, risk communication, learnings and reflections

As Figure 1 shows, the FFC works with the network of local forecasting centres in the EA and NRW, and meteorologists in the MO, to provide a daily flood risk assessment for England and Wales for all natural sources of flooding. The FFC communicates this through the FGS. An extract of the FGS during Storm Christoph, 18–20 January 2021, is shown in Figure 3.

In addition, a longer-term outlook for the month ahead is provided by the Flood Outlook (Figure 4) which is updated twice a month. The Flood Outlook aims to provide national responders with strategic planning advice, communicating the strength of any forecast signals for larger-scale flood events at 6 days to 4 weeks lead time.

As the FGS, the Flood Outlook covers all four natural sources of flooding. FFC hydrometeorologists produce this forecast using a variety of tools and information, sourced from several organisations. The forecasting and flood risk assessment process is described by Pilling *et al.* (2016). The MO medium, long range and seasonal forecasts are key to understanding possible

Figure 2 | Overview of flood risk in 2021 across England and Wales (highest forecast flood risk for each day based on impact level and likelihood across England and Wales as depicted on the FGS). Presented in both daily calendar and bar chart format. Green: Very Low, Yellow: Low, Amber: Medium, Red: (not shown) High – produced by Robert Cowling, FFC (Cumbria flooding 27–29 October not discussed).

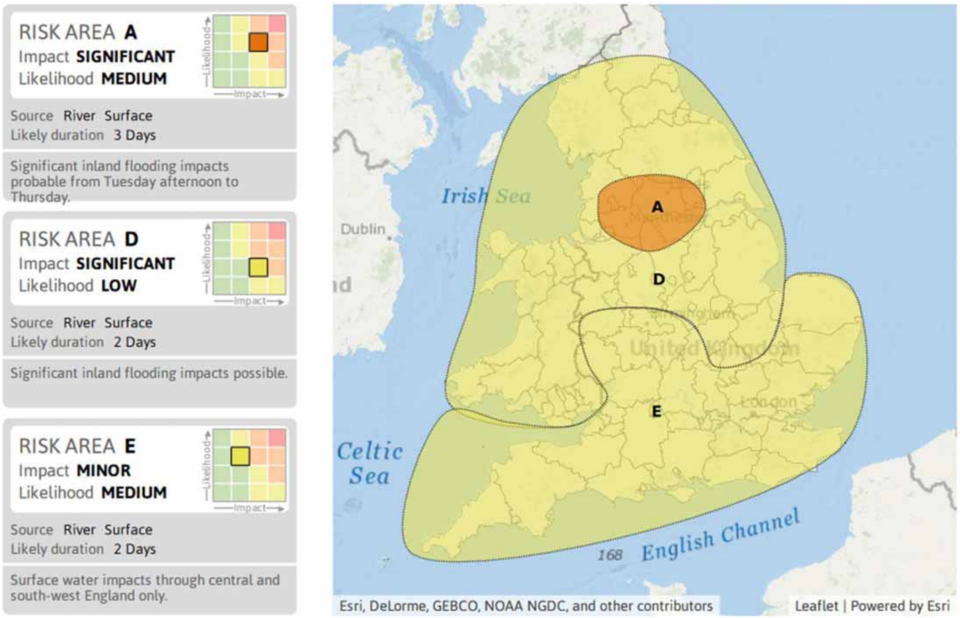


Figure 3 | An example FGS area of concern map from the FGS issued for Storm Christoph on Sunday 17 January 2021 valid for Wednesday 20 and Thursday 21 January.

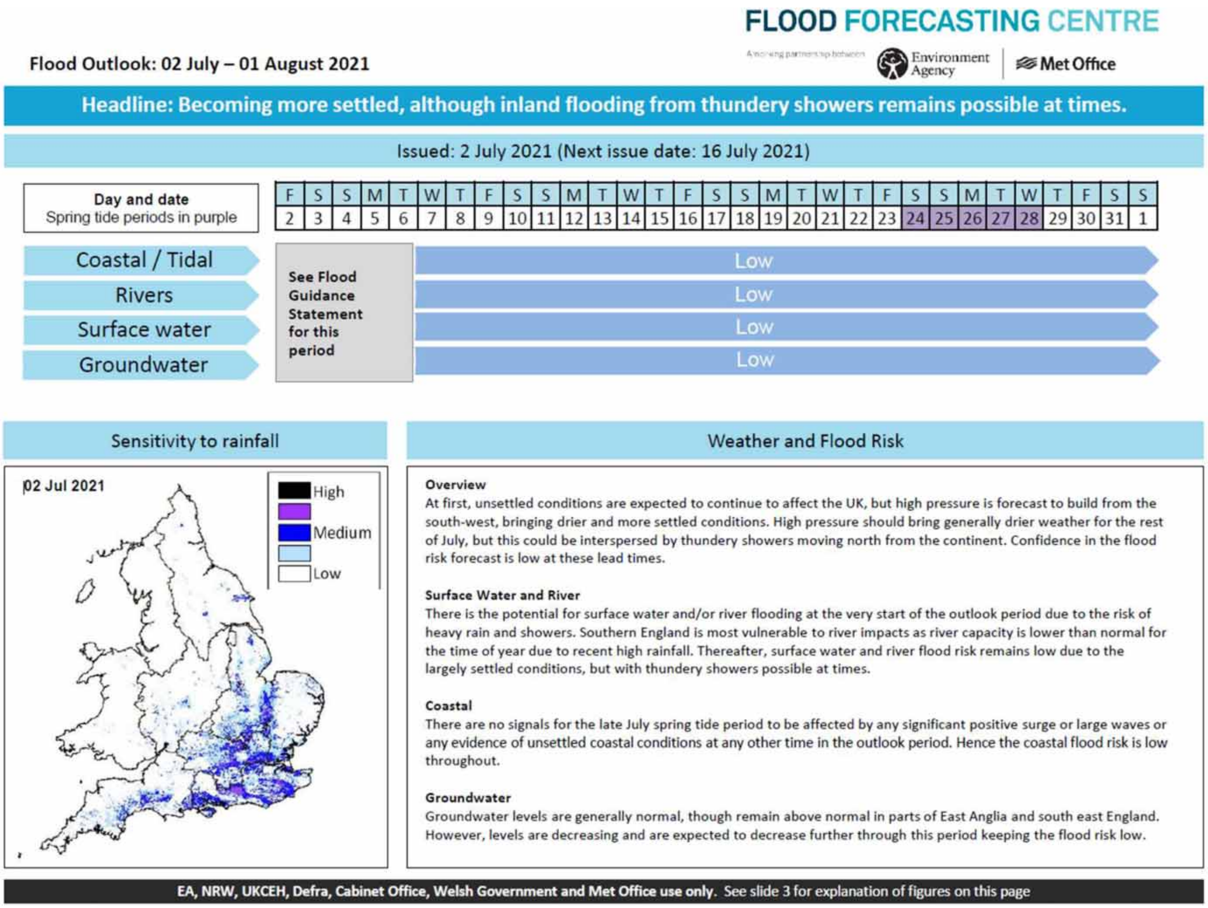


Figure 4 | Example of the Flood Outlook prior to the Spring 2022 refresh. Valid for the period 2 July to 1 August 2021, indicating low overall surface water flood risk.

weather conditions. These are supplemented by using the suite of 'Decider' tools identifying the probability of experiencing weather regimes which have been previously identified as capable of producing wet conditions or even river flooding events (Richardson *et al.* 2020; see for example Figure 2, Pilling *et al.* 2023). Antecedent catchment conditions are also analysed using EA and NRW hydrological data as well as soil moisture values and sensitivity to rainfall information from MO and UK Centre for Ecology and Hydrology, respectively. When these are combined with hydrological model forecasts from the Grid-to-Grid (G2G: Price *et al.* 2012) model, an understanding of the possible hydrological state for 6 days ahead can be obtained. Combining this knowledge with the meteorological forecast enables FFC hydrometeorologists to provide an insight into the possible flood risk from rivers and surface water up to 4 weeks ahead as illustrated in Figure 4.

As introduced in the previous section, Figure 2 presents a visual overview of the main floods that affected England and Wales through 2021. Now we consider these main events in more detail.

The forecasting and lead up to Storm Christoph and the Cumbria flooding in October are presented, followed by three surface water flood events. The Flood Outlook and the FGS are presented to illustrate lead time and accuracy. It should be noted that a key FFC project identified for 2021–22 was to refresh the Flood Outlook in line with our customers' requirements to enable more digestible and usable information, and therefore user preparedness in the lead up to key floods. This refresh capitalised on learnings from other previous flood events as well as those from early 2021. The new format is presented in Pilling *et al.* (2023; Figures 1 and 2).

Storm Christoph

Summary

Storm Christoph brought exceptionally wet weather to North Wales and the North of England between 18 and 20 January 2021. For North West England and North Wales this was one of the wettest 3-day periods on record with well in excess of 100 mm rainfall across large parts of England and Wales (Figure 5). This wet spell followed a wet December with many catchments across the North of England wet and responsive. Melting snow during Storm Christoph also added to water released into catchments.

Flood impacts

- Overall, over 570 properties in England were flooded.
- Residential properties were flooded in North West England and North Wales, with two care homes evacuated.

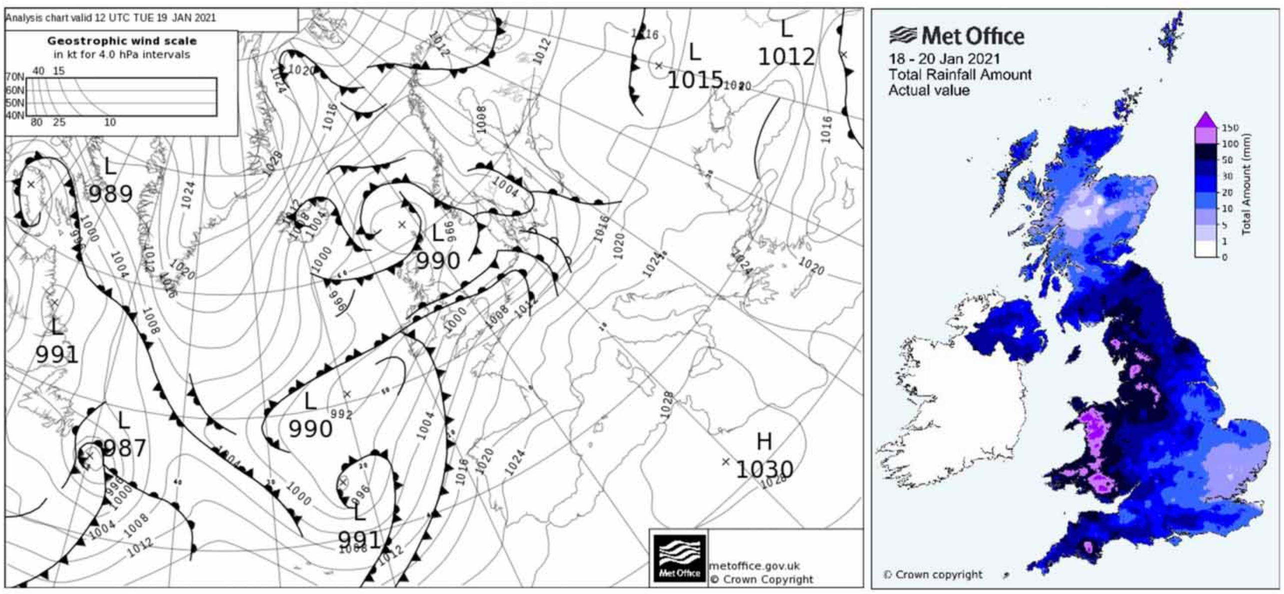


Figure 5 | Left: Analysis chart midday 19 January 2021. Right: UK rainfall for the 18–20 January 2021 (from Kendon 2021; HadUK-Grid dataset: Hollis *et al.* 2019).

- A bridge over the River Clwyd in North Wales was swept away by floodwater and a main railway line in East England was badly affected.
- Groundwater levels continued to rise with six sites recording the highest levels on record at the end of January.

Forecast verification

The Flood Outlook, issued on 31 December 2020, highlighted the possibility of significant or severe flood events in mid to late January. Wet conditions in the preceding weeks meant that catchments were sensitive to rainfall and rivers would be responsive. The meteorological signal for a period of unsettled conditions in mid to late January resulted in a possible flood event being flagged in this product in both late December and mid-January.

As we neared the flooding, more detailed guidance in the FGS was issued 5 days in advance with an area of amber risk included 3 days in advance. The National Flood Advisory Service (NFAS) (DEFRA 2014), which convenes key national responders to coordinate a response to a flood, was initiated by the FFC 3 days prior to the flooding. This action, taken on Sunday 18 January, set the 'battle rhythm' for the working week. The following day a Lead Government Department call was held and subsequently escalated to COBRA, the civil contingency committee that coordinates decision making for matters of national emergency.

G2G gave a very good early indication at 5 days lead time of the likelihood for significant river flooding impacts (Figure 6) and was a useful basis for discussion of the possibility of severe impacts with the MO and local EA forecast centres. The G2G response also helped the FFC hydrometeorologists to broaden the river flood risk areas out to include areas that had recently flooded, were sensitive to further moderate rainfall and would continue to respond on subsequent days after the initial rainfall event. Discussions with the MO helped to align the National Severe Weather Warnings Service (NSWWS) with the total area of hydrological risk, not only focussing on the areas with the highest rainfall totals.

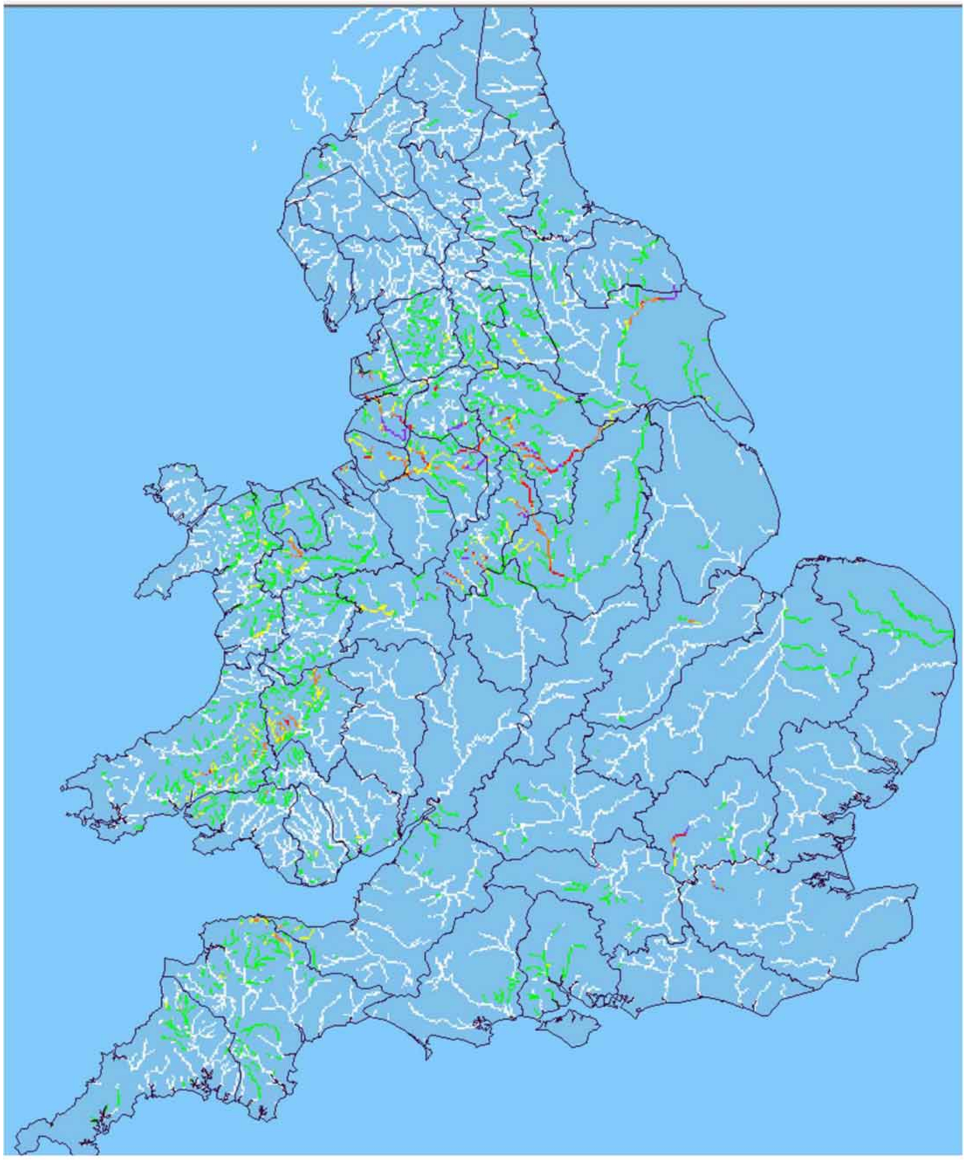
Feedback from Storm Christoph

- Positive feedback was received from partners and customers, including praise from Chief Executives of both the EA and MO (Flood Forecasting Centre 2022c).

> Sir James Bevan, Chief Executive of the Environment Agency said, '*The quality of the forecasting meant that we were able to prepare in ample time on the ground, putting up our temporary barriers, operating our defences and warning and informing communities, so that people could take action and stay safe*'.
>
> Professor Penny Endersby, Chief Executive of the Met Office said, '*In times like these, it reminds me how important the partnership we have through the FFC is. This work by the FFC often goes under the radar, but it is absolutely integral to how we manage flooding incidents*'.

Learning points identified from Storm Christoph

- It is in exactly this sort of situation, when catchments are very sensitive to further rainfall and a period of unsettled weather is consistently forecast, that the Flood Outlook is most likely to verify well at such long lead times.
- The reliable orographic rainfall signal helped with identifying significant flood impacts with enough confidence for medium flood risk relatively early on.
- The FFC hydrometeorologist should escalate consultancy with forecasting partners when the national flood model G2G contains early signals for widespread significant or severe river flooding impacts that have not yet been identified by the local EA and NRW forecasting teams.
- A National Flood Advisory Call held on Sunday evening helped the responders to prepare for widespread flooding. There was a great deal of activity around the Covid-19 pandemic. This NFAS call and subsequent coordination enabled flood mitigation to be activated; and testing sites and vaccination centres to remain operational given by the early NFAS call and proportionate action.
- Regular sensitivity tests for potentially severe impacts helped align flood risk assessments and the NSWWS issued by the MO, including naming the storm. This supported a common assessment and complementary guidance and warnings.



Possible impact level from river flooding	Q(T) thresholds (estimated from G2G)
Minimal to minor	Q_{med} to Q_{10}
Minor	Q_{10} to Q_{25}
Significant	Q_{25} to Q_{50}
Severe	Q_{50}+

Figure 6 | The G2G model return period flows for 19 January 2021, lead time 120 h. Key indicates flow return periods related to potential river flooding impact levels. G2G runs every 12 h in deterministic mode and every 6 h in ensemble mode.

Surface water flooding

Summary

Surface water, pluvial or flash flooding is not uncommon during the summer months, and indeed there were several minor to significant impact level events driven by convection during June and July. However, what was unusual when taken in combination were three surface water events that impacted London on 12 July, 25 July and 5 October (Figure 7). In addition to these being in the same part of the country, with two being in quick succession, the capital always tends to attract more attention politically and from the media. The forecasting skill, predictability and therefore warnings and lead time varied considerably for these three floods.

Flood impacts

Impacts were assessed as minor or significant on all three occasions with rainfall totals of 30–50 mm recorded within a couple of hours. However, there were some local variations around this depth duration which is associated with the severity of the impacts.

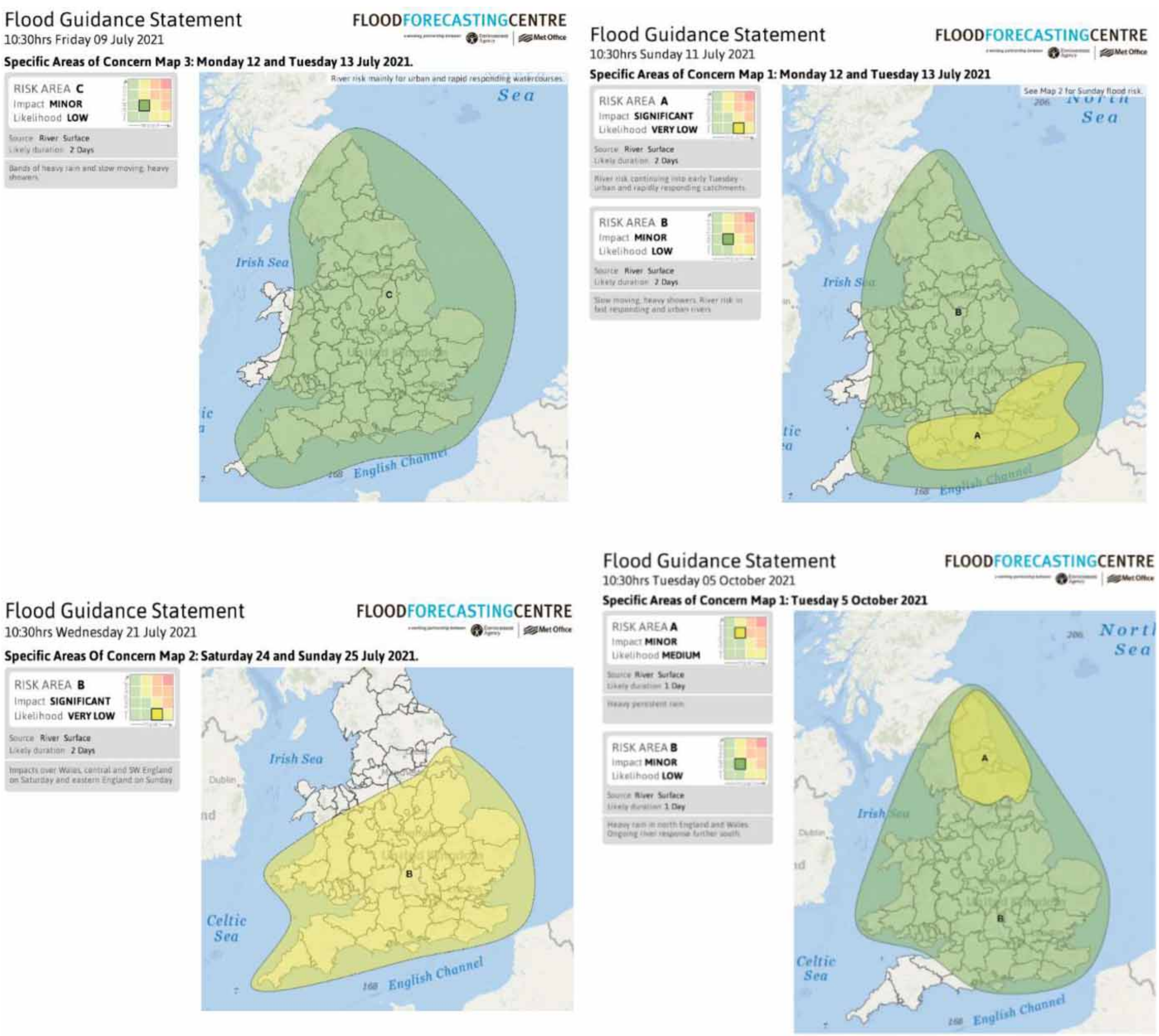


Figure 7 | FGS issued on 9 July (4 days lead time; top left) and 11 July (2 days lead time; top right) for flood risk on 12 and 13 July 2021. FGS issued on 21 July (5 days lead time; bottom left) for flood risk on 24 and 25 July 2021 and FGS issued on 5 October (1 day lead time; bottom right) for flood risk on 5 October 2021.

The 12 July event was driven by short wave troughs and an intensifying low-pressure system bringing heavy rainfall across Greater London, Hampshire and Surrey. There were numerous reports of significant surface water flooding with tens of residential properties affected, road closures and cars stranded.

The 25 July event was more complicated with a slow moving, weak, occluded front, coincident with a slow-moving upper vortex. The ingredients of surface convergence, moisture and instability were all abundant so that diurnal surface heating provided the trigger and deep convective clouds formed across the southeast of England through Sunday afternoon. Given little movement of the surface convergence through the critical part of the afternoon, and with minimal directional wind variation, torrential showers aligned and centred on areas from East Anglia, across London, towards Surrey. For example, 52.6 mm fell in just 1 h to 1,430 GMT at Bethersden, Kent. Widespread significant impacts were reported with properties affected, cars submerged and Pudding Mill Lane Docklands Light Railway under water.

The London Roundtable Progress Report (Greater London Authority 2022: p. 4) stated that '*The rain caused damage and disruption to homes and infrastructure across the city, and many Londoners required rehousing as their homes were flooded with stormwater and sewage. It rendered critical infrastructure unusable with the closure or partial closure of 30 London Underground stations and the evacuation of hospital wards and schools. Some of these schools have still not seen students return to damaged classrooms, as repairs continue. London has been spared the scale of damage seen in Germany, Belgium, the Netherlands, New York, and Henan, China from rainfall in summer 2021. But some London basement properties were flooded up to near ceiling height. Under slightly different circumstances, for example if similar rainfall had occurred late at night, the story might be very different*'.

While the nuisance factor of surface water flooding is well known in terms of urban travel disruption, this London event also highlighted the risk to lives from possible basement property flooding occurring at short notice with little warning or assistance for those at risk.

The 5 October event was associated with an active cold front moving eastwards across London between 03:00 and 06:00, which crucially had line convection embedded within it giving a short period of strong winds and very intense rainfall.

Rain gauges typically report hourly rainfall totals. On this occasion, rainfall data are available at the sub-hourly timescale indicating that 30–40 mm fell within just 30 min. Flood impacts were recorded from flooding affecting parts of London disrupting roads and railways and flooding shops and offices. Several tube lines and the London Overground were severely impacted and major commuter routes such as the A4 and M23 became impassable, resulting in many commuters being unable to get to work.

Forecast verification

Despite modern forecasting tools and techniques, it is still extremely challenging to forecast surface water flooding events. This is largely due to difficulties in accurately predicting the location and intensity of convective rainfall and an absence of real-time drainage system information. This, alongside well-known uncertainties in longer range forecasting, means it is not surprising that the Flood Outlook issued on 2 July 2021 (Figure 4) gave little indication of the timing or details of surface water events during July, although it did warn of the potential for 'thundery showers moving north from the continent' to bring localised surface water flooding issues.

An assessment of forecast skill at shorter ranges has been undertaken by subjectively comparing the FGS, and objectively comparing the FFC's Surface Water Flooding Hazard Impact Model (SWFHIM; see below), with impact observations collected by FFC hydrometeorologists and stored in the FFC's Flood Guidance Statement Verification (FGSV) system (Figure 8). The observations of flood impacts in this database are collected during or soon after an event by FFC hydrometeorologists using social media, traditional media reports, formal reports (e.g. from the EA) and any other available information. The impact level is assigned at a county scale by the hydrometeorologist based on the impact definitions used in the FGS. The benefit of this approach is that the impact level forecasted by the FGS and SWFHIM can be directly verified for individual events. It also offers the potential for future verification of flood risk forecasts over longer periods; such work is currently being undertaken for the SWFHIM and considers both probability and impact levels over the 3 years that the model has been operational. However, it is acknowledged that there is a degree of subjectivity and scope for human error in the observation collection and impact assignment process. Future developments in the field of automated impact collection will help increase the robustness of the methodology, but to date no suitable alternative 'truth' data for flood impacts exists. See the 'Feedback' section below for a user perspective on the FGS forecasts.

On the basis of these assessments, it is considered that both July events were reasonably well forecast in terms of current guidance standards.

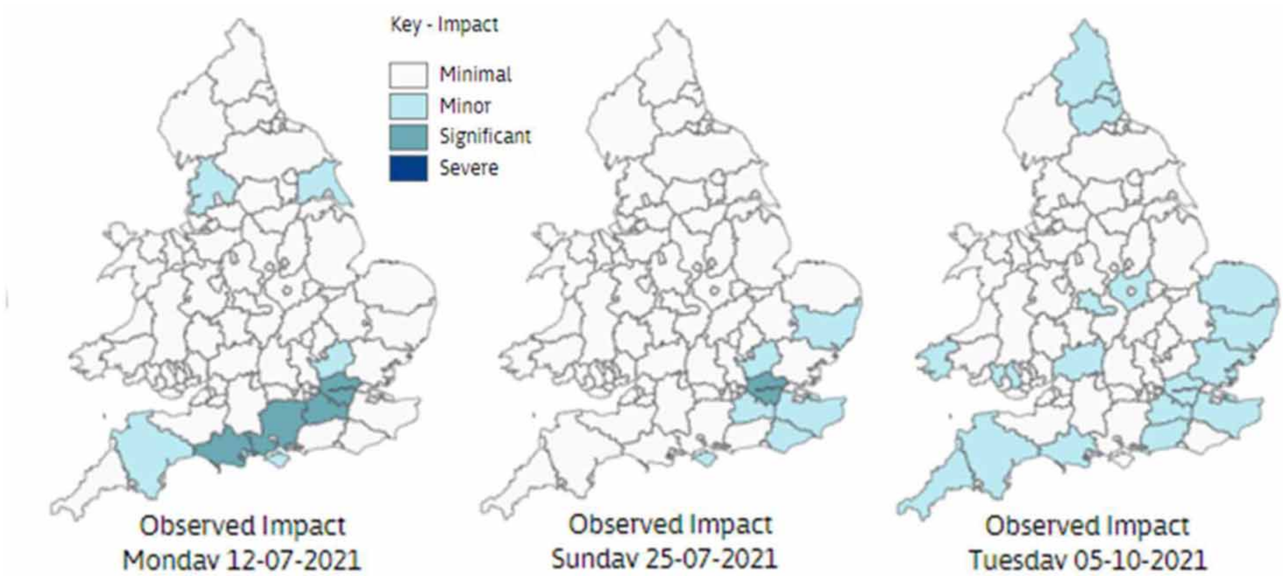


Figure 8 | Observed impacts for each event from the FFC's FGSV system.

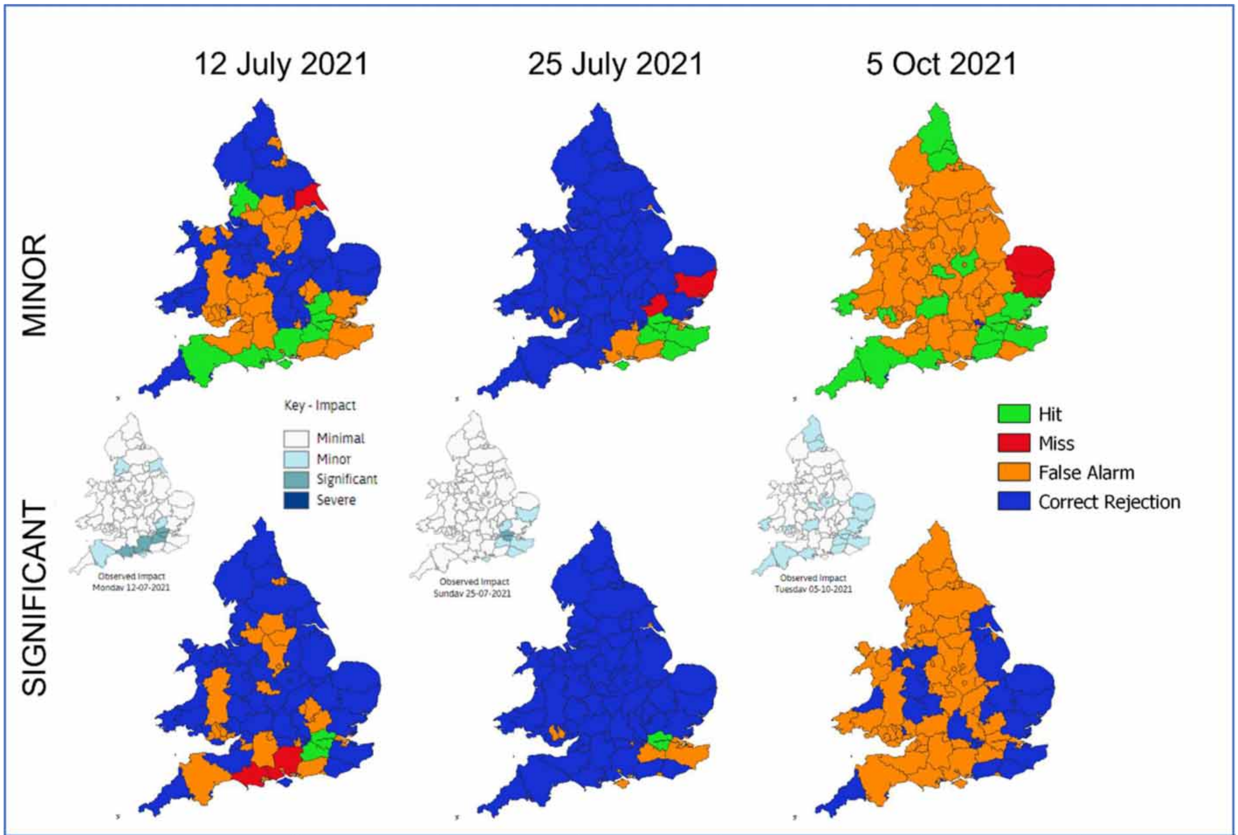
The FGS ahead of the 12 July flood indicated a broad area of concern with 4 days lead time and a more targeted yellow/low risk area for southeast England with 2 days lead time (Figure 7, top). A greater lead time of 5 days for the potential for significant surface water flooding impacts was provided ahead of the 25 July flood (Figure 7, bottom left), although on both occasions more targeted amber/medium risk areas within the broad yellow/low flood risk areas were not possible closer to the event because the confidence in the exact location of the heavy rainfall remained low in the forecast. While the July events verify well, the same is not true for the more complex 5 October event when the most flood impacts were reported in London outside of the yellow/low risk area on the FGS (Figure 7, bottom right). While it could be argued that there was an elevated risk on the FGS for London, it was very low overall, minor impacts at worst and no NSWWS was issued for this area. As such this is considered a 'miss'.

The SWFHIM is a relatively new tool that was available to the FFC during these events. It forecasts surface water flood risk (impact versus likelihood) by comparing MO ensemble precipitation data to a static impact library (Aldridge *et al.* 2020). The SWFHIM is used as part of a hydrometeorologist's 'toolkit' for assessing surface water flood risk on the FGS, and its forecasts can therefore differ from the final risk issued on the FGS. Verification of SWFHIM against FGSV impact observations identified that SWFHIM performed well in Greater London for all three events, with at least one ensemble member flagging minor and significant impacts in a majority of model runs in the lead up to the events (Figure 9). Outside Greater London, SWFHIM performance was more variable (Figure 9), but forecasts did give a reasonable indication of the broad spatial extent of impacts, especially for the events in July. On 25 July 2021, SWFHIM forecasts could potentially have been used to reduce the areal extent of the yellow polygon displayed on the FGS (Figure 9). However, SWFHIM is used alongside many other forecasting tools, and as the model is relatively new, the FFC is still learning when and where it is appropriate to rely on its output. In addition, at a county scale, there were some notable 'misses' in the east of England, and the number of false alarms was particularly high for the 5 October event.

This could be linked to the more frontal nature of the rainfall on 5 October (SWFHIM was primarily designed to be used for more 'classic' convective storms) and/or to the accuracy of the underlying numerical weather prediction (NWP) rainfall data. Ongoing and future verification of the SWFHIM, alongside scientific development of the model, should facilitate more confident interpretation of its forecasts and aid more targeted surface water flood risk assessments for the FGS.

Feedback from surface water flooding events

Following the two July floods, a roundtable review of risk management arrangements for surface water was commissioned by the Mayor of London (Greater London Authority 2022). The events highlighted the current state of play in terms of flood forecasting for surface water in that it is possible to highlight broad areas, but we lack the ability to take this level of



Run time; Forecast for the full 24 hours of the next day.	Minor 1 hr CSD	Minor 3 hr CSD	Minor 6 hr CSD	Significant 1 hr CSD	Significant 1 hr CSD	Significant 1 hr CSD
11/07/2022 00:30 Z	Hit	Hit	Hit	Hit	Hit	Hit
11/07/2022 06:30 Z	Hit	Hit	Hit	Hit	Hit	Hit
11/07/2022 12:30 Z	Hit	Hit	Hit	Hit	Hit	Hit
11/07/2022 18:30 Z	Hit	Hit	N/A	Hit	Hit	Hit
24/07/2022 00:30 Z	Hit	Hit	Hit	Hit	Hit	Hit
24/07/2022 06:30 Z	Hit	Hit	Hit	Hit	Hit	Hit
24/07/2022 12:30 Z	Hit	Hit	Hit	Hit	Hit	Hit
24/07/2022 18:30 Z	Hit	Hit	N/A	Hit	Hit	Hit
04/10/2022 00:30 Z	Miss	Hit	Hit	Correct Rejection	False Alarm	False Alarm
04/10/2022 06:45 Z	Miss	Hit	Hit	Correct Rejection	False Alarm	False Alarm
04/10/2022 12:30 Z	Hit	Hit	Hit	False Alarm	False Alarm	False Alarm
04/10/2022 18:30 Z	Hit	Hit	N/A	False Alarm	False Alarm	False Alarm

Figure 9 | Confusion matrix results for each surface water event for Greater London on 12 July 2021, 25 July 2021 and 5 October 2021. Verifying SWFHIM forecasts based on 3-h accumulated runoff (or Critical Storm Duration, CSD). Forecast data is from the 12:30 GMT SWFHIM run the day before a given event. 'Observed' impacts are shown on the small embedded maps and are taken from FGSV. It is noted that the observations collected for Greater London on 5 October were recorded as 'Minor' in FGSV, hence the SWFHIM scored a number of False Alarms here for this event. FGSV assessments are subjected and undertaken by the hydrometeorologist on duty during or shortly after an event. In hindsight, this impact level assignment may be underdone.

information and mesh it together with local tools and awareness of drainage systems on the ground. Critically, the roundtable work in London highlighted the previously not well-recognised risk of flash flooding of basement flats in London presenting an increased risk to life during the overnight period.

Learning points identified from surface water flooding events

Convectively driven surface water and flash flooding should not be expected to be highlighted at long lead times and current capabilities are limited to highlighting when showery, hot weather regimes are likely to dominate. The routine operational post-event reviews:

- Reinforced that large areas of elevated (e.g. yellow/low) flood risk are usually necessary to warn for surface water flood risk.
- SWFHIM performed well for Greater London and gave a reasonable steer for the spatial extent of flood impacts more widely. Verification is the key to giving operational hydrometeorologists the confidence to interpret SWFHIM outputs; and use them, when appropriate and in the context of other information, to adjust risk areas on the FGS. Operational, quantitative verification should be a future focus.
- The 5 October events demonstrate that impacts can result from rain falling within 30 min. However, data are often not available at this resolution, which can be challenging, especially for monitoring and post-event analysis. Do we need to increase spatial coverage of rain gauges recording sub-hourly?
- Post-event workshops with responders confirmed that they were acting on these broad areas of yellow/low risk and instigating response plans, understanding the low probability/high impact nature of these events.
- Routine operational post event reviews raised the following questions around surface water flooding:
  - Are convective forecasting capabilities able to reliably forecast rainfall depth duration rates >30 mm/hr?
  - With an increase in surface water/flash flooding and short duration high intensity rainfall, is the typical drainage design to cope with rates of up to 30 mm in 1 hour?
  - Is the current devolution of responsibility and warnings for surface water flooding fit for purpose?

DISCUSSION

The FFC routinely conducts debriefs and post-event reviews to distil best practice, optimise team working and identify issues that need further consideration and perhaps changes in forecasting tools, operational procedures or other areas. It is the material from these operational debriefs that has contributed to the event summaries above. These are important for continuous development of our forecasting team and also the improvements to meteorological and hydrological modelling. In addition, it enables us to develop our products and services with improvements being brought forward in slower time as well as learning from a customer responder survey which is run every 2 years.

From the case studies presented, it is clear that river and surface water flooding can pose very different challenges to both forecasters and responders and that current systems are more successful at forecasting and dealing with river flooding than surface water flooding.

Dynamic, broad-scale rainfall events, such as Storm Christoph, are often well captured by meteorological models although pulses of high-intensity rainfall can be missed (e.g. Lewis *et al.* 2015; Majumdar *et al.* 2021). Hydrological models are able to produce high-quality forecasts of main river responses with an accurate precipitation forecast and a good approximation of antecedent conditions (e.g. Cloke & Pappenberger 2009). Relatively high confidence in the forecast throughout the flood forecasting chain enables early communication of possible flood events with some degree of spatial accuracy and knowledge of intensity. This information enables responders to be at their most efficient and effective by acting in advance of an event to mitigate impacts, having insight into the expected location and magnitude of river flooding. Of course, even in these types of events, forecasts are not always very accurate or provided with a high level of confidence.

In contrast, surface water flood events driven by localised, convective downpours are challenging for meteorological models to pinpoint, even with the current high-resolution convective scale modelling. The London case studies presented show how different types of meteorological situations can cause surface water impacts and how intense, but localised, these can be. Current forecasts and guidance, which can share the possibility of impacts somewhere within a broad area, do allow responders to take some action, but they are restricted by the lack of spatial precision in the forecasts. Possible approaches to advance this are considered by Pilling *et al.* (2023) along with potentially coupling high-resolution weather forecast models to hydraulic models. Of course, with this approach accuracy will be limited by how accurate the driving rainfall forecast is.

Mitigation from surface water flooding is, therefore, more challenging given the shorter lead times and lower accuracy in location and timing. In addition, there is a limited understanding of the characteristics of surface water behaviour and discharge once a downpour has occurred. Furthermore, responsibility and warnings for surface water flooding are devolved which further complicates warnings and response. This presents a substantial challenge given that surface water flood risk is expected to increase due to climate change increasing the hazard. In addition, vulnerability and exposure are also likely to increase; for example, as demonstrated by basement flooding in London, but also fatalities overseas in flooded undergrounds and subways during 2021 (Zurich Insurance Group 2022; Pilling *et al.* 2023).

To help enable assessment and improvements in national early warning systems, the FFC has worked with the World Meteorological Organisation (WMO) to trial the 'Assessment Guidelines for End-to-End Flood Forecasting and Early Warning Systems' (WMO, 2022). We also exchange experiences and best practice with other National Meteorological and Hydrological Centres such as the Bureau of Meteorology, Australia. It is clear that a common challenge is to improve surface water and flash flood forecasting, and that this needs to be addressed by improved detailed ensemble rainfall forecasts coupled with appropriate impact models.

One example is highlighted above where the FFC has operationalised SWFHIM, a state-of-the-art, objective, probabilistic surface water flood forecasting system developed in collaboration with others (Aldridge *et al.* 2020). While we continue to develop SWFHIM itself for England and Wales, the system design enables improvements in convective rainfall forecasting systems to be 'plugged in' as they become available. More details are presented in Pilling *et al.* (2023) and perhaps this is a framework that could be further developed in collaboration with wider, international and partners.

Feedback from responders indicates that the FGS does not always provide sufficient information to take action. Reasons cited are that the forecasts are too geographically broad, there is a lack of local information and a lack of accuracy (Met Office 2022). Further development on improving forecasting models, tools and communication is required for all sources of flooding to help maximise responders' capabilities to mitigate flooding impacts. This is most urgently required for surface water/flash flooding. Fundamental to the success is the co-design and co-creation of future services with our users.

CONCLUSIONS

Having summarised the key floods of 2021, evaluated the forecasting, and drawn on customer insights, we have highlighted the differences in forecasting capability of fluvial and surface water flooding.

We have also identified several areas for further improvements. While some of these can be progressed by the FFC and our key customers, such as changes to the FGS and improvements to G2G, other recommendations are based on shared challenges with other countries. The greater challenges tend to relate to surface water flooding 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. Pilling *et al.* (2023) present some additional developments that the FFC are undertaking in this sphere.

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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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