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TOWARDS IMPROVED SURFACE WATER FLOOD FORECASTS FOR SCOTLAND:

A review of UK and international operational and emerging capabilities

rab Resilience and
Flood Risk

University of
Strathclyde
Glasgow

Research Report

This research report was commissioned by the Scottish Environment Protection Agency (SEPA) as part of its Flood Warning Development Framework for 2017-2021. The framework includes a commitment to explore innovative approaches to pluvial flood forecasting.

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Executive summary

In 2019, the Scottish Environment Protection Agency (SEPA) commissioned RAB in partnership with the University of Strathclyde to conduct a review of the current state of the science relevant for surface water flood forecasting in Scotland, specifically looking at both precipitation observations and forecasts, and hydrological and hydraulic modelling applications. This is the final report from this review and has been presented to inform SEPA of the best practice options available to improve surface water flood forecasting in Scotland.

The risk of surface water flooding in Scotland is high with over 100,000 properties identified as being ‘at risk’ in the SEPA National Flood Risk Assessment. To address this risk, SEPA is developing its flood forecasting service, with the Flood Warning Development Framework for 2017-2021 including a commitment to explore and trial innovative approaches to pluvial flood forecasting. This builds on the current operational use of indicative impact-based depth-duration thresholds used in the Heavy Rainfall Alerting capability and the successful trial of a detailed real-time pluvial flood forecast for the East End of Glasgow during the 2014 Commonwealth Games.

In this review, we find that SEPA’s approach to date is at the cutting edge when compared to other operational forecast centres, particularly through the unique use of probabilistic forecasts in the Heavy Rainfall Alerting tool. The risk of surface water flooding in Scotland is communicated through the Flood Guidance Statement and Flood Alerts, where assessment is based on indicative depth-duration thresholds and local hydrometeorological knowledge. Here, the ability to provide detailed information on the location or timing of impacts is more limited, however the existing information is useful to first responders and the public, and there is a growing need to provide more targeted impact-based surface water forecasts to support informed decision-making.

Using a series of international case studies, this report shows that there is the potential for SEPA to achieve this and link surface water forecasts with specific receptors or at-risk communities. Examples such as the Loughborough University surface water nowcasting approach that provides targeted advice to emergency responders trying to access the city during a flood event, the iCASP project that investigates effective way to communicate and explore the use of city-scale flood forecasts by decision-makers, and the Vigiecrues Flash application from France that is linked to specific vulnerable communities, are each good examples of where surface water flooding forecasting is at the cutting edge of science. Each of these approaches are based on a clear partnership of co-development between users and forecast developers, resulting in products that met operational needs, each of which could potentially be transferred to Scotland by focussing on Potentially Vulnerable Areas, especially those with a known high risk of surface water flooding.

SEPA’s existing approach using MOGREPS-UK in the Heavy Rainfall Alerting tool, combined with existing knowledge of catchment susceptibility, is already following international best practice for an early warning tool. However, this review identifies that this approach could be further improved with better post-processing and visualisation tools, such as the FloodAlert tool that is in use in Spain. Similarly, there are also several examples identified in this review of programmes and initiatives that could potentially improve monitoring of surface water impacts in Scotland, either with an operational focus using platforms such as Global Flood Monitor (including potentially integrating Report-a-Flood), or making better use of crowdsourced data.

In summary, we conclude that the recent introduction of convection-permitting numerical weather prediction and ensemble forecasting has resulted in a step-change in rainfall forecasting, meaning that it is now possible to forecast surface water flooding in urban areas, as well as make more targeted and better visualised forecasts to support informed decision-making. Although the probability of occurrence for any given location is likely to remain low at lead times beyond a few hours, and challenges will always remain for providing bespoke service for urban centres, numerical weather prediction capabilities are constantly improving as are approaches to impact-based forecasting, which Scotland may be able to utilise further. Precipitation detection may be a limitation to this given the relatively sparse radar network in Scotland. However, given the potential high risk of surface water flooding in Scotland, the collated evidence of best available and emerging science presented in this report may be used to support SEPA’s improvements to surface water flood forecasting at national and local scales.

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1 Introduction

1.1 Background to the research

In 2019, the Scottish Environment Protection Agency (SEPA) commissioned a research project into surface water flood forecasting in Scotland. The aim of the research was to review the current state of science relevant for pluvial flood forecasting, specifically looking at both precipitation observations and forecasts and hydrological and hydraulic modelling applications.

SEPA has a commitment to develop its flood forecasting service within the Flood Warning Development Framework for 2017-2021. This includes a commitment to explore and trial innovative approaches to pluvial flood forecasting. This builds on the current operational use of indicative impact-based depth-duration thresholds used in the Heavy Rainfall Alerting (HRA) capability and the successful trial of a detailed real-time pluvial flood forecast for the East End of Glasgow during the 2014 Commonwealth Games.

This report is the review of the current state of science relevant for pluvial flood forecasting, and will be used to inform future improvements to pluvial flood forecasting in Scotland.

1.2 Surface water flood risk and the role of effective flood forecasting

Surface water flooding, also known as pluvial flooding, is defined as “Flooding as a result of rainfall when water ponds or flows over ground before it enters a natural or man-made drainage system or watercourse, or when it cannot enter because the system is already full to capacity” (SEPA, Improved Understanding of Pluvial Flood Risk in Scotland, 2009). Surface water flooding in this context is usually the result of convective weather systems which cause intense rainfall over short periods of time. This type of rainfall typically occurs in the summer months but can occur at any time of the year (Hand *et al.*, 2004; Blenkinsop *et al.*, 2015; Flack *et al.*, 2019).

Surface water flooding presents a challenge for forecasters as events are often very localised, develop quickly and only last for short periods of time. Pilling *et al.* (2016) discussed the key future challenges for the flood forecasting community in Britain, with the most dangerous floods including those that result from rapidly developing convective systems or the organisation or alignment of storm cells that may result in flash flooding over large urban areas. This risk in Scotland is particularly high with over 100,000 properties identified as being at risk in the SEPA National Flood Risk Assessment. This is a high-profile risk with Scottish cities experiencing surface water flooding in recent years (e.g. Glasgow in 2002, and with subsequent smaller events experienced in 2007, 2011, 2012, and 2013, Aberdeen in 2001 and 2015, and Edinburgh and Stirling in 2019).

Currently, the risk of surface water flooding in Scotland is communicated through the Flood Guidance Statement (FGS) and Flood Alerts. Assessment is based on indicative depth-duration thresholds and local hydrometeorological knowledge. The ability to provide detailed information on the location or timing of impacts is limited. While the existing information is useful to first responders and the public, there is a growing need to provide targeted surface water forecasts to support informed decision-making (Cabinet Office, 2008; Halcrow, 2011; Ipsos MORI, 2013; Ochoa-Rodriguez *et al.*, 2018; Speight, 2018; DEFRA, 2018).

The high uncertainties around predicting the location and timing of convective events make them difficult to forecast. The introduction of convection-permitting numerical weather prediction (NWP) and ensemble forecasts (Golding *et al.*, 2014, 2016) resulted in a step-change in rainfall forecasting (Clark *et al.*, 2016) meaning that it is now potentially possible to forecast surface water flooding in urban areas. However, the probability of occurrence for any given location is likely to remain low at lead times beyond a few hours (Speight *et al.*, 2018). Numerical weather prediction capabilities are constantly improving as are approaches to impact-based forecasting. Given the potentially high impact of surface water flooding, there is a growing need to make the best use of available and emerging science to develop surface water forecasting tools that can save lives and livelihoods through effective forecasts at national and local scales. Accepting that doing so may involve re-thinking how to deal with short lead times and uncertainty in decision-making.

There are three main challenges:

1. Dealing with location and timing uncertainty on a time scale useful to responders
2. The high computational resource required to use convection-permitting NWP and ensembles in hydrological and hydrodynamic urban flood models
3. Communicating the risk to first responders and the public particularly when probabilities of impact may remain low until very close to the event.

1.3 What has changed in surface water flood forecasting since the Glasgow pilot in 2014

As part of the development of the pilot surface water alerting tool for Glasgow in 2014, a review of current and emerging surface water flood forecasting capabilities was carried out. The key findings of the review (as reported in Moore *et al.*, 2015) were as follows.

Forecasting intense rainfall likely to cause surface water flooding:

- Accuracy of real-time surface water flood forecasts is constrained by rainfall forecast accuracy. The Met Office UKV model is often very skilful at predicting maximum rainfall accumulations, however, the timing and location are subject to substantial uncertainty (typically one hour and 25km, respectively)
- The remaining forecast uncertainty, particularly in the location and timing of convective rainfall, makes it necessary to make management decisions using probabilistic rainfall forecasts. Even with planned scientific enhancements to NWP spatial uncertainty will still exceed 10km and ensemble processing will remain a key part of the forecasting chain
- At very short lead times, the Short-Term Ensemble Prediction System (STEPS) nowcast provides useful radar-rainfall extrapolation ensemble forecasts, blended with the deterministic UKV model up to six hours ahead
- Initialisation, calibration and verification of forecasting systems depend on good quality rainfall observations. Currently, significant parts of Scotland are under-observed due to (i) sparseness of the real-time reporting rain gauge network, (ii) distance from weather radar and other factors influencing radar's ability to estimate ground-level rainfall, and (iii) the hilly and remote nature of the terrain that makes extensive ground monitoring difficult.

Surface water flood forecasting models:

- Detailed flood modelling combining both surface runoff and the underground sewerage network system is not feasible on a national scale and in real time. Instead, an estimate of the sewer capacity is required to consider the amount of flow that is expected to enter the sewerage network during extreme events. Even then, 2-D hydraulic modelling of surface water flooding remains infeasible to meet the real-time forecast run-time requirements at the present time. Although advances in computing are expected to make this possible in the future, the sustained investment required to support a robust and verified operational system should not be underestimated
- A further consideration for real-time application is the need for continuous running of a model, involving maintaining model states (e.g. antecedent conditions of water volumes) across all time-steps up to the

time the forecast is made. Not all inundation models originally implemented for design and planning are well suited in this respect for real-time application.
- Real-time surface water flood inundation modelling is still in a research phase. Of the candidate surface water inundation models reviewed, only ISIS-FAST was identified as fast enough to run in real-time.

Since 2014, there have been several significant developments in the fields of convective precipitation forecasting and real-time surface water flood modelling leading to a growth in the science and application of urban surface water flood forecasting in the UK and internationally. This growth has been helped by the upgrade of the UK radar network to dual-polarisation which has enabled improved observations of heavy rainfall (Section 2.1), improvements to NWP for convective forecasting and increased understanding and use of probabilistic forecasts (Section 2.2), growth in the use of citizen observations for flood risk modelling and monitoring (Section 4), growth of cloud computing and the development of faster inundation models (Section 3.4) and the increased integration between hydrologists, meteorologists and end users working together to meet the challenge of surface water flood forecasting.

As is detailed in this report, it is no longer correct to say that real-time surface water flood inundation modelling is in a 'research phase' as this is a rapidly maturing area of research with multiple examples of operational or near-operational systems. Similarly, nor is it true that ISIS-FAST is the only tool suitable for this application. However, there are still limited examples of operational surface water flood forecasting models at urban scales. The challenge is perhaps no longer the computational ability (although this is not insignificant and should not be taken lightly) but the difficulty of communicating the remaining uncertainties around the location and timing of the heavy rainfall forecasts and the resulting impacts at an urban scale.

1.4 Specific challenges of surface water flood forecasting in Scotland

Surface water forecasting presents a unique challenge in Scotland due to the high uncertainties around predicting the location and timing of events. Pilling *et al.* (2016) discussed the key future challenges for the flood forecasting community in Britain, with the most dangerous floods including those that result from rapidly developing convection systems or the organisation or alignment of storm cells that may result in flash flooding over large urban areas. The risk in Scotland is particularly high with over 100,000 properties identified at risk from surface water flooding.

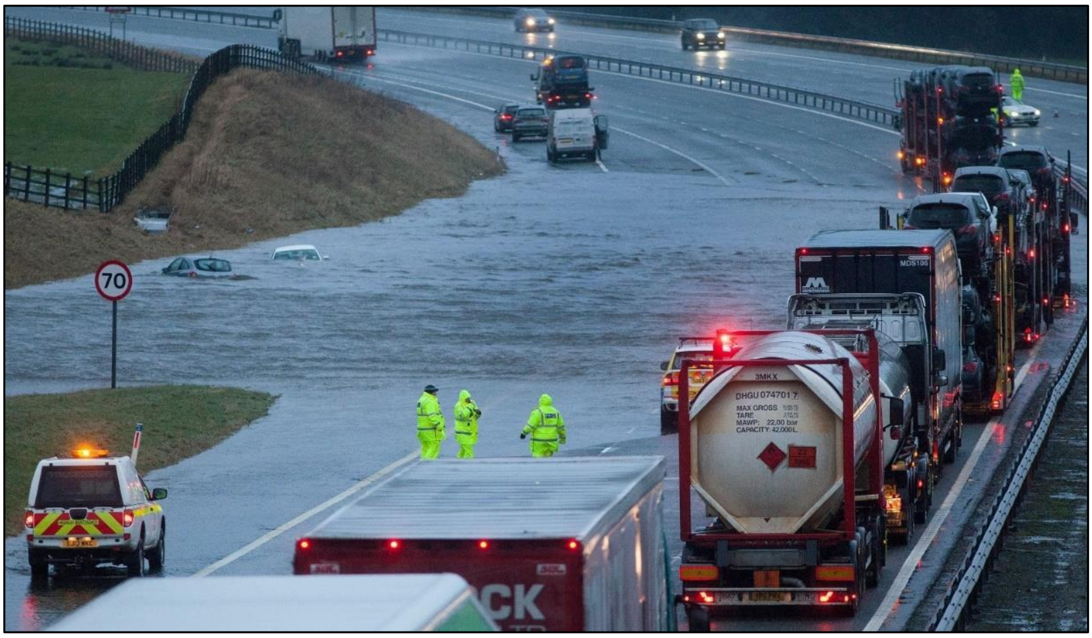


Figure 1. Surface water flooding on the M74 during Storm Frank in 2015 causing disruption to the transport network. (Source: The Press and Journal, 2015)

There are, therefore, specific challenges for improved surface water flood forecasting in Scotland. Precipitation detection and forecasting is one area of concern, especially given the sparse radar network in Scotland (Cranston and Black, 2006) and an area that is considered in this research given recent scientific developments. Whilst the Scottish Flood Forecasting Service, by combining expertise and skills of both meteorologists and hydrologists to better forecast and warn for surface water flooding (Cranston *et al*., 2012), challenges remain for providing bespoke service for urban centres (Speight *et al*., 2018).

Identifying the potential impacts and disruption associated with potential surface water flooding as highlighted in Figure 1 is a key requirement of any operational service but remains a challenge. The trial of operational forecasting for service for the Commonwealth Games in 2014 attempted to deliver an impact-based service (Speight *et al.,* 2018), as do other systems presented in this report. However, what scale is appropriate for representing the impacts given the uncertainties associated with any forecast remains an open question.

1.5 What level of information is needed to support end users' decision-making?

Fluvial and coastal flooding warning systems have been developed that offer long lead times and bespoke local information for individual at-risk areas. Due to the challenges of forecasting surface water flooding, however, the same level of information is not available for pluvial events. Surface water flood forecasts in Scotland are communicated through the Flood Guidance Statement, NSWWS or Flood Alerts. Whilst the current guidance is perceived as useful multiple studies have shown that more targeted information would be beneficial to support local decision-making (Cabinet Office, 2008; Halcrow, 2011; Ipsos MORI, 2013; Ochoa-Rodriguez et al., 2013; DEFRA 2018). The DEFRA Surface Water Management Action Plans makes a direct call for developing "better systems for sharing short term storm forecasts so that local authorities and others have the best available information about whether a storm is likely to hit their area" (DEFRA, 2018 p6).

Before developing the surface water forecasting pilot for the 2014 Commonwealth Games, SEPA established a steering group of key stakeholders in Glasgow including the City Council, Transport Scotland, Scottish Water, and those involved in the Commonwealth Games organisation. One of the first exercises with the stakeholders was to establish the requirements for the system. The key requirements were (Speight *et al*., 2018):

- To focus on the 6–24-hour lead time to enable proactive preparations; twelve hours was seen as a critical forecast horizon.
- To provide guidance on event timings, specific locations that might be affected, and possible impacts and severity.
- To communicate a stand-down message when the event is over or the risk level reduced.

Although these findings give a useful indication of the type of information that is useful to decision-makers they were focused on the Commonwealth Games example. Similarly, the case studies included in this report are designed to support different purposes and for different end users and therefore may not deliver the required outputs to support all of SEPA's surface water forecasting aims and objectives. Before developing any new surface water forecasting system, it will be important to establish realistic aims for the system that balance both the end user requirements and the scientific and practicality feasibility and to understand how the system will be used to support decision-making. The iCASP project detailed in case study 7 illustrates this process in more detail.

1.6 Report outline

This report presents the key findings of the review of surface water flood forecasting. The work has been based on an extensive literature review and focused discussions with industry experts. Section 2 of the report presents a review of approaches to precipitation observations and forecasts, particularly focused on the UK. Section 3 illustrates a wide range of international approaches to surface water flood forecasting with the differing approaches set within a conceptual framework. Section 4 presents differing approaches to monitoring surface water flooding impacts, from the use of social media to sensors. Section 5 provides a discussion on the relative merits of the various approaches and how they could benefit future surface water flood forecasting in Scotland, and Section 6 provides some concluding remarks.

2 Precipitation observations and forecasts

Accurate and reliable precipitation observations and forecasts are crucial for effective forecasting of pluvial flooding. Pluvial flooding is often caused by small scale thunderstorms whose magnitude and distribution are difficult to monitor and predict. Precipitation observations and forecasts are thus required at high spatial and temporal scales (Rodriguez, 2012).

The aim of this section is to present current approaches for observing and forecasting precipitation (both in-situ and remote sensing).

Section 2.1 discusses precipitation observations in terms of approaches which are established/in operational use, those which are considered emerging developments (3-5years) and in outlook (>5 years). Section 2.2 discusses precipitation forecasts in the same manner.

2.1 Precipitation observations

There are several methods used to measure precipitation which are categorized into gauging instruments and satellites. Gauging instruments take measurements from the ground and include rainfall gauges, disdrometers and weather radar (Sun *et al*., 2018). Satellites take measurements from high above the earth and are either geostationary or polar orbiting. The most popular methods used for the observation of precipitation are rain gauges and weather radar and these are discussed in the following sections. Often, these datasets are used in combination to produce a more accurate dataset, for example, rainfall gauge data is commonly used to adjust radar data. This approach is adopted by HyradK in Scotland which brings together observed rain gauge data from SEPA's network and the Met Office composite radar to produce an adjusted precipitation grid (Cranston *et al*., 2012).

Rainfall gauges

Rainfall gauges are considered in situ instruments, that is, the instrument is in direct contact with the medium it senses. Rainfall gauges collect rainfall at the ground surface and measure the depth of rainfall as it accumulates over time. Their function can be affected by environmental factors such as wind and evaporation, and other errors such as site location and instrument errors (Sun *et al*., 2018). Although rainfall gauges provide high accuracy when used in rainfall forecasting as they directly collect the rain droplet, a major challenge for their use for surface water flood forecasting is maintaining a dense enough spatial coverage of gauges to observe localised intense rainfall. In the UK, the rain gauge network is not sufficient for this purpose as illustrated in Figure 2 which shows the radar-derived rainfall over south-west England from 18th July 2017.

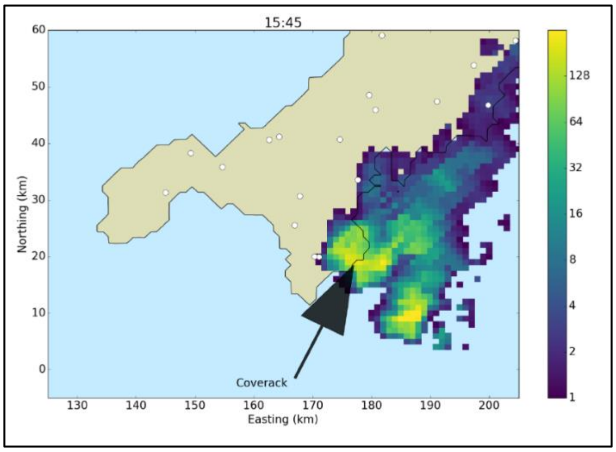


Figure 2. Radar-derived rainfall over the South-West peninsula of the UK, at 1545 UTC on 18 July 2017 (when a major flash flood occurred in Coverack). The circles indicate the position of rain gauges, the colour scale refers to the radar-derived instantaneous rainfall rates in mm/hour. (Source: Flack *et al.*, 2019)

On this day, the area of Coverack experienced one of the most extreme short duration rainfall events ever seen in the UK, with 44 properties flooded and fast flowing water and debris presented a risk to life. However, as reported in Speight (2019) and JBA Consulting (2018), the nearest Environment Agency rain gauge which is located 8km away showed no recorded rainfall.

Rain gauges provide accurate point rainfall estimates; however, they cannot capture the spatial variability of rainfall. Gauge data is used in several rainfall prediction methods such as numerical weather prediction (NWP) and nowcasting which are discussed in Section 2.2.

Weather radar

A remote sensing instrument is an instrument not in direct contact with the medium that it senses. Weather radar is classified as an active remote sensing device and it is a type of radar instrument which is used to measure precipitation. It is also known as weather surveillance radar (WSR) and Doppler weather radar. It works by sending a pulse of electromagnetic energy into the atmosphere, and this energy is reflected back to the radar device if it interacts with something in the environment. Modern weather radars are Doppler radars and can be either single or dual polarisation. The UK radar network has recently been upgraded to dual polarisation bringing a significant improvement to the skill in observing and forecasting intense rainfall (see Case Study 1).

UK Met Office Radar Upgrade

Background

In January 2018, the UK Met Office completed its upgrade of the UK radar network. This was the largest upgrade for 30 years and involved converting all 15 existing radars to dual polarisation. Dual polarisation radars capture data in both the vertical and horizontal polarisations (Figure 3) meaning that much more information about the size and composition of precipitation can be captured.

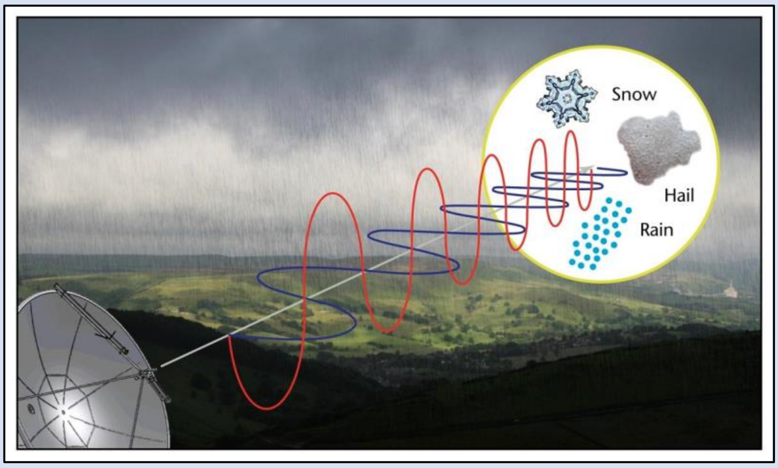


Figure 3. Schematic of dual polarisation measurement (Source: Darlington *et al.*, 2016)

Benefits for surface water flood forecasting

The updated radar network increases the accuracy of rainfall forecasts “particularly in very intense events, allowing for more accurate and timely warnings, which will give emergency responders and the public better and earlier information to help protect lives, livelihoods and property.” (Darlington et al., 2016). The recent dual polarisation upgrade to the UK radar network and associated scientific development in the processing of the new data has led to a marked improvement in radar observed rainfall rates either for use directly in rainfall monitoring or as input to forecasting and nowcasting systems.

In particular, the dual polarisation upgrade has led to:

- The correction and improved quality of the radar-derived rainfall rates to account for non-meteorological effects on the signal (e.g., insects, birds, trees, buildings)

- Using the radar as a radiometer for attenuation estimation, to correct observations in heavy rainfall, but also to monitor the randome for maintenance purposes
- Using newly available polarisation parameters to improve the conversion from radar reflectivity to rainfall rate
- Better accounting for variations in the raindrop size distributions and identification of precipitation type (water or ice)

Further details of these improvements are reported in Dance *et al.* (2019), Darlington *et al.* (2016) and Flack *et al.* (2019). For areas of Scotland where radar coverage is good, the dual polarization upgrade will improve the accuracy of radar observations (and radar nowcasts) during heavy rainfall events which could lead to surface water flooding.

Unlike rainfall gauges, radars can survey large areas and capture the spatial variability of the rainfall. They also provide real-time data and can calculate the motion, intensity and type of precipitation falling. Like rain gauge data, weather radar data is used in precipitation forecasting, for example, radar raw images can be used to make short term forecasts of future positions and intensities of rain.

Although the dual polarisation upgrade will improve the accuracy of radar rainfall observations, radar cannot guarantee to capture high intensities and local conditions accurately. The accuracy of the data from weather radar can be low when used in rainfall forecasting due to the measurement being obtained from the indirect process which introduces more uncertainty. There are known issues with radars poorly representing intense rainfall from convective precipitation when hail forms a part of the precipitation, and this continues to be an active research area for meteorologists.

The radar coverage in Scotland is not as dense as elsewhere in the UK and there are known gaps in coverage, particularly across Dumfries and Galloway and the Highland including Inverness. The mountainous terrain also means that radars might not be able to "see" in all directions as the beam is blocked by hills. Analysis by the Met Office for SEPA (Worsfold *et al.,* 2014) showed that outside of the central belt the probability of detection (POD) of rainfall by radar compared to rain gauge was quite low (Figure 4).

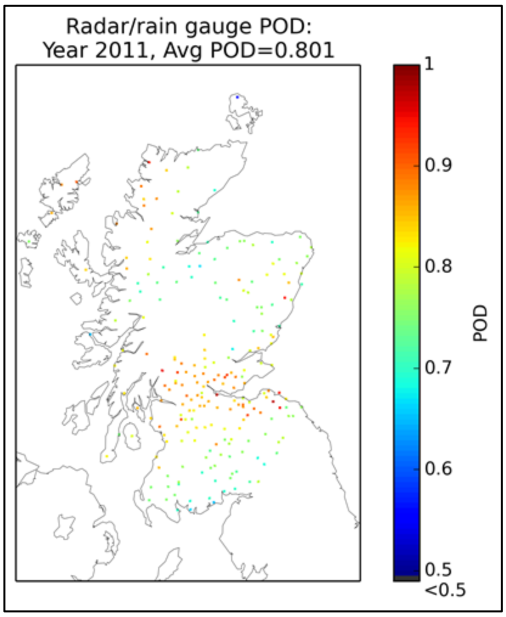


Figure 4. The Probability of Detection (POD) of rainfall by radar compared to rain gauge showing a marked increase in radar quality in the Central Belt compared to other areas of Scotland (Source: Worsfold et al., 2014)

The use of high-resolution X-band radar is starting to be used to improve rainfall detection in urban flood environments with examples in Japan (Kimura, 2012) and Europe (ten Velduis, 2012). In the UK, the National Centre for Atmospheric Science has deployed a high-resolution radar in Moray. Initially, it was deployed for the COPE (COnvective Precipitation Experiment) project to understand the physical processes involved in the production of heavy convective rainfall (Neely, 2018). RAINS (Radar Applications in Northern Scotland) saw a trial deployment of the X-band radar to examine the value of additional, high-resolution radar observations for creating more accurate Quantitative Precipitation Estimates (Cranston, 2016).

2.2 Precipitation forecasts

There are several methods used to forecast precipitation which can be categorised into deterministic, for example, a single Numerical Weather Prediction (NWP) model, and probabilistic, for example, an ensemble NWP model.

Numerical Weather Prediction (NWP) and Data Assimilation Methods (DAS)

NWP uses mathematical models of the atmosphere to predict future precipitation based on current weather conditions, and as such the models must have data which is as close to current weather conditions as possible (i.e. have exact initial conditions). Traditionally, using point rainfall measurements in the model was not satisfactory due to errors from real-world measurements. Today, current weather observations are input to the models through a process known as data assimilation.

Data assimilation, also known as data assimilation systems (DAS), is a technique where observational data from different sources are processed and adjusted. The aim of data assimilation is to provide as close to initial conditions as possible (Lu *et al*., 2018). The different sources of data typically include recent measurements of precipitation as well as a previous forecast valid at the same time the measurements are made (Dance *et al*., 2019). Data assimilation techniques use statistical and mathematical analysis to find the solution to the problem and as such would be difficult to manually perform because of the large amount of calculation involved (Lu *et al*., 2018). Precipitation data can't be used directly in NWP models because it's not a prognostic variable, however, in the past few decades, several approaches for assimilating precipitation observations in NWP have been developed including initialization scheme, nudging techniques, variational data assimilation and ensembles (Ban *et al*., 2017).

Data assimilation techniques have been the topic of international research interest over the past few years. The development of convection-permitting NWP models has necessitated some of this development. Convection-permitting NWP models can represent convective structures directly whereas large scale models rely on some form of parametrisation process to add in these features (Clark *et al*., 2016). To do this well, existing convective features need to be represented in the initial conditions. As part of the NERC funded Flooding from Intense Rainfall (FFIR) programme improvements to the Met Office, data assimilation methods were proposed. One of these improvements enables more data to be assimilated into the NWP initial conditions, allowing for better representation of the small-scale features that lead to intense rainfall (Dance *et al*., 2019; Flack *et al*., 2019). These improvements are currently in the process of being incorporated into the Met Office operational system, and when complete they will be a seamless upgrade to the currently available NWP. Another method being tested is a technique to assimilate radar reflectivity observations directly into the NWP model rather than through the current latent heat nudging technique (Dance *et al*., 2019; Flack *et al*., 2019).

The UK Met Office UKV model is an example of a world-leading convection-permitting NWP model. Its current configuration provides forecasts on a 1.5km grid across the UK for up to 120 hours ahead (5 days) with frequent updates for up to 54 hours ahead. Few other countries have NWP models on such a small resolution. The UKV model can produce very realistic looking showers compared to radar observed rainfall which is a considerable improvement over larger scale model configuration (Figure 5). This development in precipitation forecasting led to a significant improvement in the ability of hydro meteorologists to forecast surface water flooding. Nonetheless, the size of typical convective features is smaller than the 1.5km grid length meaning that showers (especially small showers) are still under-resolved (Clark *et al.*, 2016). Comparison between the Nowcast Demonstration Project, the STEPS nowcast and the UKV forecast all showed issues forecasting light, scattered showers. For the UKV model, the problem that was the showers were missing in the initial conditions and therefore did not show up until a short time into the forecasts but then at too large a scale with too few individual cells (Clark *et al.*, 2016).

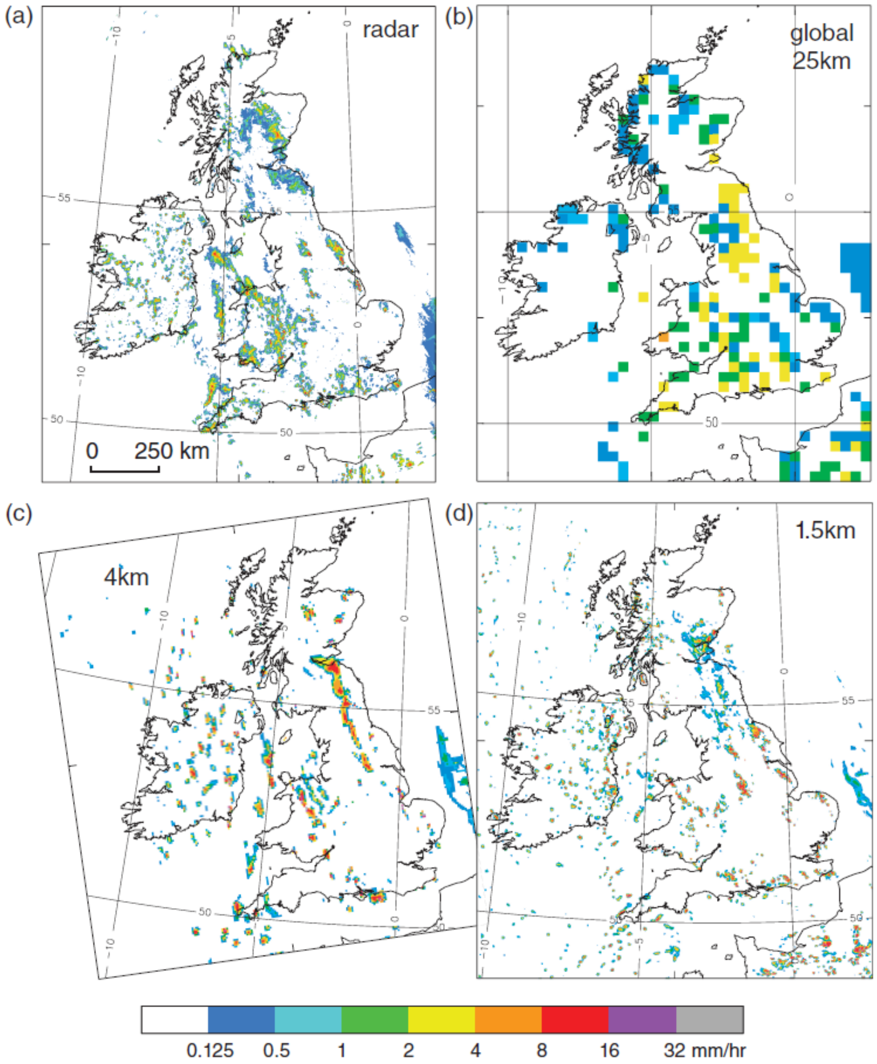


Figure 5. Comparison of convective showers over the UK on 8th June 2014 from a) Radar-derived rain rates (mmh-1) at 1 km resolution shown with instantaneous rain rates from the (b) MetUM Global model (c) Euro 4 (4 km down-scaled) and (d) UKV (1.5 km convection-permitting model) forecasts (Source: Clark *et al.*, 2016)

Precipitation forecasts obtained from a single NWP model are deterministic and do not convey any information about the uncertainty around the prediction. Convection-permitting forecasts are known to be sensitive to uncertainties in the initial conditions, boundary conditions and physical processes (Hagelin *et al.*, 2017). This is a disadvantage for weather-related decision-making, particularly for intense rainfall where location and timing uncertainties are known to be high. It is largely accepted that it is not possible to rely on deterministic forecasts of convective rainfall at a grid scale and a probabilistic approach is needed (Clark *et al.*, 2016).

Nowcasting

Nowcasting is the term given to weather forecasting on a very short-term period of 0-6hours. Nowcasting is an alternative method to NWP for precipitation forecasting. Within these small timescales, small features such as individual storms can be forecast with reasonable accuracy. Nowcasting uses surface weather station data (radar echo maps and rain gauge data), wind profiler data, and any other weather data available blended with NWP models. The method mainly focuses on extrapolating radar echoes, as such very high-quality radar is required. The quality of the nowcasts is dependent on the quality of the radar data. As radar data is very detailed and picks out the size, shape, intensity, speed and direction of movement of individual storms, for short term forecasts nowcasting can solve problems that NWP cannot.

UK nowcasting is well respected amongst the international meteorological community. The UK Met Office first developed a system for generating automated very short-range forecasts, called 'Nimrod' in the mid-1990s (Golding, 1998). Since then, the system has been continually developed and now includes the Short-Term Ensemble Prediction System (STEPS) (Bowler et al., 2006). STEPS is a probabilistic precipitation nowcasting scheme developed at the Australian Bureau of Meteorology in collaboration with the UK Met Office. STEPS introduced small scale features into the nowcast using a stochastic technique. This allowed features smaller than the NWP resolution to be represented whilst also representing the spatial and temporal uncertainty of such features.

STEPS has also been integrated in the current operational deterministic precipitation nowcasting system in Belgium (referred to as STEPS-BE), producing 20-member ensemble nowcasts (in real time) at 1km and 5-minute resolutions up to 2-hour lead time. Originally this integration was a task set by the PLURISK project (forecasting and management of extreme rainfall-induced risks in the urban environment), a research program by the University of Leuven, the Royal Meteorological Institute (RMI) of Belgium and 3 other partners. The task was assigned to the Royal Meteorological Institute of Belgium and is discussed in detail in Foresti *et al.* (2014).

The Met Office nowcasting capabilities were further developed in support of the 2012 Olympics, where hourly cycling, 1.5km resolution Nowcast Demonstration Project using four-dimensional variational data assimilation (4D-Var) was run in support of the games. The skill of the Nowcast demonstration project was shown to be greater than the UKV NWP forecast for the 6 hour nowcast period and better than the operational nowcast at times beyond T+2 hours (Ballard *et al*., 2015). Work is ongoing to implement the 4D-Var nowcast system for the whole of the UK.

Nowcast data is currently available for the UK at a 2km resolution updated every 15 minutes. Nowcasts are very important for surface water flood forecasting in urban areas as demonstrated in case of studies 5 and 6 (Glasgow and Loughborough). The value of nowcasts in these situations is their ability to represent the development of convective rainfall features over small areas. As the reliability of nowcasts improves so will the reliability of short-term surface water flood forecasting.

Probabilistic ensemble forecasting

Probabilistic forecasting is a technique for weather forecasting that relies on different methods to provide an estimation of the respective probabilities for all the possible future outcomes of a random variable. Ensemble forecasting is a type of probabilistic forecast which produces a set (or ensemble) of forecasts aimed at providing a range of possible future outcomes. Ensemble forecasting is carried out by an Ensemble Prediction System (EPS). Ensemble members are produced by either varying the initial conditions to account for uncertainty at the beginning of the forecasts or by varying the representation of physical processes (Clark *et al.*, 2016). This contrasts with a deterministic forecast which produces one single best estimate prediction. The value of ensemble forecasting for surface water flood forecasting is well described in the following quote from Golding *et al.* (2015, p1384);

> *"A single, deterministic forecast of the future state of the atmosphere is unlikely to match reality because of incompleteness of the initial state specification and because of biases in the representation of atmospheric processes. For some purposes, the fact that the forecast is usually near to reality will be sufficient. However, when lives and property are at stake, potential consequences of different possible weather outcomes need to be considered. An ensemble prediction system (EPS) produces a range of forecast scenarios that, taken together, can be used to assess the likelihood of particular hazardous weather situations occurring or of hazardous thresholds being surpassed."*

Today, ensemble predictions are commonly made at most of the major operational weather prediction facilities worldwide, including:

- The National Centres for Environmental Prediction (NCEP) of the United States
- The European Centre for Medium-Range Weather Forecasts (ECMWF)
- The UK Met Office
- The French national Meteorological Service (Météo France)
- The German Meteorological Service (Deutscher Wetterdienst; DWD)
- Environment Canada
- The Japan Meteorological Agency (JMA)
- The Australia Bureau of Meteorology
- The China Meteorological Administration (CMA)
- The Korea Meteorological Administration
- The Brazilian Centre for Weather Forecast and Climate Studies (The Centro de Previsao de Tempo e Estudos Climaticos; CPTEC)
- The Indian Ministry of Earth Sciences (formed from a merger of the India Meteorological Department (IMD), the National Centre for Medium Range Weather Forecasting (NCMRWF), the Indian Institute of Tropical Meteorology (IITM), Pune, the Earth Risk Evaluation Centre (EREC), and the Ministry of Ocean Development).

The Met Office Global and Regional Ensemble Prediction System UK (MOGREPS-UK) provides an ensemble of short range (convective-scale) NWP forecasts (Hagelin *et al*., 2017). The MOGREPS-UK system has been running since 2012 and the system configuration as described by Hagelin *et al.* (2017) has been operational since 2016. It provides a 54-hour lead time 12-member ensemble forecast based on the UKV model but at a 2.2km resolution (due to computational costs). Verification techniques have shown that MOGREPS-UK outperforms the deterministic UKV model for forecasting rainfall, although quite a large neighbourhood sampling size was needed to account for location uncertainties. As the Met Office continues to increase its computations power there are ongoing discussions about the benefits of increasing the ensemble size, resolution, domain size and forecast length of MOGREPS-UK. Hagelin *et al*.'s (2017) tests show more benefit in running a larger member ensemble (24 opposed to 12) over increasing the model resolution. Since 2017, the MOGREPS-UK system has been increased to 18 members using a time lagging technique with a 120-hour lead time. It is also able to provide hourly updates (compared to the previous 6 hourly updating cycle) which allows close monitoring of the development of convective showers. Met Office scientists are working to develop new diagnostic tools to take full advantage of these recent developments to the system. Further information is available at https://www.metoffice.gov.uk/research/news/2019/mogreps-uk-hourly-cycling-updates

Other European weather centres also have comparable convection-permitting systems to MOGREPS-UK e.g. the German COSMO-DE-EPS model runs of a 2.8km resolution with 30 members providing a 21 hour lead time 8 times a day (Hagelin *et al*., 2017) and Meteo-France 2.5km ensemble with 12 members run twice a day (Hagelin *et al*., 2017). Internationally research is ongoing to balance the relative merits of improving the resolution of convection-permitting ensemble models against the computational cost.

The skill of NWP forecasts for convective events is related to the larger scale weather situation. The speed at which errors grow in the forecast increases as the resolution of NWP models get more detailed. Rapid error growth indicates a limit to the predictability of a forecast. Studies have shown that the predictability of convective precipitation depends on whether it is controlled by large scale or local factors (Flack *et al*., 2018). As part of the FFIR programme, forecasts of convective rainfall have been examined in kilometre-scale ensembles. In 85% of cases, the convection driving process was found to result in scattered showers (rather than organised convection) and displayed relatively large uncertainty in the rainfall locations (Flack *et al*., 2016, 2018; 2019).

The limited number of ensemble members in convective permitting EPS means that for these situations the ensemble may not be able to capture the full range of uncertainty. This means that approximately 85% of convective ensemble forecasts will show confidence in the total rainfall, but lack confidence in the location of the event (identifying the potential for a surface water event just not where), and the other 15% will show confidence in the location of the rainfall but lack confidence in the amount (so you can say where the heaviest rainfall will fall but not if there will be enough rainfall to produce the flood). However, this knowledge enables forecasters to have a better understanding of the behaviour of ensembles including when they are likely to be able to capture the possible range of rainfall from a convective event and when other factors mean that the observed rainfall is more likely to be outside the forecast ensemble. This is particularly important when ensemble rainfall forecasts are being used further down the chain to drive flood inundation and impact models due to the localised nature of surface water impacts. For example if scattered showers were predicted across Greater Glasgow and each of the rainfall ensemble members was run through an inundation model, each model run would show flooding in a different area of the city resulting in a low probability of impacts across a large area. If the convection was more organised then the ensembles from the inundation model would show floods of varying magnitude (non to severe) in a focused location.

Understanding the limits of predictability of convection-permitting NWP is an active area of international research (Flack *et al.*, 2018). The insight into understanding the skill of convective ensembles from the FFIR programme is currently being considered by the Met Office ensemble and post processing team and the FFC have shown interest in incorporating the knowledge into their working practices. Hopefully, this will be incorporated into Met Office forecast products after further development.

Ongoing increases in computational power have allowed operational use of convection-permitting NWP at lead times of up to 5 days. However, users need to remain mindful that NWP at a 1.5km resolution is unable to accurately forecast the timing and location of convective rainfall. Although ongoing scientific developments will improve the skill of the forecasts there is likely to remain a limit to the deterministic predictability of convective rainfall. Golding (2009, also discussed in Spe*ight et al., 2018*) estimates this to be 3 hours ahead for a 10km by a 10km rainstorm and just 30 minutes ahead for the most intense 1km by 1km part of the storm. Therefore, the use of probabilistic forecasts will be essential to support surface water flood forecasting. The recent improvements to MOGREPS-UK to provide an 18-member ensemble out to five days are a clear indication of the Met Office's commitment to supporting this need. The interpretation of probabilistic forecasts requires user expertise. It is known that in some situations the skill of the forecast is better than others. The interpretation of probabilistic forecast also requires knowledge of the post-processing technique used (discussed below) as this can have a large influence on how the probability of heavy rainfall is presented).

As concluded by Clark *et al.* (2016, p178) "the current state of the art [of convection-permitting NWP] represents a beginning, not a conclusion, and it is anticipated that many advances in various directions will be possible in the future."

The introduction of convection-permitting NWP models has led to a step change in the ability to forecast the type of rainfall events that lead to surface water flooding. However, although the output from the models looks realistic, the development of convection-permitting NWP also led to several other research challenges. Most notably the need for improved techniques in data assimilation and ensemble forecasting to account for the increased speed at which errors grow in the forecast.

Post-processing

Post-processing is defined as the processing of data after other process have been completed. Post-processing converts rainfall predictions from forecasting systems (i.e. ensemble NWP model outputs and nowcasting outputs) into forecast products. They add value to the raw data, correcting bias and producing forecasts that reliably quantify uncertainty. Post-processing techniques are generally statistical and include; the rank histogram technique, ensemble dressing, Bayesian model averaging and logistic regression amongst others.

Postprocessing for intense rainfall is particularly challenging due to the small-scale nature of the features of interest. This means that probabilities for specific locations will remain very low and may not alert meteorologists or flood forecasters to the risk of an event. To help account for this, neighbourhood processing is often used to search for events within a spatial and temporal search window that could be considered equally likely to occur anywhere within the window. The neighbourhood sampling technique removes some of the noise of the result and effectively increases the ensemble size. The noise is a result of the ensemble not being large enough to convey the uncertainty in the process (Hagelin *et al*., 2017). The Met Office are currently developing a new post-processing and verification system called Integrated Model postPROcessing and VERification (IMPROVER). This system is expected to replace the existing post-processing system by 2020. The new system “will be probabilistic at its heart to fully exploit the ensemble forecast data and will have integrated verification at every step to enable improved assessment of future developments” (Met Office, 2019b). It is important that end users such as SEPA maintain close links with the scientists developing post-processing systems as the thresholds and metrics used will have a significant impact on the usefulness of the outputs to support flood forecasting.

3 Surface water flood forecasting approaches

This section presents the various international approaches to surface water or pluvial flood forecasting. From the 'simple to use' rainfall alarms to the more complex 2D urban modelling, each approach has been developed based on end user needs and each has its respective advantages and challenges. Parkinson and Mark (2005) illustrate the typical architecture to urban flood forecasting, where data is collected and used within a decision support tool (or model), which is then communicated to recipients and often followed by a feedback process. The UK is relatively unique in its development of surface water forecasting techniques separately to flash flooding. Most of the international examples reviewed in this section consider the two types of flooding as a continuation and therefore do not explicitly separate between them.

Attempts have been made to classify the various approaches to urban flood modelling. Henonin *et al.* (2013) developed a classification of real-time flood forecasting systems that focused on the use (or not) of hydraulic models in the decision support tools aspect of the system. For the purposes of this report, we have adapted and updated the approach developed by Henonin *et al.* (2013). We encompass all the approaches that were identified during this review, but maintain a broadly similar three-type classification as follows:

- Empirical-based rainfall scenarios: Surface water flood forecasting based on observed or forecast rainfall scenarios, typically based on historical data and evidence of pluvial flooding
- Hydrological forecasting linked to pre-simulated impact scenarios: Real-time flood forecasts using hydrological modelling with warning triggers based on scenarios or results catalogue built from offline hydraulic simulations, applied at either a national or regional scale
- Hydrological forecasting linked to real-time hydrodynamic simulations at the urban scale: Real-time operation and simulation of hydraulic model(s).

Figure 6 presents the conceptual approaches to surface water flood forecasting in a systematic diagram.

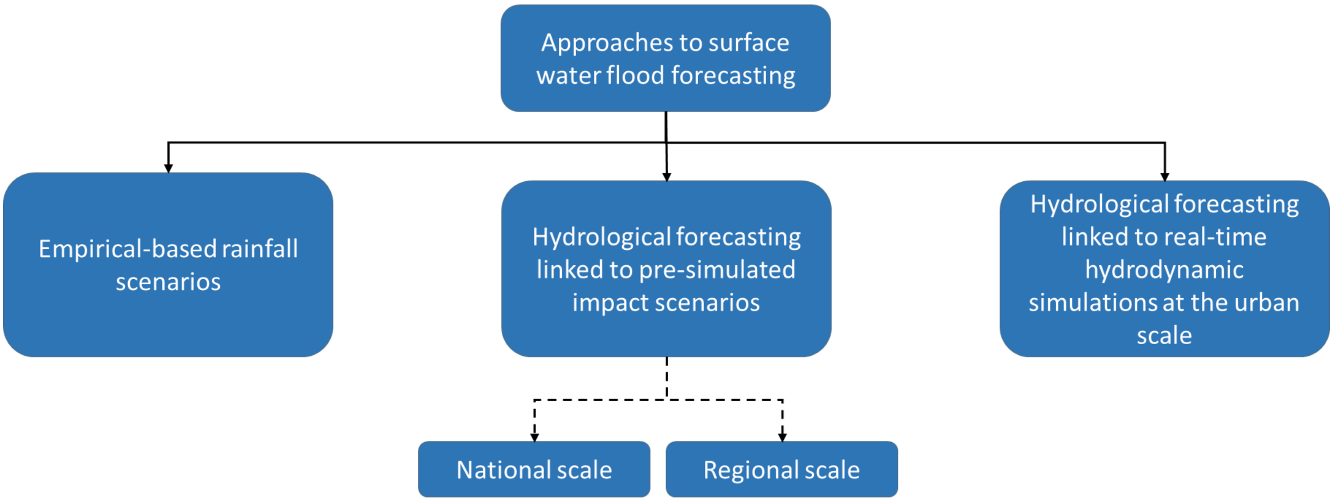


Figure 6. Conceptual approaches to surface water flood forecasting

3.1 Empirical-based rainfall scenarios

The use of pre-calculated rainfall thresholds to identify the risk of pluvial flooding is a quick means of post-processing NWP output or radar observed rainfall to support decision-making. Depth-duration threshold is set based on existing knowledge of the amount of rainfall falling within a specified time period that could cause flooding impacts. The thresholds are then validated against observed events. The rainfall input can be either an empirical or probabilistic forecast or observed rainfall. The UK Met Office terms the use of this type of threshold system as a “first-guess early warning” (Neal *et al.*, 2014). Due to their low development and running costs, such systems are in widespread use.

Large scale systems

In the UK, there is a long history of using rainfall threshold systems for surface water flooding starting with the Extreme Rainfall Alert (ERA) system introduced by the Met Office and the Environment Agency in 2009. The service was based on the likelihood of exceeding depth-duration thresholds for a 30-year return period event, but it took no account of surface-subsurface processes or vulnerability (Pilling *et al.*, 2016).

The UK Met Office uses pre-calculated thresholds to inform their National Severe Weather Warning System (NSWWS) using the MOGREPS-W system (Neal *et al.*, 2014). Thresholds are set for all types of severe weather (e.g. wind gusts, snow, rain) and probabilities are extracted from MOGREPS-UK to enable risk to be calculated against the standard NSWWS/FGS risk matrix. The impact thresholds vary by country to take account of the varying levels on the impact of severe weather for different parts of the UK. The Chief forecaster also has the capability to vary the thresholds to account for varying seasons or antecedent conditions (Neal *et al.*, 2014). MOGREPS-W produces colour coded maps shaded by the warning level; these are used to help inform forecaster decisions to issue a NSWWS warning but are not directly available outside the Met Office.

Moving on from the ERA, the FFC developed a more targeted system that takes account of urbanisation and antecedent conditions called the Surface Water Flooding decision support tool (SWFDST) which was introduced in 2010 (Pilling *et al.*, 2016). Its current form uses MOGREPS-UK forecasts to assess surface water flood risk as a weighted score in each county/unitary authority in England and Wales based on the:

1. Maximum probability of rainfall thresholds being exceeded for 1,3,6 hour durations and 10 year and 30 year return periods giving thresholds for 20mm/1hr, 30mm/3hr and 40mm/6hr (10 year) and 30mm/1hr, 40m/3hr, 50mm/6hr (30 year)
2. Rainfall spatial extent (meteorological characteristics of localised or widespread storms)
3. Soil moisture deficit taken from Met Office Surface Exchange scheme (MOSES)
4. A pre-calculated ‘blue squares percentage’ used as a proxy for urbanisation and potential impacts on the ground based on 1km squares where at least 200 people, 20 businesses or 1 critical service might be flooded to a depth of 0.3m in a 1 in 200 year rainfall event. (The vulnerability assessment is taken from the Environment Agency flood risk maps) (Ochoa-Rodríguez, 2018)

The weightings were calibrated against historic events. Ongoing calibration occurs after events and with Met Office model changes. Each country is assigned a surface water flooding risk category of very low, low, medium or high.

Like MOGREPS-W, the SWFDST is used alongside “expert judgement and feedback from local Environment Agency flood teams, public weather service civil contingency advisers and the Met Office chief forecaster to produce the surface water flooding element of the FGS” (Cole *et al.*, 2013).

The SFFS developed its own rainfall threshold-based approach, the Heavy Rainfall Alert (HRA) tool in 2013 to support surface water forecasting for the FGS. The HRA uses probabilistic forecasts from MOGREPS-UK against rainfall threshold for 1, 3, and 6-hour durations. The thresholds vary across the country to account for variations in the amount of rainfall that catchments can cope with before flooding impacts occur. As well as showing threshold exceedance for the FGS areas, the newest version of the HRA tool includes specific reporting for seven urban areas across Scotland and known flashy catchments (Maxey, 2015).

In comparison to the SWFDST the HRA provides more details about the rainfall forecast but the assessment of impact is based on national level thresholds rather than spatially varying vulnerability. The expert knowledge and experience of the hydrometeorologists is required to identify which locations are at higher risk of impacts given the forecast rainfall. Using the above structure the methodological differences are:

1. The HRA gives details of the forecast rainfall and timings for all durations and thresholds whereas the SWFDST only gives the maximum probability of exceeding any threshold for the 10 year and 30 year event. The HRA reports threshold exceedances at a lower return period that the SWFDST for minor impacts. The 10yr return period in the SWFDST is equivalent to the significant impacts threshold in the HRA.
2. The HRA makes no explicit assessment of the spatial extent of rainfall (although the spatial exceedance probabilities should be higher for more widespread storms)
3. The HRA uses different thresholds for wet and dry antecedent conditions and the hydrometeorologists have to use their expert judgement of the current conditions to know which threshold to use (although no assessment of antecedent conditions is used in the urban areas assessment).
4. There is no formal inclusion of vulnerability and exposure within each FGS area in the HRA, although the latest upgrade includes an assessment for individual cities as well as the whole FGS area.

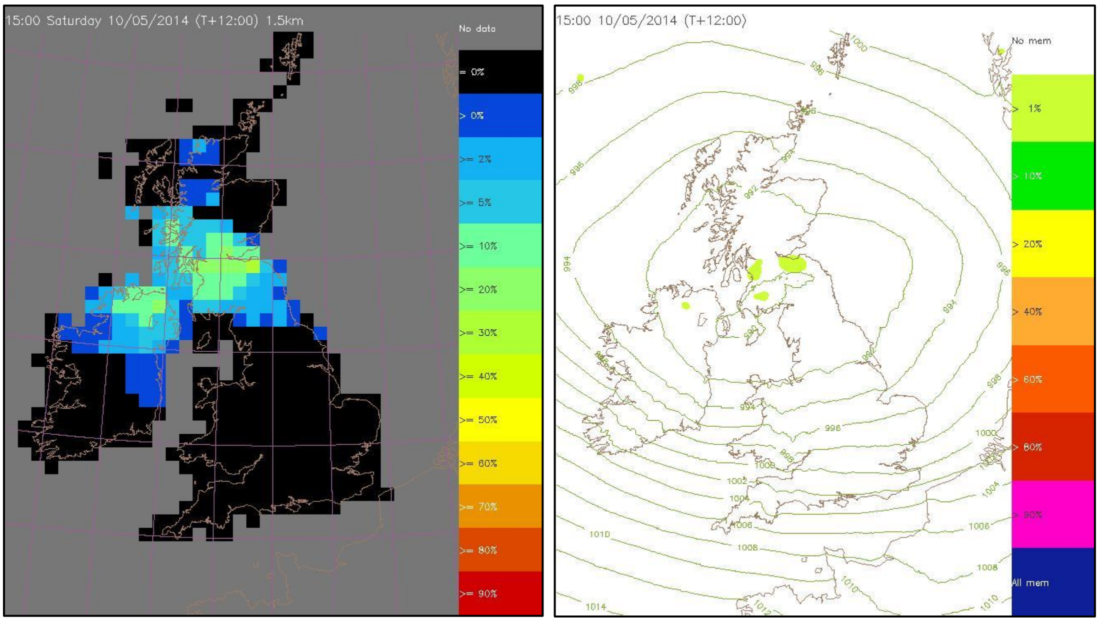


Figure 7. Comparison of the exceedance probability for 15mm in 1 hr of rainfall between the HRA tool map (left) and MOGREPS UK (right) (Source: Buchanan, 2014)

A key difference between the above three systems (SWFDST, MOGREPS-W and the HRA tool) is their approach to neighbourhood sampling. For example, MOGREPS-W places more emphasis on grid point warnings (Neal *et al.*, 2014) whereas the HRA tool uses a neighbourhood sampling approach over 60km to account for the location uncertainty when forecasting heavy rainfall. For urban areas, the HRA tools use a search area of ~1000km^2. As observed by Buchannan (2014) this creates an interpretation challenge for forecasters as the MOGREPS-UK raw output (reported on a 2km grid square) show smaller probabilities of occurrence that the HRA tool map (reported on a 32km grid square) and both, in turn, will be lower that the probabilities across an FGS area (see Figure 8).

Similar threshold-based systems are also used around the world. For example, case study 1 provides details of the flash flood guidance system used in the USA and case study 2 discusses a regional scale system in Spain.

Scenario-based threshold approaches can provide useful ‘first guess’ information on the likelihood of surface water flooding on a broad scale although, like other approaches, the probabilities at individual city scales remain low. However, they are limited as without manual intervention the thresholds are static and cannot account for changes in vulnerability of antecedent conditions. Similarly, the probabilities are solely based on the rainfall probabilities and no account is taken of hydrological and hydraulic processes in individual areas. Due to the reliance on some form of neighbourhood sampling approach, the interpretation of probabilities to inform the FGS, NSWWS or flood alerts relies on expert knowledge and experience. There appears to be limited confidence in the use of this type of system as a standalone approach. For all of the examples discussed above, the exceedance probabilities are used alongside other sources of information, and expert judgement, to inform decision-making on flood risk.

Case Study 1: Flash Flood Guidance in the United States

Background

The National Weather Service (NWS) flash flood warning program was implemented in 1971 in response to a growing impact of flash flooding (Mogil *et al*., 1978). Flash flood guidance is classified as the amount of rain that is required over the given duration and spatial extent that could produce bank full conditions on smaller streams, considered to be associated with flash flooding. A 6-hour threshold is operationally adopted across the US to separate the hydrological forecasting responsibility between regional River Forecast Centres (RFCs) who have responsibility for fluvial floods over longer timescales, and the local Weather Forecast Offices (WFOs) who are responsible for flash flooding (Gourley *et al.,* 2012).

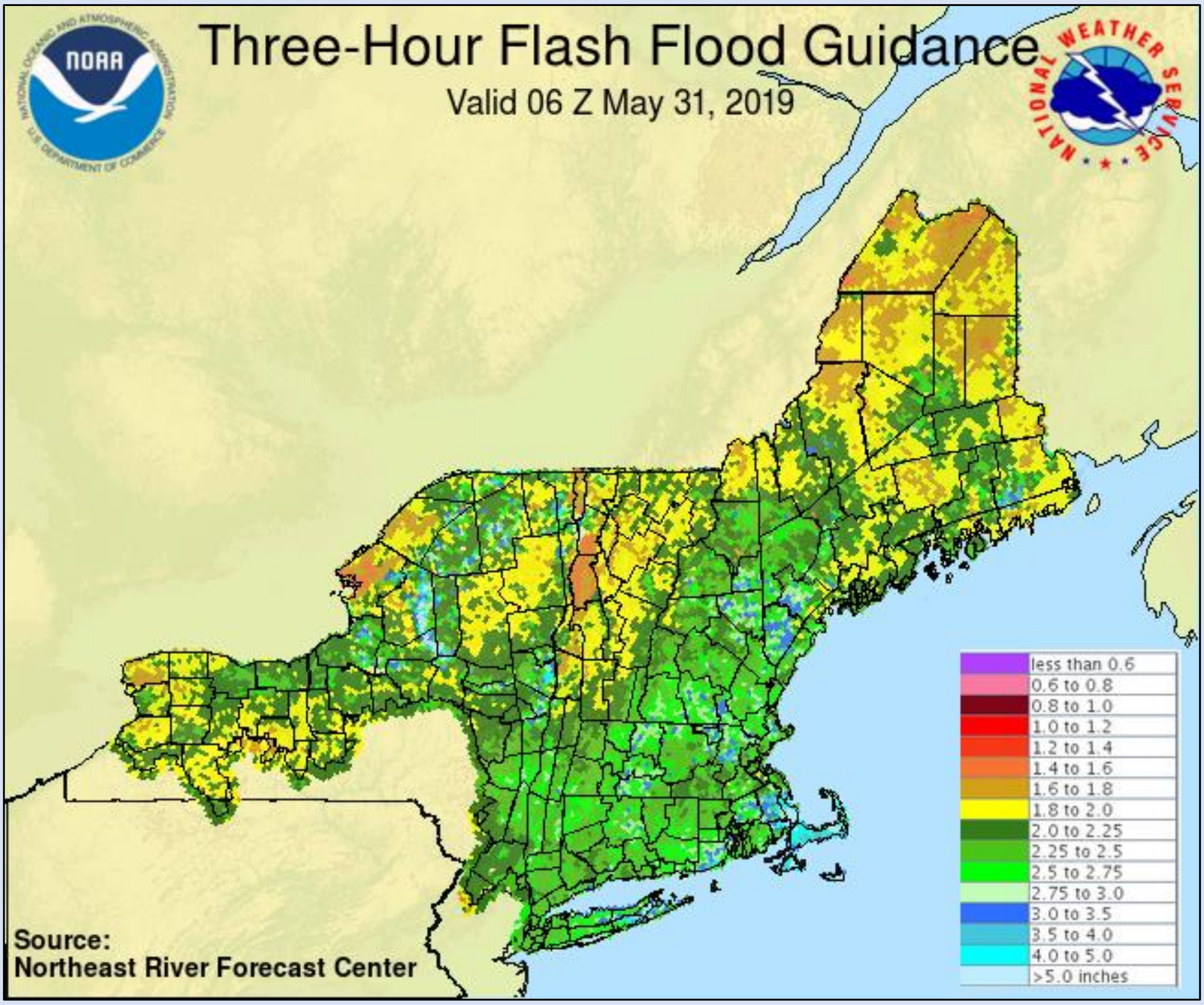


Figure 9. Three-hour flash flood guidance issued by the National Weather Service. Flash Flood Guidance is an estimate of the amount of rainfall required over a given area during a given duration to cause small streams to flood. (Source: weather.gov/nerfc)

Empirical-based rainfall flash flood guidance

The WFOs use the most accurate and timely precipitation estimates (from radar) and overlay these onto Flash Flood Guidance (FFG) values. Where the rainfall exceeds the FFG values, then flash flood warnings are considered and include publicly available products. For decades the main element of the FFG was based on knowledge of catchment conditions and past rainfall (Mogil *et al*., 1978), however various programs aimed to modernise and standardise approaches have been adopted.

In the 1980s, the Lumped Flash Flood Guidance (LFFG) sought to use the Advanced Weather Interactive Processing System (AWIPS) and higher resolution precipitation estimates from the WSR-88D network (Sweeney and Baumgardner, 1999). Under the LFFG approach, rainfall-runoff models were used to determine the necessary bankfull runoff for specific soil moisture conditions and lumped to provide areal averages or average values applied for single states (Gourley *et al.,* 2012).

Whilst recognising that flash flooding occurs on smaller scales than the river basin, the Flash Flood Potential Index (FFPI) was developed to determine gridded information on susceptibility to flooding. In their evaluation of the National Weather Service Flash Flood Guidance products, Gourley and Hong (2014) concluded:

- Flash flood guidance has proved a vital service since its introduction over 40 years ago;
- Future work should look at generating FFG with more advanced distributed hydrological models;
- A move to higher resolution gridded guidance would be advantageous and aligns with high-resolution precipitation estimation.

Forecasting a Continuum of Environmental Threats (FACETs)

FACETs is an ongoing research programme which is intended to allow forecasters to improve upon the standard weather watches and warnings such as the FFG. The programme aims to deliver detailed hazard information through the use of ‘threat grids’ and will be applied to severe convective and flash flooding events. Currently, the approach to flash flood guidance is a ‘warn on detection’, however, the new approach of ‘warn on forecast’ will combine satellite, numerical weather prediction and radar data to forecast the future track of severe convection (Rothfusz *et al.,* 2014).

Local-scale systems

Due to their cheap set up costs and ease of use, threshold-based alerting systems are used widely at a city and local scale. For example, in Bonn in Germany, water levels in a local stream are continually monitored and sent in real-time to the fire brigade who issues a warning if the specified thresholds are exceeded (Hofmann and Schüttrumpf, 2019). Other examples can be found across the world of simple triggers linked to rain gauges, radar systems or sewer sensors that provide pluvial flooding alerts directly to the authorities or the public usually through web apps or mobile phones (for examples see Acosta-Coll *et al*., 2018). A standard setup for such systems is shown in Figure 9.

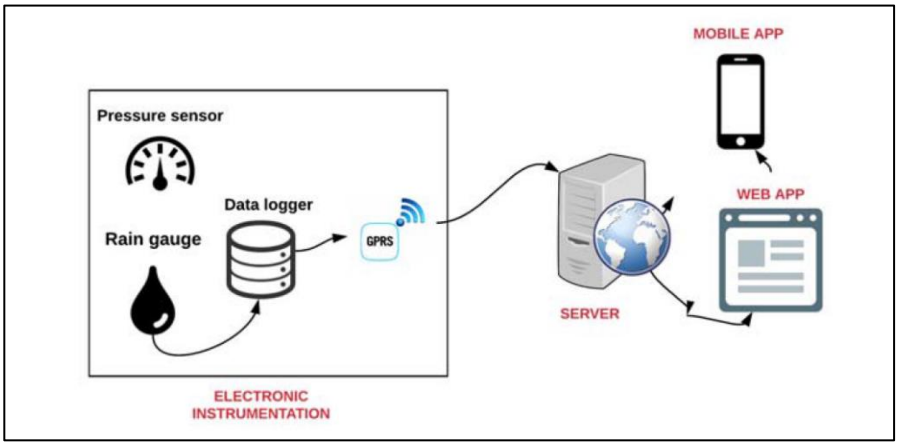


Figure 10. The example set up of a local scale flood alerting system (this one is taken from the Urban Flood Monitoring System for Manilla Metro project in the Philippines. Source: Acosta-Coll *et al*., 2018)

Accepting that the density of formal discharge and rainfall gauges is not always sufficient to support such systems, there is a strong link between the developments of local threshold-based systems and crowdsources data (Section 4). One such example is the ongoing FloodCitiSense project which can be accessed via https://jpi-urbaneurope.eu/project/floodcitisense/ . FloodCitiSense aims to develop urban pluvial flood early warning services for, but also by citizens and city authorities. It has case studies in Brussels, Rotterdam and Birmingham.

The Environment Agency are key stakeholders in the Birmingham project which focusses on the Selly Park area. Selly Park has a known history of surface water flooding and engaging residents in building their own rainfall sensors and reporting flooding via a new app is seen as a positive step towards establishing a local pluvial flood warning system (Rodriguez, 2018).

Since these local systems are based on observed rainfall or flow, they offer limited lead time to prepare for surface water flooding. However, they do provide an opportunity for increased community-level awareness and ownership of flood risk. Whilst there is no published material on the value of such systems, many local authorities in England and Wales (e.g. East Sussex County Council and Wrexham County Borough Council) are now adopting rainfall threshold-based information and alarms through HydroMaster to support their duties under the Flood and Water Management Act. The systems are planned to be exploited for a more proactive operational response for surface water flood events (MeteoGroup, 2019).

Case Study 2: Radar-based Early Warning System for Urban Flooding in Spain

Background

In some regions of Spain, a simplified Early Warning System (EWS) has been adopted which is based on the use of radar observations to issue localised flood warnings. Llort *et al.* (2014) explain that whilst radar observations may have sources of error, they are the quickest way to produce reliable estimates of precipitation accumulation. When merged with radar-based nowcasting techniques, this allows for short-term forecasting which is seen as a crucial method of warning for urban floods.

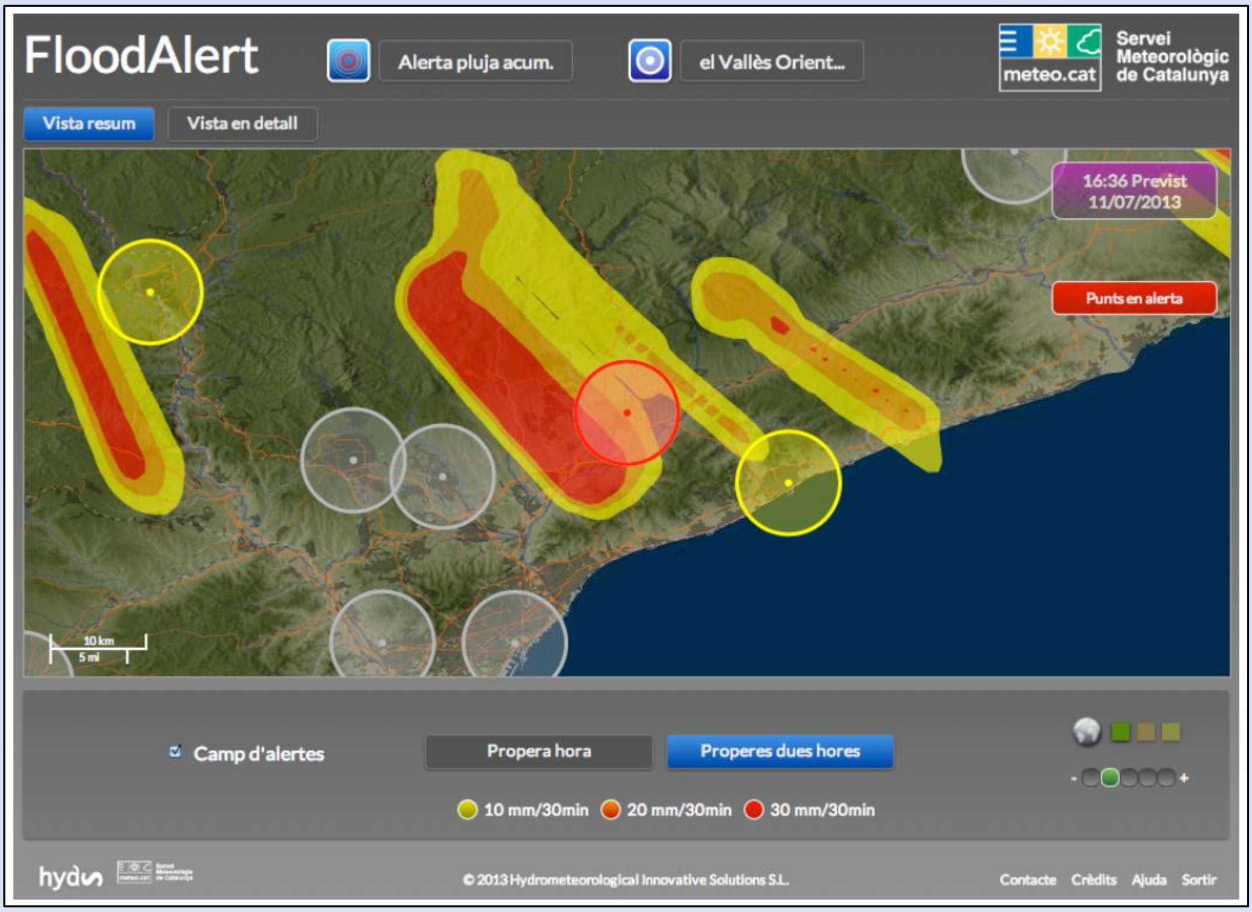


Figure 11. Example of FloodAlert early warning showing areas that are forecast to be higher the predefined thresholds in the following two hours. The image corresponds to the 11th of July 2013 in a town close to Barcelona. (Source: Llort *et al.*, 2014)

Simplified radar-based early warning system

The FloodAlert system uses quality-controlled radar data before a movement field of precipitation module is used to calculate the precipitation nowcast. The movement field extrapolates radar observations to the next few hours before it is known to decay and is based on approaches developed by Berenguer *et al. (*2005).

Using both radar observations (past two hours) and nowcast (next two hours), FloodAlert calculates 30-minute rainfall moving accumulation. This duration was selected to be most representative of urban flooding and is specifically linked to sewer system design (Llort, *et al*., 2014). In Barcelona, the depth-duration values have been determined partly on urban drainage and using local and historical knowledge of flooding impacts (Llort, personal communication, 2019).

FloodAlert calculates flood warnings on intelligent areas around specific locations of infrastructure and is calculated dynamically based on precipitation direction and speed. Figure 10 illustrates the dynamic warning areas linked to predetermined rainfall threshold values of 10mm/30min (yellow), 20mm/30min (orange) and 30mm/30min (red) (Llort *et al*., 2014).

Integrating radar nowcasting and 1D/2D modelling in real-time

Whilst the example has demonstrated the use of simple empirical-based rainfall scenarios linked to radar and nowcasting, attempts have been made to link this approach to real-time modelling. Russo *et al*., explain how the precipitation estimates have been coupled with a 1D/2D model (Infoworks ICM) to model the sewer system and overland flow in Marbella. This approach is being used to assess the impacts on human activity including pedestrian and vehicle movement.

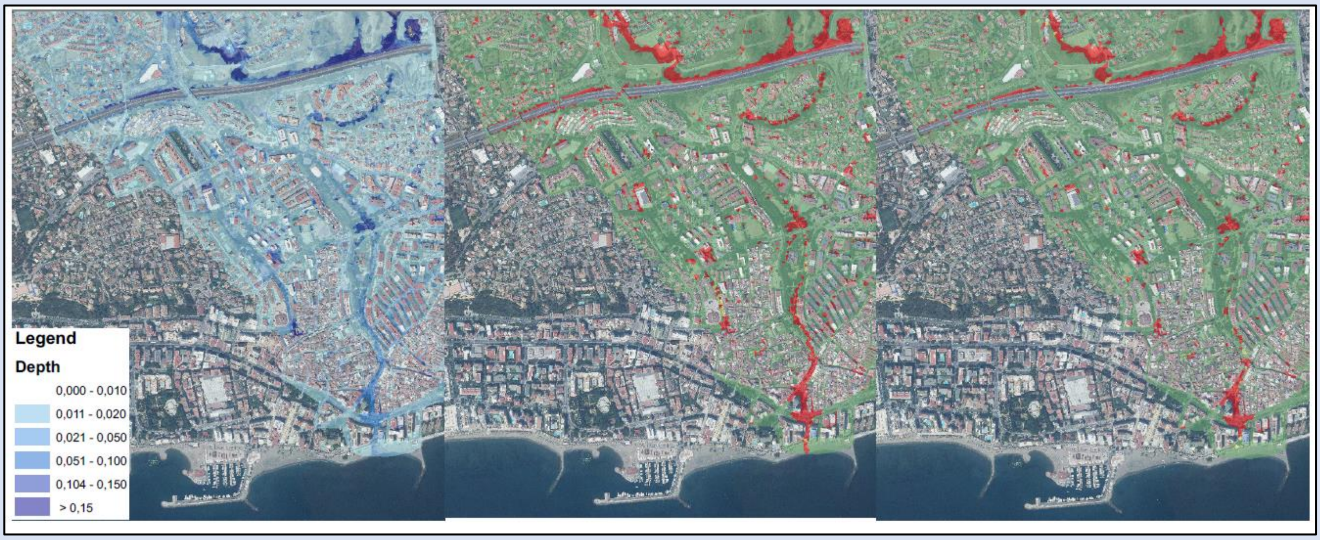


Figure 12. **Flood map (left), pedestrian hazard map (centre) and vehicular hazard map (right), for a 1 in 100-year (1%) risk (Source: Russo *et al*., 2017)**

This approach linking radar observations and nowcasts under the FloodAlert system with hydraulic modelling has enabled the operational use in Marbella (under the EU Pearl Project):

- Dynamically linked real-time precipitation estimates with pre-calculated hazard maps;
- Operation of the coupled model (via the Cloud) using real-time nowcasting data, generating hazard maps in real-time for dissemination with responders (Russo *et al*., 2017); and
- Warnings sent via email and SMS of rainfall intensity (observations and forecast for next two hours), 1D/2D simulations of key infrastructure.

This approach illustrates how a simple empirical-based nowcasting system can be developed to provide more detail on surface water impacts, examples of which are provided later in this report.

3.2 Hydrological forecasting linked to pre-simulated impact scenarios

The use of pre-simulated scenarios for flood forecasting is becoming an acceptable compromise between benefitting from the detail available from detailed hydraulic inundation mapping, reducing the operational computation time and allowing a direct link to the assessment of impacts. There are examples at a local scale (see Case Study 5), at national scales (see case study 3 and 4) and at international scales (for examples linked to the European Flood Awareness System for fluvial flood risk see Dottori *et al*., 2017, and JBA, 2019). The approach is based on the assumption that a link can be made between the real-time forecasting model and the static inundation and impact assessment, for example in the case studies 3 and 5 that effective rainfall used to produce the static flood maps is equivalent to the surface runoff from the Grid-to-Grid model.

The success of the approach relies on the quality of the original hydraulic inundation modelling and the representation of urban drainage capacity, and on having a large enough library of events (in terms of return periods and event durations) to be able to reflect the varying response to the forecast rainfall event. Unlike the threshold scenario approaches (section 3.1) the spatial variability of rainfall is accounted for by linking forecast rainfall and effective rainfall at a grid cell level as well as the spatial variability of impacts through the use of spatial impact databases. The use of a real-time hydraulic model (e.g. Grid-to-Grid (G2G) in case studies 3 and 5) allows incorporation of antecedent conditions. Using a library of inundation maps and impact assessments allows for full consideration of rainfall forecast ensembles rather than focussing only on deterministic forecasts or short range nowcasts, something that has not yet been demonstrated for real-time hydrodynamic simulations (see section 3.3). The static inundation maps and impact assessments have often been made at a finer resolution that the predictability of the forecast rainfall, therefore consideration must be made of an appropriate reporting scale that meets end-user needs but also reflects the uncertainty in forecasts of convective rainfall.

Case Study 3: Surface Water Forecasting Hazard Impact Modelling in England and Wales

Background

Under the banner of the Natural Hazards Partnership the FFC, CEH Wallingford and the Health and Safety Laboratory have been working on a national surface water forecasting model to inform the surface water forecasting component of the FGS. Work began in 2013 and the resulting model is now running in a pre-operational trial at the FFC with operational use expected by summer 2020. The latest developments of the surface water HIM are detailed in Cole *et al.* (no date)

Modelling approach

The model uses ensemble rainfall forecasts from MOGREPS-UK to generate surface runoff from G2G. There is also an option for short-range forecasts (up to 6 hours) using the STEPS nowcast. It is assumed that the G2G surface runoff equates to the effective rainfall input used to derive a library of static JFLOW flood maps, enabling the most appropriate map for the forecast to be selected. There are 9 maps available for 9 different rainfall scenarios (30yr, 100yr and 1000yr return period at a 1, 3, and 6-hour duration).

Combining the flood outline with receptor data from the National Receptor Database enables assessment of the impact of the event. Combining the multiple impact assessment from each of the rainfall ensemble members enables the real-time assessment of surface water flood risk. The modelling approach is summarised below.

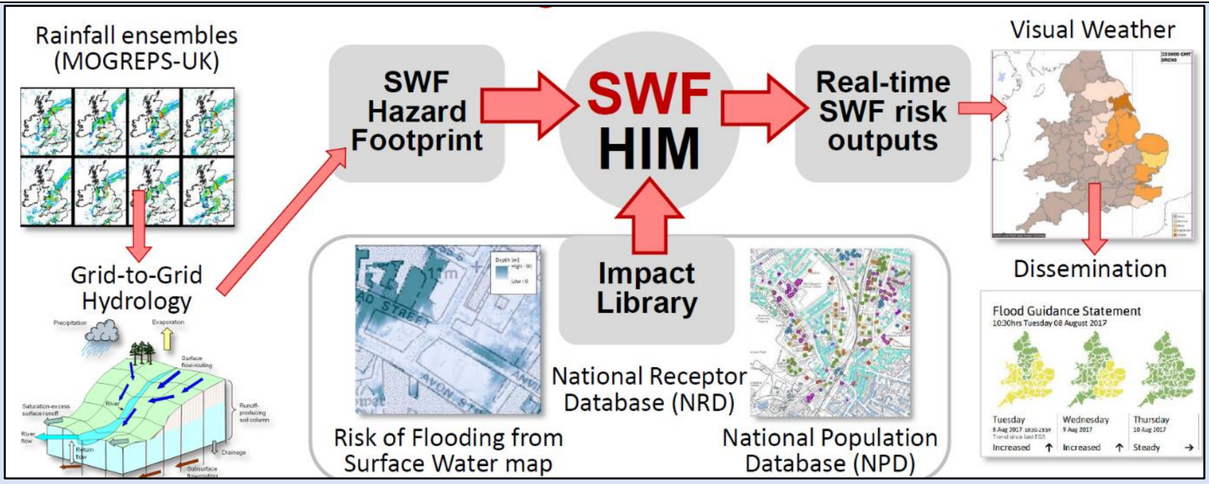


Figure 13. Overview of Surface water forecasting hazard impact model structure (Source: Cole *et al.*, 2019)

Scale of assessment

Surface runoff is produced at a 1km resolution from G2G. The JFLOW maps are produced using a 2m resolution. Although impacts are calculated at a 1km resolution they are reported as regional summaries (Figure 13). Impact threshold has been specified for flooded properties (residential and non-residential), key sites and infrastructure, population and transport links. Risk is assessed based on the existing FGS probability and impact matrix.

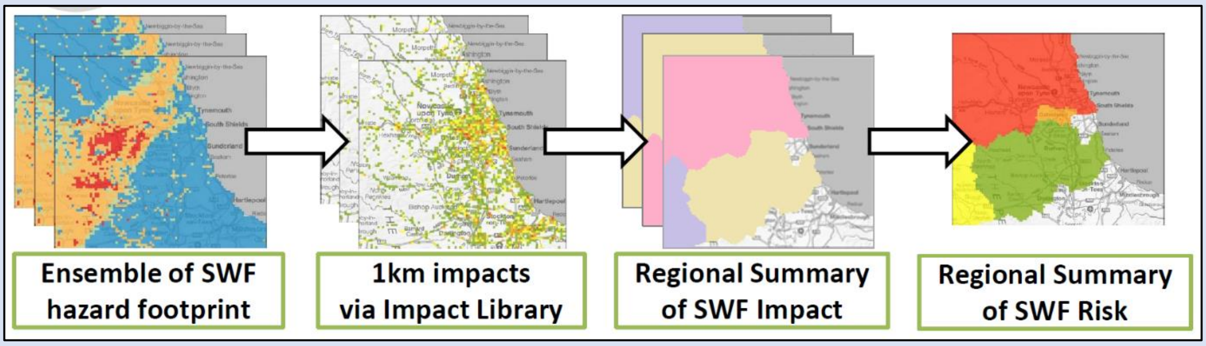


Figure 14. Process of aggregation to regional surface water flood risk summary (Source: Cole *et al.*, 2019)

The HIM has been designed to support the national FGS and therefore the regional level assessment relates to the existing FGS maps. Although it would be possible to produce output at a more detailed spatial scale from the HIM, this is not currently useful by the FFC due to the additional interpretation and communication time that would be required to explain the uncertainties around forecasting the spatial extent of convective rainfall that leads to surface water flooding.

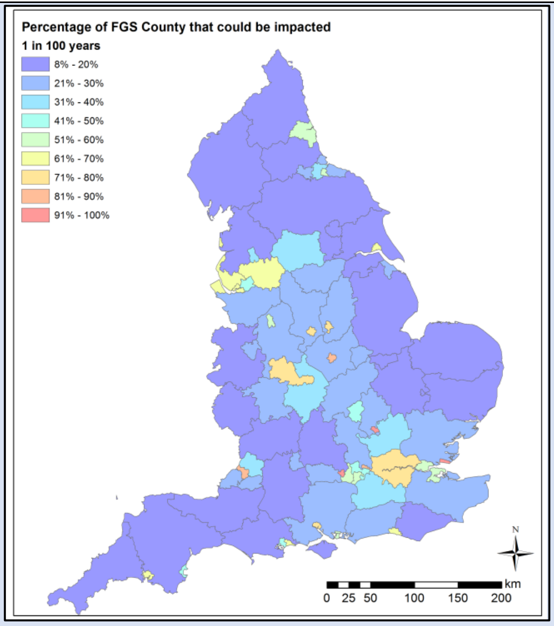
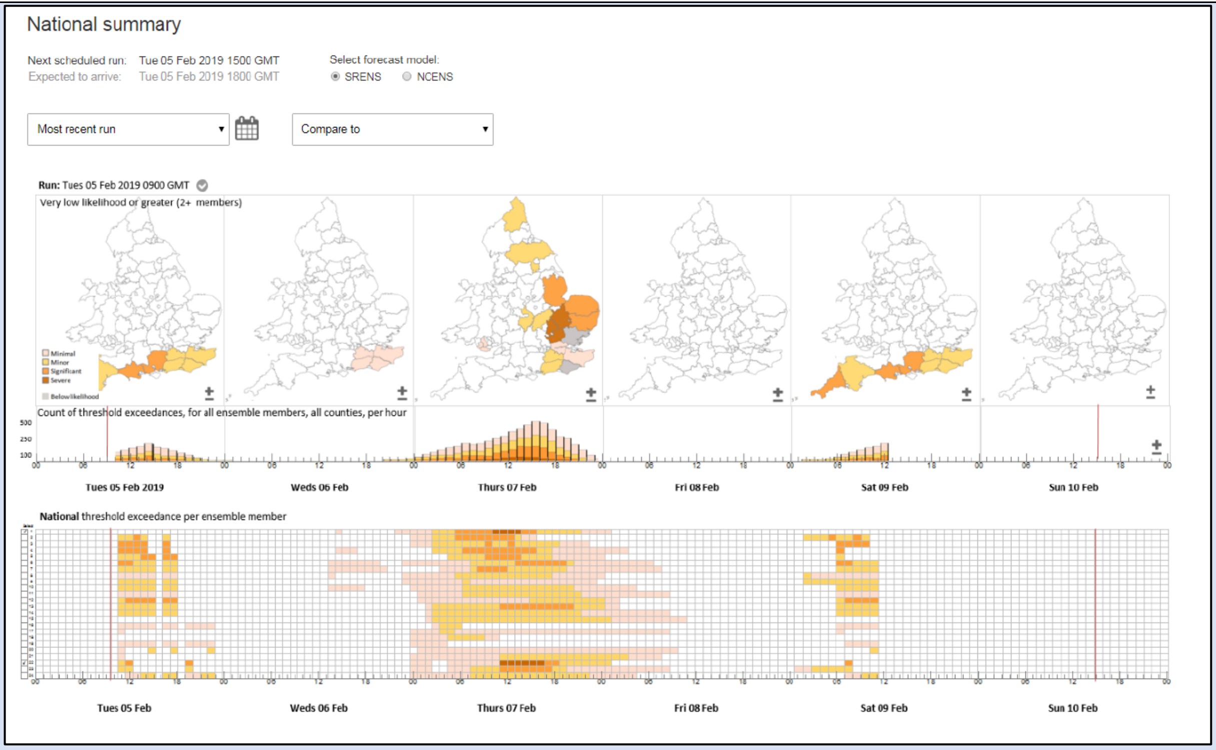


Figure 15. Percentage of cells in each FGS county that could be impacted at the severity of minor or greater for a 1 in 100-year event (Source: Gunawan and Aldridge, 2016)

The process of aggregating risk to the regional level results has been carefully tested by the HSL (see Gunawan and Aldridge, 2016). Figure 14 shows the percentage of cells in each FGS county that could be impacted for a 1 in 100-year event. Thresholds are assigned based on the size of the county for how many cells are required to assign each impact severity level (e.g. a county of 2000km^2 would be 10 cells whereas a county of 100km^2 would be 1 cell). For some smaller counties, 1km^2 hotspot cells (classified as cells that experience impacts classified as *Severe* for the lowest return period (1 in 30 years)) result in the whole county being assigned a severe impact level for all events. Similarly, there may be counties that can never be classified as *Severe*, as the number of 1 km^2 cells that can possibly be classified as *Severe* is below the threshold. Some sensitivity analysis has been carried out on this issue, but no strong evidence was found to change the thresholds, therefore, end-users are advised on the need to understand why such hotspots exist and their potential impact on results and summaries (Gunawan and Aldridge, 2016).

Visualisation

The FFC is able to view the output from the SWF HIM using the Met Office visual weather system. The Visual Weather display includes the country level summary maps for each risk level, information on the timing of the maximum number of threshold exceedances and the spread of threshold exceedances for each individual ensemble member (Figure 15). It also provides a country level summary of impacts table. The last phase of the project is to finalise the Visual Weather display to support the requirement of the FFC.



National summary

Next scheduled run: Tue 05 Feb 2019 1500 GMT
Expected to arrive: Tue 05 Feb 2019 1800 GMT

Select forecast model:
● SRENS ○ NCENS

Most recent run ▾

Compare to ▾

Run: Tues 05 Feb 2019 0900 GMT

Figure 16. Example of the SWF HIM output available in Visual Weather (Source: Boyce, 2019)

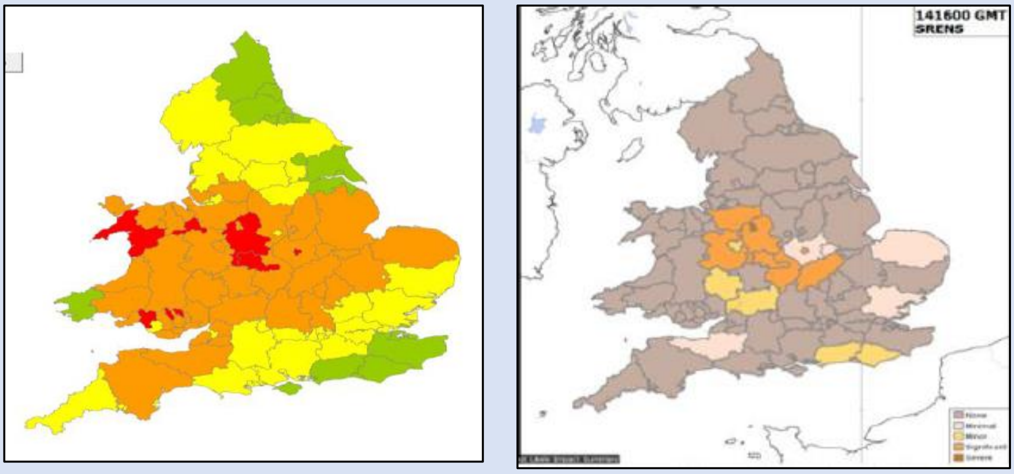


Figure 17. Comparison of the forecast for 14th June 2016 from the surface water forecasting decision support tool which identifies large areas of the country at risk and the WF HIM which is able to pinpoint risk to specific areas (Source: Boyce, 2019)

Validation and comparison with existing approaches

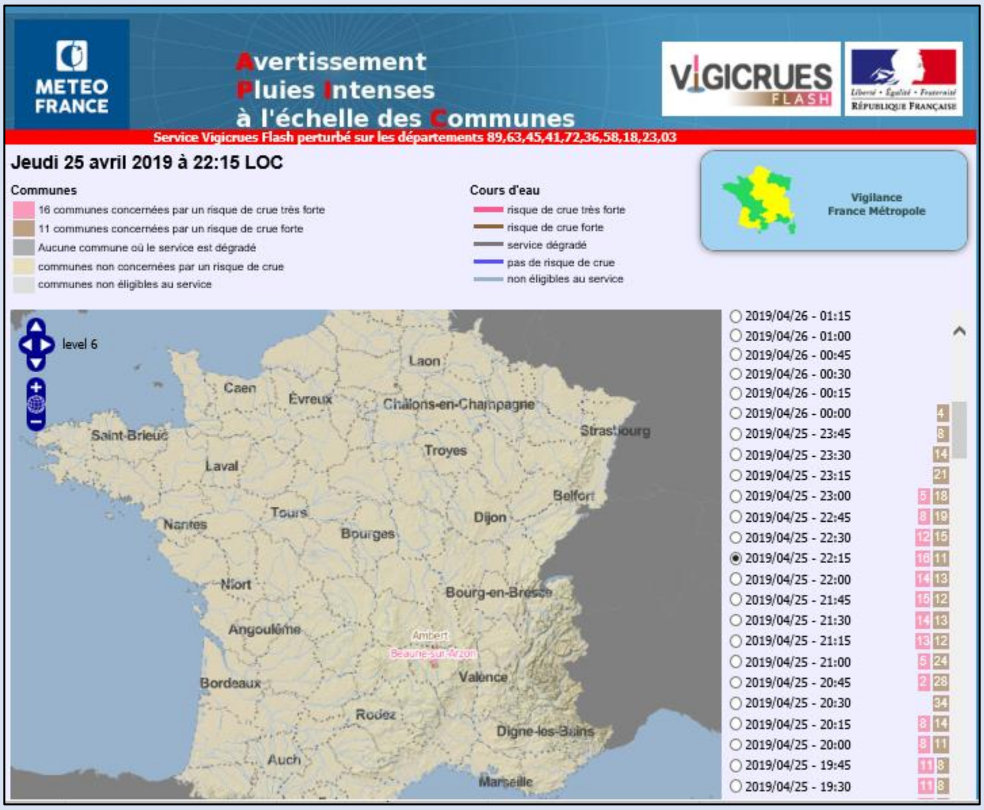
The SWF HIM has been formally validated against 11 recent events (between 2012 and 2014) including assessment of observed flood extents and impacts (for detail see Aldridge and Gunawan, 2016). For the Toon Monsoon in Newcastle in June 2012, the model was shown to perform very well. For the other examples, the validation was less successful, but this was heavily influenced by the availability of observed rainfall data and impacts (as is common of many surface water flooding studies). During operational testing, the SWF HIM was shown to provide more focused guidance than the existing surface water forecasting decision support tool (SWFDST) as shown in Figure 16 which compares the outputs from both models for a surface water flooding event in the Midlands in June 2016 (Boyce, 2019).

Case Study 4: Vigicrues Flash Flood Forecasting Service in France

Background

Between 2002 and 2005, the provision of flood warning activities in France moved from 52 autonomous flood warning units to 22 regional flood forecasting units. The main driver for the change was to improve their ability to predict and forecast flood events with activities coordinated through the Service Central d'Hydrometeorologie et d'Appui a la Prevision des Innodations (SCHAPI) – the national centre for flood forecasting in France. The centre's key concept is that vigilance is not an alert, where vigilance enables the public to be ready to react appropriately if danger materialises – this is promoted through a national flood vigilance map, Vigicrues.

One of the key issues for the national centre is forecasting flash flooding where there is a very short lead time and often no data is available. The AIGA method for flash flood warning was developed by Cemagref and Météo France and is based on a simple 1km^2 distributed hydrological model for rivers, using radar rainfall as input and a soil moisture accounting scheme (Javelle *et al.*, 2012 and Javelle *et al.*, 2016).



Avertissement
Pluies Intenses
à l'échelle des Communes

Service Vigicrues Flash perturbé sur les départements 89,63,45,41,72,36,58,18,23,03

Jeudi 25 avril 2019 à 22:15 LOC

Communes
16 communes concernées par un risque de crue très forte
11 communes concernées par un risque de crue forte
Aucune commune où le service est dégradé
communes non concernées par un risque de crue
communes non éligibles au service

Cours d'eau
risque de crue très forte
risque de crue forte
service dégradé
pas de risque de crue
non éligibles au service

○ 2019/04/26 - 01:15
○ 2019/04/26 - 01:00
○ 2019/04/26 - 00:45
○ 2019/04/26 - 00:30
○ 2019/04/26 - 00:15
○ 2019/04/26 - 00:00 4
○ 2019/04/25 - 23:45 8
○ 2019/04/25 - 23:30 14
○ 2019/04/25 - 23:15 21
○ 2019/04/25 - 23:00 5 18
○ 2019/04/25 - 22:45 8 19
○ 2019/04/25 - 22:30 12 15
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○ 2019/04/25 - 21:45 15 12
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○ 2019/04/25 - 21:00 5 24
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○ 2019/04/25 - 20:30 34
○ 2019/04/25 - 20:15 8 14
○ 2019/04/25 - 20:00 8 11
○ 2019/04/25 - 19:45 11 8
○ 2019/04/25 - 19:30 11 8

Figure 18. **APIC – community scale warning of intense rain on 25th April 2019 (Source: https://apic.meteo.fr/index.php)**

Vigicrues Flash

This national service – Vigiecrues Flash – has been operated by the French flood forecasting centre (SCHAPI) since 2017 and provides warnings for 10,000 municipalities. Using the AIGA method, the system determines rivers exceeding high impact or very high impact thresholds (associated with return period) and are routing published via a web platform as illustrated in Figure 17 (Demargne *et al.*, 2019). Whilst Vigiecrues Flash and the use of the AIGA method is predominantly used for ungauged rivers, the warning system is a surrogate for identifying the potential for pluvial flooding in communities (Dermagne and Javelle, personal communication, 2019).

Integrating nowcasts and impacts to flash flood warning

Whilst Vigicrues Flash system is providing an operational service, there are several limitations in the approach such as limited anticipation (lack of nowcast precipitation) and limited representation of flooding impacts. The

PICS project (Prévision immédiate intégrée des impacts des crues soudaines) intends to address these limitations through coupling various modelling components with short range deterministic and ensemble forecasting (nowcasting) linked to impact-based modelling (Payrastre *et al.*, 2019).

Case Study 5: Surface Water Flood Forecasting for the Commonwealth Games, Glasgow

Background

Glasgow has a known history of surface water flooding. Prior to the Commonwealth Games being held in Glasgow in summer 2014, the SFFS judged that if heavy rainfall was to occur during the event, the existing surface water forecasting capabilities would not be sufficient to support the expected increased briefing requirements. A project team was set up involving experts from the Met Office, SEPA, CEH Wallingford, CREW, James Hutton Institute and Deltares to develop an innovative city scale surface water forecasting model for the Commonwealth Games. The description of the model in this section is taken from Moore *et al.* (2015) and Speight *et al.* (2018).

Modelling approach

The model provided risk-based surface water forecasts on a 1km grid for a 10km x 10km area of central Glasgow (although the actual modelling area was 22km x 22km to account for boundary effects). Based on end-user requirements the forecasts were provided with a 24-hour lead time to support timely and informed decision-making at a local scale. The modelling approach is summarised in Figure 18.

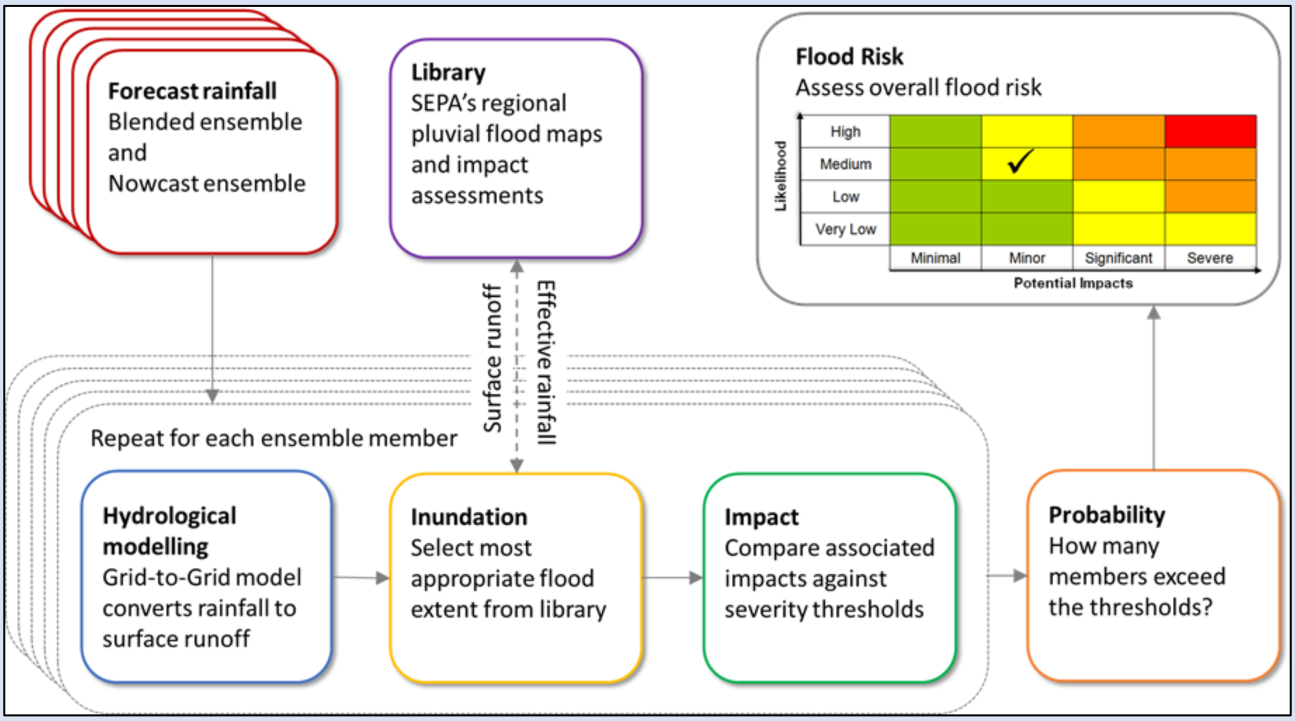


Figure 19. **Forecasting chain for the Glasgow surface water forecasting system (Source: Speight *et al.*, 2018)**

The rainfall input was driven by the Met Office MOGREPS-UK ensemble provided 4 times a day at a 2km resolution. A maximum of 27 forecast hours was chosen to mitigate the effects of increasing uncertainty in forecasting convective rainfall at longer lead times while maintaining the operational requirement for 24-hour lead time. In between the MOGREPS-UK runs, the STEPS nowcast ensemble was also used. This enables the SFFS to review model performance and provide updated forecasts throughout the working day.

G2G was used to convert the forecast rainfall into surface runoff on a 1km grid. The model assumed that the surface runoff from grid to grid was equivalent to the effective rainfall used to produce SEPA's regional pluvial flood maps. The regional pluvial flood maps (produced in JFLOW+) formed a library of flood inundation areas and associated impacts for five different rainfall return periods (10, 30, 50, 100, and 200 years) for two different storm durations (1 and 3 h). This meant that for each 1-km grid square, the most appropriate flood inundation map and impact assessment from the offline library could be identified.

The impacts were grouped into people and property impacts (population, utilities, commercial properties, and community services) and transport (road and rail). Thresholds were specified for each grid cell to convert impacts to the established SFFS impact category. For example, if any of the following were true the grid cell would be classed as having significant impacts; 1-100 residential properties, >2 community services, > 2 utilities, >20 commercial properties, >5m road flooded or > 5m of railway flooded. Further details of the impact assessment are provided in (Moore *et al*., 2015; Speight *et al*., 2018).

Visualisation

The output from the Glasgow surface water forecasting pilot was made available through HTML web reports generated by FEWS. Maps were produced giving a summary for the whole 24-hour period and also for 6hr time steps. The 6-hr time step was chosen to best account for the timing uncertainty within the rainfall forecast ensemble. The full 24-h period could show higher probabilities than the 6-h output by accounting for the probability that the threshold would be exceeded in any of the contributing 6-h periods. An example is shown in Figure 19 of the 24-hour summary for 3 August 2014 when heavy rainfall was experienced in Glasgow. In addition, the surface runoff ensemble showing the maximum surface runoff for each ensemble member over time was available to hydrometeorologists. This enabled the identification of the spread of ensembles in magnitude and time and was useful for adding additional information to the overall risk assessment.

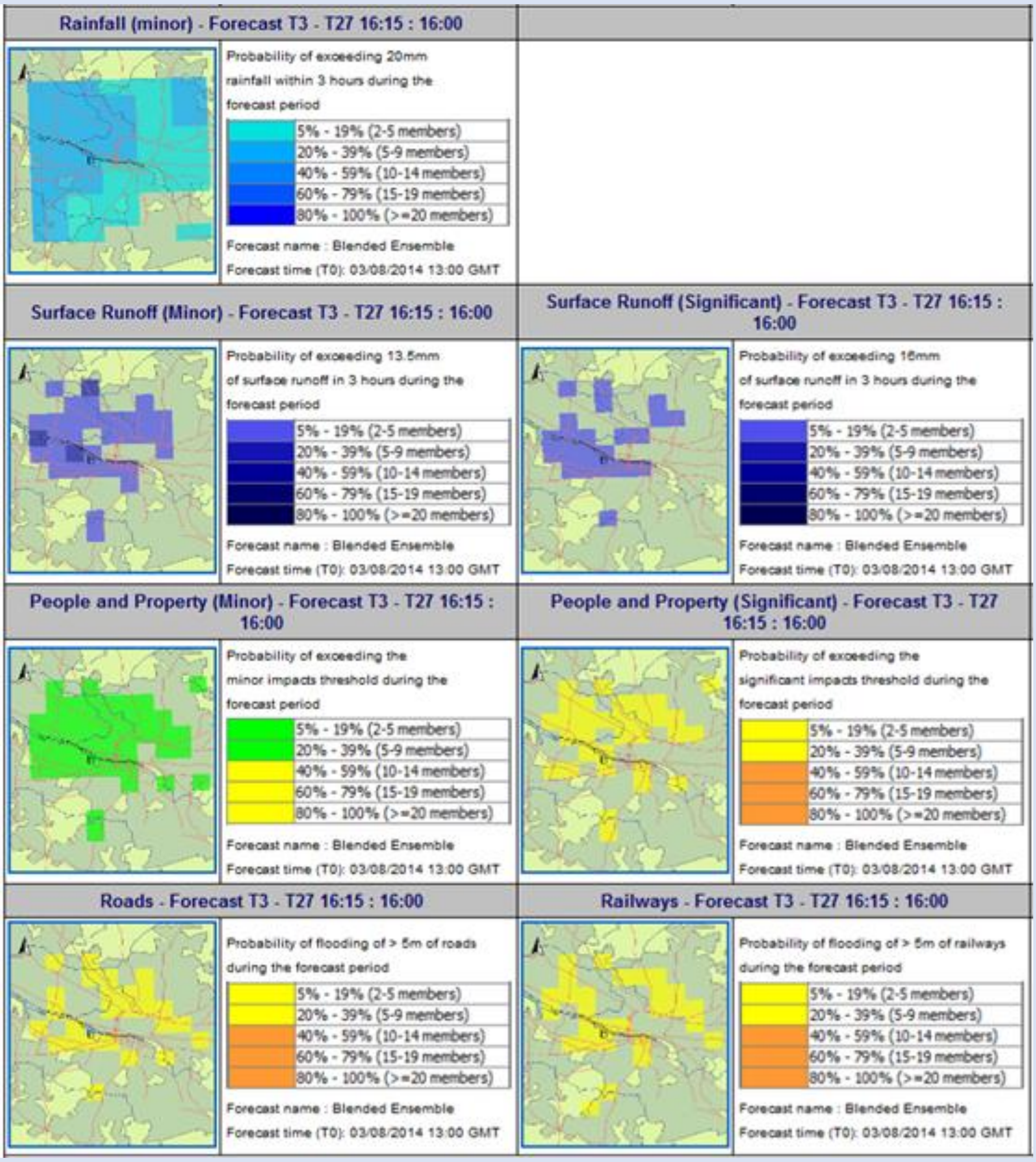


Figure 20. **Visualisation of the precipitation and surface water forecast and predicted impacts on people, property and transport (Source: Speight *et al*., 2018)**

Operational experience

The operational experience of using the Glasgow surface water forecasting model during the summer of 2014 and in particular for the Commonwealth games highlighted some of the operational challenges of city-scale surface water forecasting. Most significantly the low probabilities of impact for specific areas made communication challenging. This also led to a challenge of maintaining a consistent message between the Glasgow forecast and the national FGS and weather warnings, for example on one occasion the FGS highlighted a risk of surface water flooding across south west Scotland but the Glasgow forecasts identified that the chance of any impacts in Glasgow itself was very low. A high staff resource was needed to interpret and communicate the output from the Glasgow surface water forecasting pilot and this needs to be considered in the operational design of any future surface water forecasting systems (Speight *et al*., 2018).

3.3 Hydrological forecasting linked to real-time hydrodynamic simulations at the urban scale

The review of surface water flood forecasting for the Glasgow project (Moore *et al*., 2015) concluded that only G2G and ISIS Fast had the potential to be run in real-time. Five years on there are now several examples of urban hydrodynamic models being run with radar or forecast rainfall as inputs. As part of the FFIR programme, Exeter University has developed new approaches to represent sewers and shallow flood water in urban areas. This has led to faster, more efficient flood models which can represent detailed flows in urban areas and with the potential to run in real-time (an example is shown in Figure 20 for the Coverack flood in July 2017). Cloud computing and GPU (Graphical Processing Units similar to those used in computer games technology) have developed rapidly over the past few years and have become a realistic and affordable way to run computationally demanding models in less time.

The benefit of real-time hydrodynamic simulations is the ability to directly model the forecast spatial variability of rainfall on inundation and impacts at a city scale. Another potential benefit is the potential to set thresholds based on the velocity of flow as this is known to be important when considering a danger to people, movement of vehicles or damage to property (Hofmann and Schüttrumpf, 2019).

Newcastle University has developed two efficient flood models for urban areas HiPIMS (Xia *et al*., 2016) and CityCAT (Glenis *et al*., 2018) and JBA Consulting have been exploring the use of GPU technology to decrease the run time of city-scale hydrodynamic models using their JFLOW model. In Germany, a research project compared the runtime for a hydrodynamic pluvial flooding model of a 36km^2 area of the city of Aachen on a 1m to 3m grid. The results showed that the computational time using the GPU was 10.5 times faster than a standalone CPU but at 4610mins and 439mins respectively (Hofmann and Schüttrumpf, 2019), neither would be suitable for operational surface water forecasting. In this instance, Hofmann and Schüttrumpf (2019) envisage a multifunctional system whereby full hydrodynamic simulations are used to understand more about the flood hazard and validate the model, but a pre-simulated library of flood inundation maps is used in real-time.

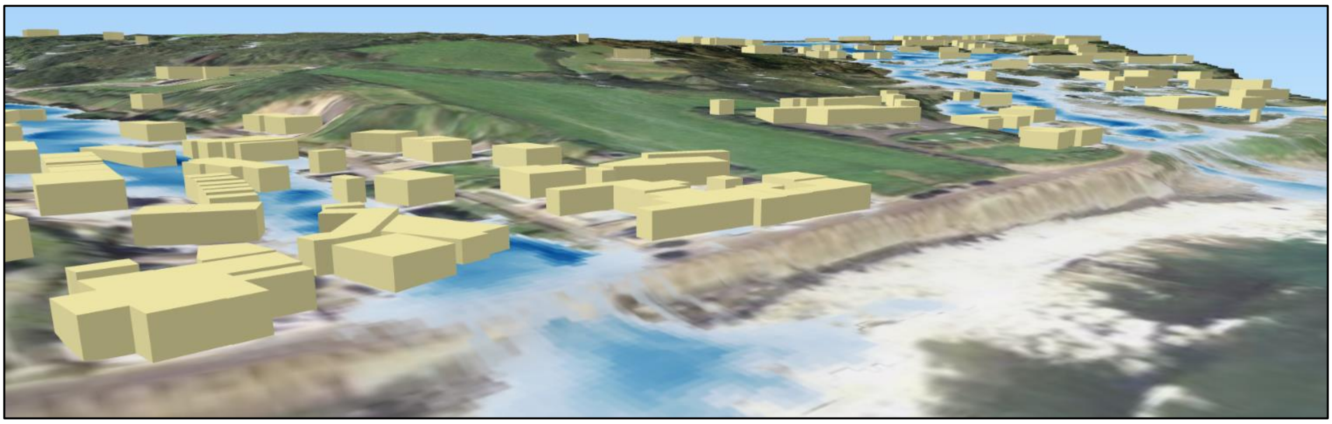


Figure 21. Example of Exeter hydrodynamic model of Coverack flood (Source: Albert Chen, the University of Exeter from the FFIR Research summaries)

While these examples have, to date, only been used offline to investigate case study events in urban areas, Loughborough University has been using their FloodMap-HydroInundation2D (Yu and Coultard, 2015) system with radar nowcasts to provide real-time forecasts of urban flooding (see case study 6). Although there is now the emerging potential to use real-time hydrodynamic simulation at the urban scale there remains a key research question around how much detail do decision-makers need to make informed decisions given the computational costs involved. Like the pre-simulated inundation scenarios, real-time hydrodynamic modelling also has the potential to display results at a more detailed resolution than is appropriate given the known uncertainty in the rainfall forecasts.

This is a question that is currently being investigated by the iCASP project in Yorkshire (see case study 7). This is also an ongoing need for more ingratiation between the researchers developing real-time flood forecasting systems and the users of such systems to understand more about the operational requirements and the compatibility with existing systems and processes (Flack *et al.*, 2019; Speight *et al.*, 2019).

Case Study 6: Loughborough University surface water nowcasting

Background

Flood nowcasting refers to forecasting urban flooding in real-time using the rainfall nowcast as input to a city scale hydro-dynamic model. Loughborough University are not the only organisation to use the term flood nowcasting (see also Willems *et al.*, 2016 who describe a similar approach for Ghent, Belgium using the probabilistic STEPs nowcast), but their work provides a useful example of an operational ready system in use in the UK.

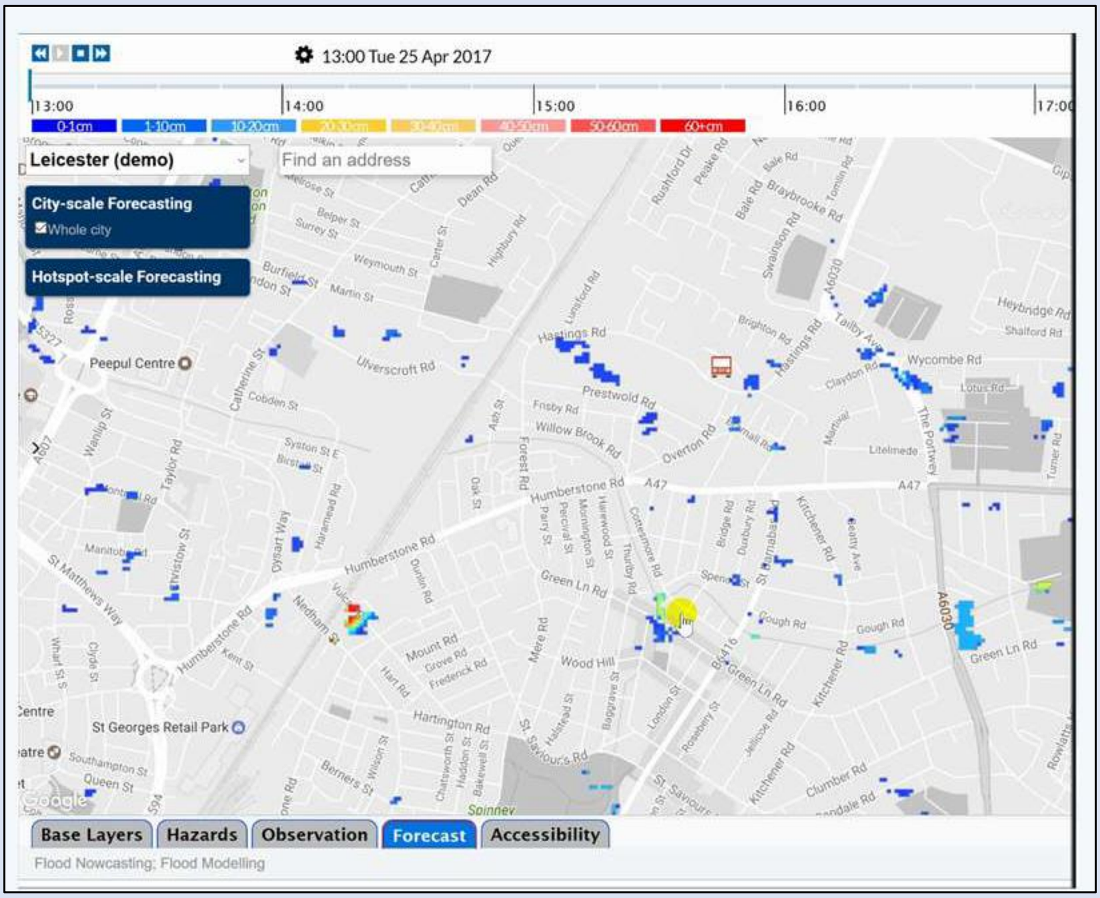


Figure 22. Example of the output available on Resilience Direct. (Source: Yu, 2019)

Flood modelling

The Loughborough system uses FloodMap-HydroInundation2D (Yu and Coultard, 2015) to provide high-resolution flood mapping at a street-level resolution (2-50m). FloodMap integrates surface water runoff modelling with a simplified representation of sewer surcharge in urban areas. It also represents hydrological inflow to the urban area from multiple upstream sources. FloodMap has been validated against a number of urban flood events in the UK including Hull 2007 (Yu and Coultard, 2015), Newcastle 2012 and London 2016 (Yu, 2018) and internationally e.g. Shanghai in China (Yin et al., 2016) and is shown to represent known flood inundation and impacts well.

Input data and validation

Rainfall input for the flood nowcasting system comes from the Met Office 6-hour rainfall Nowcast and is updated every 30 minutes (Yu, 2019). No probabilistic forecast data is used so the system produces deterministic output only. It is unclear if the system includes impact information beyond inundation to the road transport network.

The system was originally developed to help identify access routes for emergency responders during flood events in Leicester (Green *et al*., 2017, Yu *et al*., 2017) and has been well received. Simon Cole the Chief Constable of Leicestershire Police said "It's passed the ultimate test for me which is its met the real people, who do the real stuff, who will be up to their ankles and knees in water at the time, and they thought it was useful" (Loughborough University, 2017). It has since been developed for 30 UK cities (including Edinburgh and Glasgow, Yu, 2019) and real-time is currently available on the Cabinet Office Resilience Direct website for Birmingham, Greater Manchester, Leicestershire, and London.

Future development

The Loughborough University Flood Nowcasting system has been funded by various NERC research grants. The most recent of which (NE/S017186/1, running from February 2019 - January 2020) aims to investigate:

- Uncertainty propagation from precipitation nowcasting and forecasting products to high-resolution surface water flood predictions;
- Effective communication of complex surface water flood risk information;
- Support emergency responders' operational decision-making (Yu, 2019).

The system is already available on Resilience Direct and although it has been developed as a research project, commercial use of the system is supported by Innovate UK's ICURe programme (https://www.lboro.ac.uk/enterprise/floodmap-live/).

Case Study 7: iCASP Enhanced surface water flood forecasts project

Background

Yorkshire's Integrated Catchment Solutions Programme (iCASP) is a 5-year Natural Environment Research Council (NERC) funded the programme. The Enhanced Surface Water Flood Forecasts project is one project within this programme. Accepting that there is an operational need for regional-scale surface water flood forecasts at a finer scale than those provided by the FFC in the FGS, the project seeks to "test the feasibility and usefulness of converting the latest advances in probabilistic rainfall forecasting and high-resolution surface water modelling into real-time forecasts and/or warnings for Lead Local Flood Authorities (LLFAs) and other decision-makers" (iCASP, 2019).

Based in Yorkshire the project team includes key stakeholders such as the Environment Agency, UK Met Office, FFC, local councils and Yorkshire Water. The iCASP project is ongoing and full results are not available at the time of writing. It would be beneficial for SEPA to review the final output from the iCASP project as it seeks to address the question of how to use the latest advances in surface water forecasting to improve decision making.

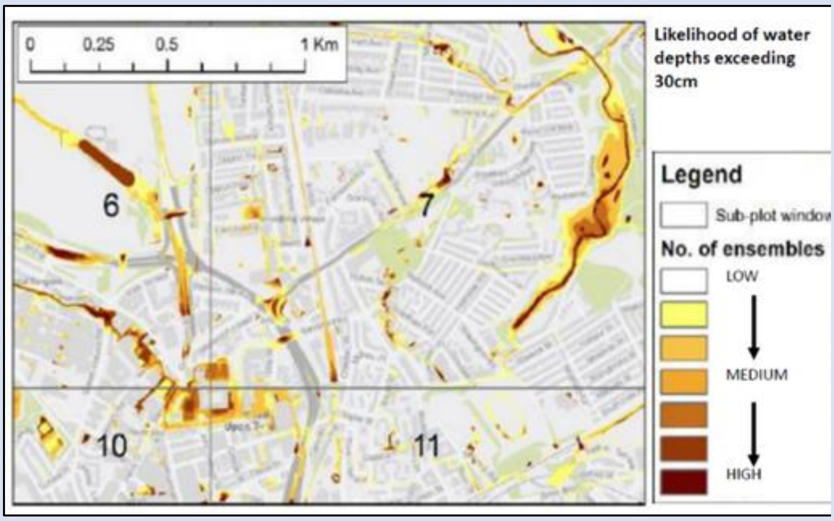


Figure 23. Example of probabilistic surface water flood forecast combining MOGREPS with JFLOW (Source: Rabb 2019)

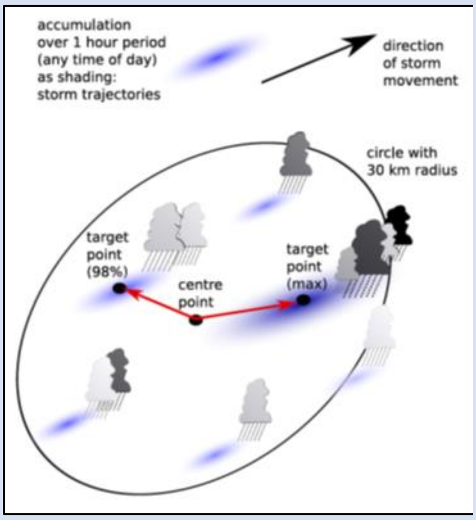


Figure 24. Approach for searching for high rainfall totals within a given radius (Source: Rabb 2019)

Approach to probabilistic forecasting

The iCASP project is working to understand how the latest advances in probabilistic rainfall forecasting and high-resolution hydrodynamic modelling can be combined into probabilistic, forecasts with short lead times for making decisions at a local scale (Boeing *et al*., 2019). One approach being tested is combining the MOGREPS forecast ensemble with JBA's JFlow® flood model as shown in Figure 22.

The project does not aim to produce an operational ready solution for surface water flood forecasts, rather it seeks to test the feasibility and usefulness of different ways of processing and presenting the probabilistic forecasts for decision-makers.

One interesting example is the approach to 'neighbourhood sampling' being trialled which seeks to address the challenge of low probabilities of occurrence of heavy rainfall at individual locations by seeking to identify rainfall within a given radius that could be considered equally likely to fall on the specified location hence increasing probabilities (Figure 23). The findings will feed into the FFC's five-year science strategy to enhance wider benefits (Boeing *et al*., 2019).

Incident Workshop

On 15th March 2019, an incident workshop was held with key stakeholders to test the 'new' forecast products based on a real flooding incident that took place in Leeds on 22nd August 2015. The aim was to see how decision-makers responded to the information they were given (alongside the FGS), and what decisions and actions they would take as a result (Shelton, 2019). The findings from this workshop are still being written up but should include a discussion of the most relevant information to share (rainfall forecasts or flood model outputs) and the most effective means of communication (Rabb, 2019).

4 Monitoring surface water flood impacts in real-time

The nature of surface water flooding often makes it difficult to monitor impacts in real-time. The lack of observations means limited feedback for operational forecasters to review their decision-making and provide real-time updates. They also restrict the options for forecast verification and future development.

A review by Acosta-Coll *et al. (*2018) summarises various approaches in the use of sensors for supporting pluvial early warning systems with examples in Florida, Columbia, the Philippines and Thailand. Remote sensing offers a potentially valuable source of monitoring flood extent data, which given the decline of field observations could be of value especially in remote areas and developing countries (Domeneghetti *et al.*, 2019). Whilst using sensors and remote sensing provides a structured approach to monitoring in support of surface water early warning, it's potentially crowdsourced information which offers the greatest potential for operating authorities (See, 2019).

The aim of this section is to present current approaches for observing, measuring or monitoring surface water flooding impacts. This section will also present some emerging techniques to support the observation of surface water flooding impacts in real-time.

4.1 Sensors

Monitoring using sensors is a traditional means of capturing and detecting flooding impacts, however, the cost of formal monitoring networks often restricts meaningful observations of urban flooding.

Using crowdsourcing techniques to increase the coverage of monitoring networks is an emerging area. The development of the RiverTrack device is seen as a vital community engagement tool for at-risk communities in Scotland, with low-cost sensors linked to households and community displays providing important hyper-local information on flooding (Scottish Government, 2019). These devices are now being linked to flood forecasts to provide an early warning system of flash floods on small rivers in Spain (Cranston, Martin and Smith, 2019).

Of most relevance to pluvial flooding may be the FloodCitiSense project (2017-2020), Figure 24, which aims to integrate crowdsourced hydrological data, collaboratively monitored by local stakeholders (city authorities), including citizens, making use of low-cost sensors and web-based technologies into an early warning system for urban pluvial flooding (Verbeiren *et al*., 2019). Three European pilot cities were targeted; Brussels, Rotterdam and Birmingham. Expected results include an operational crowdsourced data collection 'FloodCitiSense' platform in pilot cities, urban pluvial flood warning systems co-created in living labs and a summary of lessons learnt of the crowdsourcing and co-creation of flood EWS.

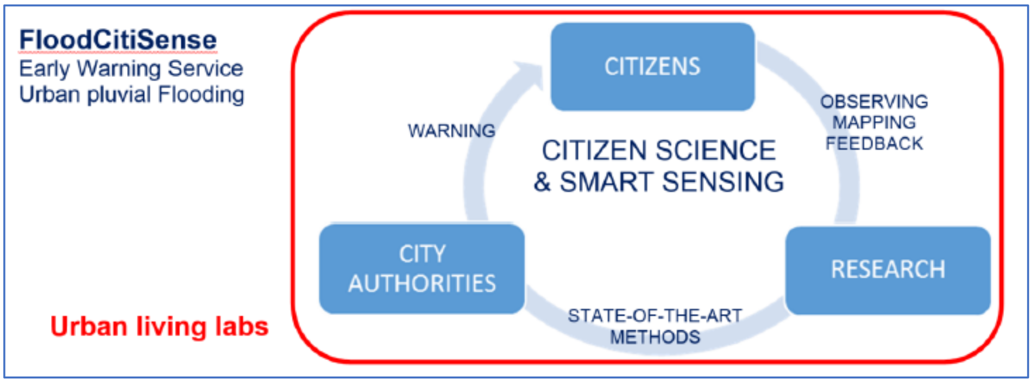
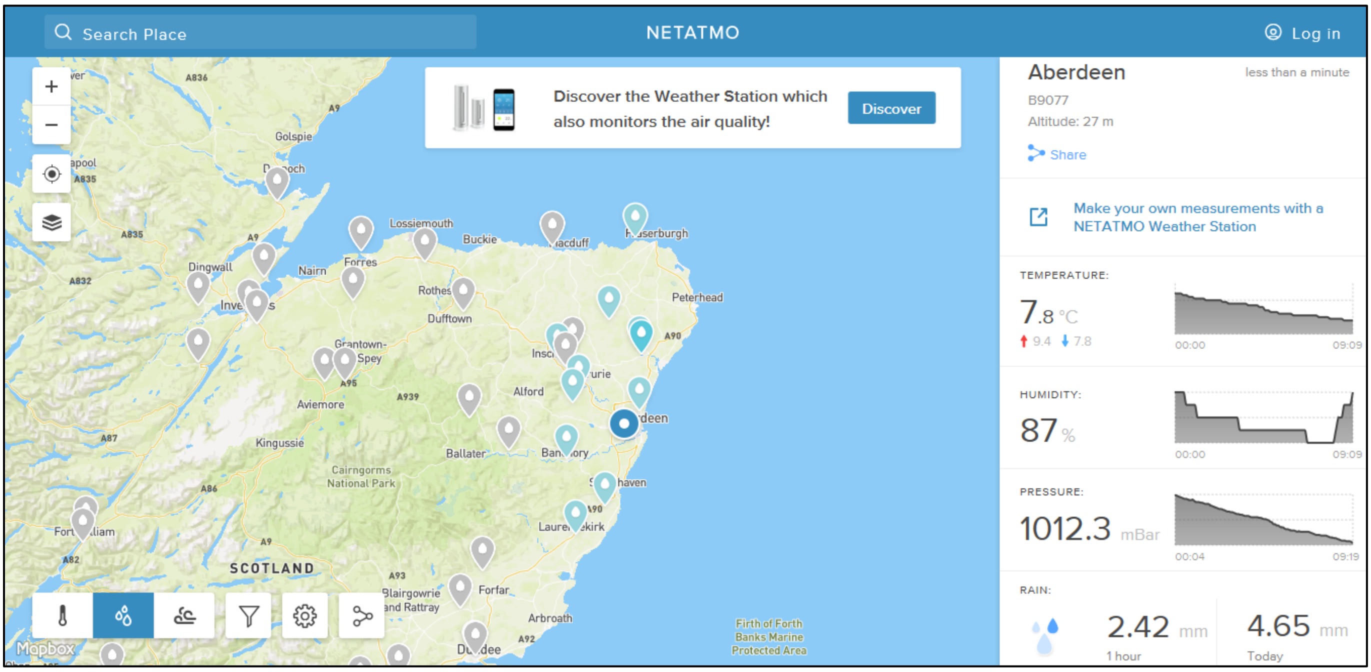


Figure 25. FloodCitiSense – an early warning service for urban pluvial floods for and by citizens and city authorities (Source: Verbeiren *et al*., 2019)

Further afield, De Guzman *et al. (*2016) developed a flood detection system to automatically detect flooding and send the data to the Local government Unit and to residents in the Philippines via an SMS advisory service providing notifications on flooding. The tools comprised an Arduino Yun microcontroller board, LED, ultrasonic sensor, solar power bank, camera (showing a live stream of flooding events) and a software user interface. The conclusion was a recommendation to the local government to consider this study for implementation.

Personal weather stations maintained by weather enthusiasts or amateur meteorologists can provide an alternative crowdsourced network of rainfall information. Weather platforms such as NetAtmo (see Figure 25) collate and visualise this data in real-time. Whilst data from these low-cost sensors are vulnerable to data quality issues, work by de Vos *et al. (*2019) to quality control this data, have demonstrated the feasibility of using such crowdsourced rainfall observations for high-resolution countrywide monitoring of rainfall.



Discover the Weather Station which also monitors the air quality!

Aberdeen
less than a minute
B9077
Altitude: 27 m
Share

Make your own measurements with a NETATMO Weather Station

TEMPERATURE: 7.8 °C (9.4, 7.8)
HUMIDITY: 87 %
PRESSURE: 1012.3 mBar
RAIN: 2.42 mm 1 hour; 4.65 mm Today

Figure 26. NetAtmo – an international weather enthusiast data gathering portal. Image showing real-time data for North East Scotland on 13th June 2019 (Source: https://weathermap.netatmo.com, 2019)

An emerging research area is in the area of data assimilation for urban flood prediction. Work by the University of Reading is looking at techniques that combine model forecasts and observational data to improve urban predictions. These techniques will take account of short spatial and temporal timescale and nonlinearity of observations such as satellite images, CCTV and smartphone images. Hintz *et al. (*2018) provide a useful summary of the emerging developments in collecting and utilising crowdsourced data for numerical weather prediction.

4.2 Remote Sensing

The use of satellite data to identify flood water in urban areas could be a tool to assist operational response. Examples are based on fluvial flooding in urban areas (from the Thames and the Severn) but potentially the same approach could be used for severe surface water flooding (Mason *et al*., 2018). Some strengths include real-time observations of flood extents rather than relying on social media or other reports of impact. However, for pluvial flooding limitations would include the potential processing time, cloud cover and extent uncertainties limiting suitability for surface water flooding and availability of satellites – again less reliable for short duration surface water events.

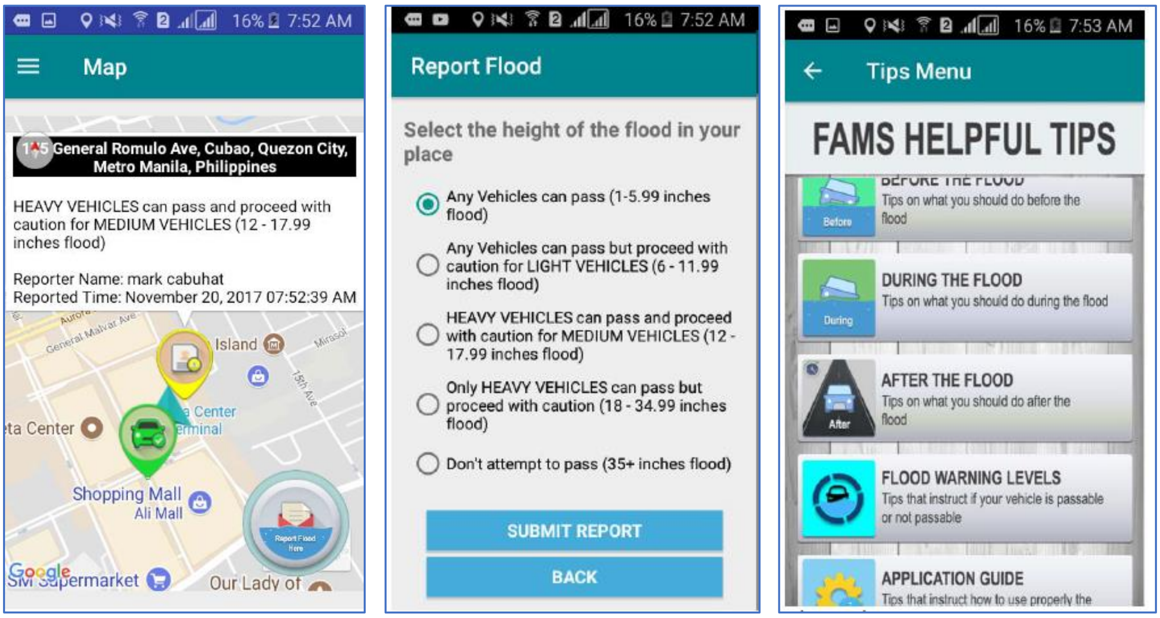
Copernicus is the European system for monitoring using satellites and supports the Copernicus Emergency Management Service. This service provides information for emergency response in relation to various disasters including floods (Boccardo and Tonolo, 2014).   However, whilst this system offers value to near real-time flood hazard mapping and risk assessment (Dottori, 2015), its application may be limited to larger rivers and fluvial flooding.

Another emerging approach to remotely capturing flood extent information is through the use of unmanned aerial vehicles (UAVs). Perks *et al.* (2016) demonstrate the use of such approaches for capturing flash flood information for flooding on the Alyth Burn, Scotland. However, as with the use of satellites, being able to quickly deploy and capture pluvial flood extents remains a challenge.

4.3 Crowdsourcing

Data collection which involves citizens is called ‘citizen science’ or ‘crowdsourcing’ (See, 2019). The data can be used to calibrate and validate flood forecasting models or contribute to an early warning system (EWS) by refining the thresholds of the alerts issued. Techniques for monitoring in real-time can be categorized into automated flood detection, social media, online reporting and mobile apps as discussed below with examples (See, 2019). Using crowd-sourced images for flooding detection is associated with many challenges including the presence of reflection and shadow from nearby structures and overhead cloud/sky. Specific examples include:

- The Met Office Weather Observations Website (WOW) (International) – online reporting. The WOW website, an online reporting tool, was launched in June 2011 by the Met Office Public Weather Service, with support from the Royal Meteorological Society and the Department for Education, to provide a platform for the sharing of current weather observations and include specific categories for rainfall rate (Met Office, 2019a).
- Report-a-flood (Scotland) – online reporting. SEPA’s ‘report a flood’ tool is a tool which enables anyone to report and share current flooding issues across Scotland. Reports are sourced by members of the public (typically through the Floodline service) or organisations and can help alert people to localised flooding (SEPA, 2019).
- Arduino Mobile Flood Report App (Philippines) – mobile app. Amagsila *et al.* (2018) presents an Android mobile application to monitor flood conditions and notify vehicle users about flood conditions, via voice notification. Using an Arduino microcontroller device to detect the height of the flood. The mobile app includes a map module, a reports module (users can send in their reports of flooding) and a tips module (on what to do before, during and after a flood, and meaning of flood levels). There is also a web application (Figure 26).



HEAVY VEHICLES can pass and proceed with caution for MEDIUM VEHICLES (12 - 17.99 inches flood)

Reporter Name: mark cabuhat
Reported Time: November 20, 2017 07:52:39 AM

Select the height of the flood in your place

● Any Vehicles can pass (1-5.99 inches flood)
○ Any Vehicles can pass but proceed with caution for LIGHT VEHICLES (6 - 11.99 inches flood)
○ HEAVY VEHICLES can pass and proceed with caution for MEDIUM VEHICLES (12 - 17.99 inches flood)
○ Only HEAVY VEHICLES can pass but proceed with caution (18 - 34.99 inches flood)
○ Don't attempt to pass (35+ inches flood)

BEFORE THE FLOOD
Tips on what you should do before the flood

DURING THE FLOOD
Tips on what you should do during the flood

AFTER THE FLOOD
Tips on what you should do after the flood

FLOOD WARNING LEVELS
Tips that instruct if your vehicle is passable or not passable

APPLICATION GUIDE
Tips that instruct how to use properly the

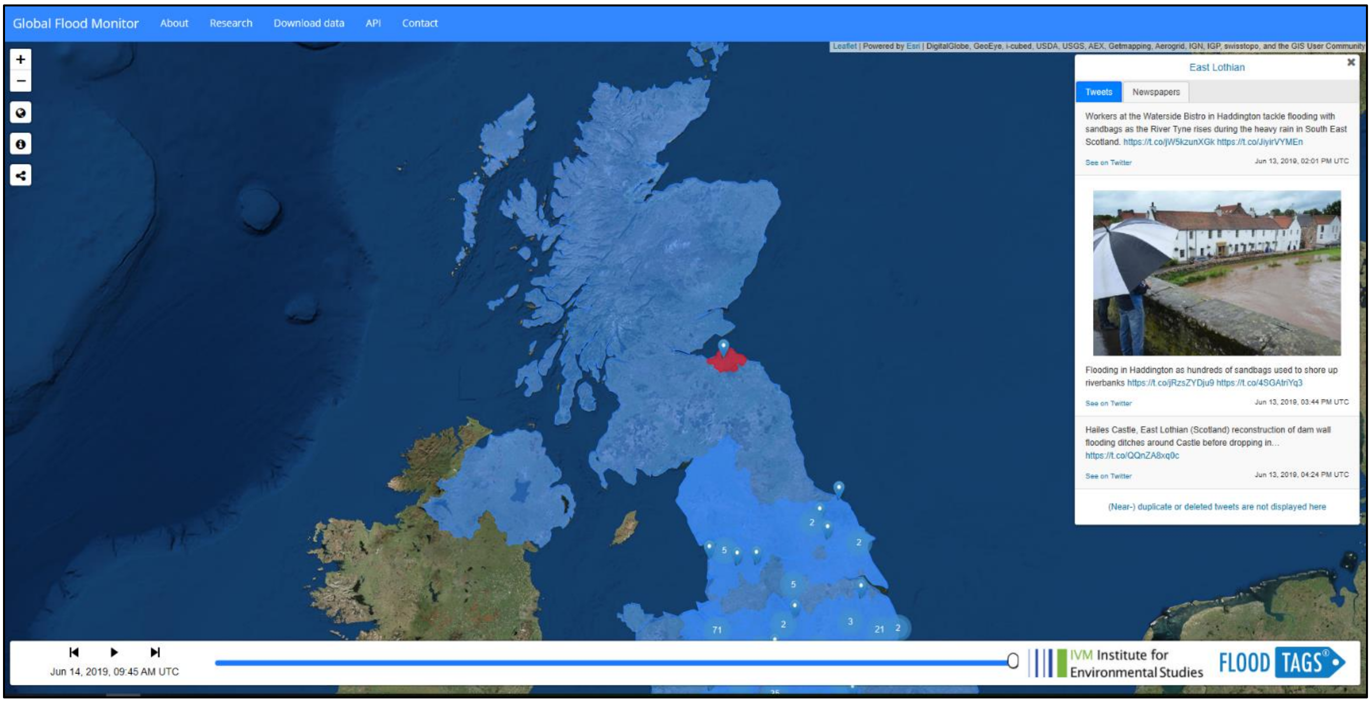
Figure 27. Arduino mobile flood reporting app in the Philippines aimed at vehicle users (Source: Amagsila *et al.*, 2018)

Emerging developments in crowdsourcing across social media include developments at the Flood Forecasting Centre. Work to develop a *Media Gathering Virtual Assistant* will commence aiding the real-time verification of flooding impacts. Formerly called Social Sense Flood Impact Verification (Twitter) Project, this will support the development of a tool to support objective verification of the Flood Guidance Statement across England and

Wales using social sensed data including Twitter. The driver to improve the verification process (of surface water flooding) by increasing visibility of flooding impacts to the verifier (Forecaster) (Pilling, *pers. comm.*, 2019).

One such application which is being developed through the ANYWHERE (Enhancing Emergency Management and Response to Extreme Weather and Climate Events) Horizon 2020 programme. The ANYWHERE social media and crowdsourcing application have been designed based on extensive assessment of available tools. The ANYWHERE programme has the advantage of having various stakeholders on board that has enabled co-design of the crowdsourcing platform together with final end-users such as civil protection authorities (Kalos, 2019). The early warning system integrating the crowdsourcing module is currently being piloted across several European countries.

One such live system that utilises social media to report flooding is the Global Flood Monitor (see Figure 27). The system provides a real-time overview and historical report of flooding based on data filtered from the platform Twitter. The platform applies geoparsing algorithms to extract and locate the geographical location of the Tweet (de Brujin *et al*., 2018).



Workers at the Waterside Bistro in Haddington tackle flooding with sandbags as the River Tyne rises during the heavy rain in South East Scotland. https://t.co/jW5kzunXGk https://t.co/JiyirVYMEn

Jun 13, 2019, 02:01 PM UTC

Flooding in Haddington as hundreds of sandbags used to shore up riverbanks https://t.co/jRzsZYDju9 https://t.co/4SGAtriYq3

Jun 13, 2019, 03:44 PM UTC

Hailes Castle, East Lothian (Scotland) reconstruction of dam wall flooding ditches around Castle before dropping in... https://t.co/QQnZA8xq0c

Jun 13, 2019, 04:24 PM UTC

(Near-) duplicate or deleted tweets are not displayed here

Figure 28. Live reporting of flooding from Twitter on the platform Global Flood Monitor on 14th June 2019 highlighting reports in East Lothian (Source: www.globalfloodmonitor.org)

Witherow *et al.* (2018a) proposed a method for extracting street inundation information from crowdsourced images taken at near ground level. Images at this level provide a local perspective on roadway inundation. The crowdsourced images of flooding were taken in the city of Norfolk, Virginia and analysed, using an image processing pipeline algorithm, to extract the inundated area. The images were compared to images of the area under dry conditions. The results of the algorithm were validated by quantitative evaluation. It was concluded that future methods should focus on gathering data from a camera fixed to a stationary location, due to the challenges in the recreation of perspective and angle from images under dry conditions.

This study was further developed in Witherow *et al.* (2018b) which offered improved overall flood detection accuracy when compared to Witherow *et al.* (2018a). The used an object removal system consisting of 3 operations: 1) object detection; 2) water edge detection, and 3) object removal by inpainting. These methods helped to create a more robust and dynamic flood detection.

Smith *et al.* (2017) present a real-time modelling framework to identify areas likely to have flooded using data obtained only through social media (Twitter). Newcastle upon Tyne is used as a case study. The methodology involved development of a process to extract georeferenced information from tweets on flooding (i.e. locations, flood depth and disruption). This crowd sourced information was then used in graphics processing unit (GPU) accelerated hydrodynamic modelling to simulate flooding in a 48km^2 area of Newcastle upon Tyne. The results of the model simulation were automatically compared against the flooding identified through the Twitter data in order to find a single model simulation which best matched the known flooding. This approach eliminates the need for obtaining rainfall observations during the event which may not be available due to the location of rain gauges and the spatial variability of rainfall patterns. Once the best match simulation was found, this allowed inundation to be inferred elsewhere in the city where no tweets were available. For example, Twitter data informed the model that a specific road was flooded in the city and that water was travelling through back gardens and collecting near a junction with Danby Gardens. Even though there no Twitter data available to indicate any flooding in the Gardens, the model simulation showed a small area of flooding here.

As with the examples provided in this section and as Brouwer *et al.* (2017) report, crowdsourcing social media reports of flooding can provide useful estimates of flood extents and could aid operational response and decision-making. There are limitations associated with extracted valuable information and as Smith *et al.* (2015) note, this use may be better suited to incident management applications rather than forecasting, although work in the ANYWHERE programme is moving towards this integration.

5 Discussion

The preceding Sections 2–4 have identified and reviewed the current state of science relevant to surface water flood forecasting, focusing on the existing use of observations and precipitation forecasts, the range of surface water flood forecasting approaches available (at both the local and large scales), and the monitoring of surface water flood impacts in real-time. In this section, these findings are discussed relative to the key challenges and recommendations associated with the improvement of surface water flood forecasting in Scotland, including precipitation forecast uncertainty and lead time, together with a summary comparison of the advantages and disadvantages associated with the various approaches to surface water flood forecasting, and their suitability to make future improvements to surface water flood forecasting in Scotland.

5.1 Key challenges and recommendations

Precipitation forecast uncertainty

Convection-permitting NWP has developed significantly over the past 5-10 years. The UK Met Office UKV model, for example, can produce realistic forecasts of convective rainfall on a 1.5km grid for lead times of up to five days, although users need to be cautious about the exact location of rainfall particularly at very short lead times (i.e. less than 2 hours) and at longer lead times (i.e. greater than 48 hours). The developments in radar processing, data assimilation and nowcasting will soon lead to further improvements in the ability to observe and model convective features at the shorter lead times, however, even within the nowcasting timeframe (<6 hours), the use of probabilistic forecasts will remain essential to support surface water flood forecasting due to the high degree of uncertainty in forecasting convective rainfall.

The recent improvements to MOGREPS-UK are at the forefront of international best practice for convective forecasting with an 18-member ensemble updated every hour providing information up to 5 days ahead. Any surface water flood forecasting methodology should seek to make the best use of this valuable information alongside the STEPS nowcast at shorter lead times. SEPA's HRA tool already utilises this data, however, interpretation of probabilistic forecasts remains an active area of research at both the UK Met Office and internationally. Hydrometeorologists need to continue to actively work with meteorologists and academics to improve the interpretation of probabilistic forecasts to support surface water flood forecasting. For example, by understanding when forecasts are likely to be able to capture the uncertainty within the forecast and when they might perform poorly and continuing to develop expert interpretation skills by reviewing forecast performance for past events. Hydro-meteorologists should also seek to have an active involvement in the development of post-processing techniques. Such techniques could balance the requirement to smooth the grid scale ensemble forecasts to reflect the location uncertainty of rainfall with the need to provide flood forecasts with targeted information for responders.

Given the known challenges of forecasting convective rainfall at small scales the probabilities of heavy rainfall that could lead to surface water flooding will continue to remain low. The communication challenge that this presents for all parties will continue to be an active research area for the foreseeable future. Hydrometeorologists should seek to understand more about the implications of this uncertainty on decision-makers. Accepting that there is a scientific limit to the predictability of convective rainfall, work can then begin on developing surface water flood forecasting methods to support decision-making that that make full use of the current state of the art of probabilistic rainfall forecasts but with a realistic consideration of uncertainty.

Lead time

The recent increase of MOGREPS-UK from 36 hours to 5 days has unlocked the potential to provide probabilistic convection-permitting flood forecasts at longer lead times. During the 2014 Glasgow Commonwealth Games pilot, only a 36-hour lead time was provided by MOGREPS-UK (although concerns over the increasing uncertainty at longer lead times led to limiting the lead time further to 24 hours). The increased number of ensemble members combined with longer lead times now available in MOGREPS-UK should help reduce the forecast uncertainty.

The NHP surface water forecasting HIM also takes full advantage of the recent improvements to MOGREPS-UK forecasts and provides a lead time of up to 5 days. This model is designed to support the production of the FGS, providing forecasts for experts to use alongside other sources of information and at a broad county level. Given the known location and timing uncertainties in convection-permitting NWP, the use of the full 5-day ensemble may not always be appropriate for other applications, particularly if this information is being shared with a wider audience.

These two examples of pre-simulated impact scenarios are the only examples of operational systems we were aware of in this review that provide forecasts on lead times beyond 3-6 hours. The reasons other operational systems have much shorter lead times are either due to a focus on radar or nowcasts as forecast input or due to the high computational demands of running a full ensemble through a real-time hydrodynamic model (which is currently not feasible in real-time). The stakeholder steering group from the 2014 Glasgow Commonwealth Games pilot identified a critical operational requirement for forecasts at a 12-hour lead time to enable proactive preparation, a need that was echoed in the iCASP project. The review of operational surface water flood forecasting methods did not identify any real-time hydrodynamic methods that could offer lead times of beyond 6 hours. Stakeholders in the Glasgow project were aware of the uncertainties in surface water flood forecasts but were better able to use detailed information at the 6-24-hour lead time in decision-making than more general information at longer lead times.

Where longer lead time forecasts are required, for example, to help plan staff resources within hydrometeorological forecasting centres an ‘early heads up’ of the potential for convective activity that could lead to surface water flooding, this can be found by using meteorological information such as the CAPE index or perceptible water content (as used by the FFC). This information is available at lead times beyond 5 days using medium-range ensembles from ECMWF. Champion *et al.* (2019) also did some work as part of the FFIR programme to identify the large-scale synoptic drivers of intense rainfall in the UK allowing identification of potential for convective activities weeks ahead of impacts which could help improve preparedness (Flack *et al.,* 2019).

Use of crowdsourced data

The use of data collection by citizens (known as crowdsourced data) has become popular in recent years for monitoring flooding in real time. The most common techniques appear to be the use of online reporting platforms and social media data.

Examples of online reporting platforms, with good success to date, include the Met Office Weather Observations Website and SEPA’s report-a-flood. Considerations here could be given to creating coinciding apps given the popularity of apps with the general public today, and subsequent marketing campaigns to inform the public of them and encourage their use.

Examples of systems using twitter data include the Global Flood Monitor, a live system providing a real-time overview and historical report of flooding based on filtered Twitter data (de Brujin *et al*., 2018). Smith *et al.* (2017) present a real-time modelling framework to identify areas likely to have flooded for a case study in Newcastle upon Tyne. And developments at the Flood Forecasting Centre are focused on developing a Media Gathering Virtual Assistant to support the development of a tool which will provide real-time verification of flooding impacts (i.e. verification of the Flood Guidance Statement across England) using Twitter data.

As the examples show, crowdsourcing social media reports of flooding can provide useful estimates of flood extents and could aid operational response and decision-making, however, there are limitations associated with the extracted information. Currently, such information may be better suited to incident management applications rather than forecasting, although work in the ANYWHERE (Enhancing Emergency Management and Response to

Extreme Weather and Climate Events) Horizon 2020 programme is moving towards this integration. It is currently being piloted across several European countries (Kalos, 2019).

5.2 Advantages and disadvantages of the methodological approaches to surface water flood forecasting in Scotland

Table 1 provides a comparison of the advantages and disadvantages of the operational flood forecasting methodological approaches presented in Section 3 of 1) Empirical-based rainfall scenarios, 2) Hydrological forecasting linked to pre-simulated impact scenarios, and 3) Hydrological forecasting linked to real-time hydrodynamic simulations at the urban scale, including comments on the operational challenges of each approach and their suitability for use in Scotland.

Each of the case studies reviewed in Section 3 had a different objective (e.g. to inform national flood guidance, or to provide local detail to emergency responders), therefore it was not possible to review them against the general objective of improving flood forecasting in Scotland. Instead, in this Section, we provide a general assessment on the potential of each of the methodological approaches below (classified in Figure 6) to support surface water flood forecasting in Scotland, with the summary data provided in Table 1.

Empirical-based rainfall scenarios

These are widely used and provide a good ‘first guess’ early warning of the potential for surface water flooding. Recent improvements to convection-permitting NWP have improved their reliability, however, they do not take account of real-time changes to vulnerability and cannot provide detail at the local scale. In most cases, they are used alongside other sources of information. There is potential to link empirical-based solutions such as the HRA, which can provide early warnings at lead times of up to 5 days, with local sensor-based systems to provide updated local warnings at lead times of less than 6 hours. By working with research scientists to improve the post-processing of ensembles and through working with end users to improve communication of probabilistic forecasts, there is potential for these systems to provide a useful low-cost early warning for surface water flooding.

Hydrological forecasting linked to pre-simulated impact scenarios

This approach is becoming widely used for both surface water and fluvial flood forecasting at a range of scales. It provides a compromise between incorporating the spatial and temporal variability of rainfall and impacts with computational resources. By using a pre-simulated impact scenario approach, it is possible to provide a fully risk-based forecast out to five days in advance. At a national scale this approach has been shown to provide a more targeted forecast than empirical-based rainfall scenarios alone. The approach is sensitive to the way that impact and probability thresholds are calculated which can result in reporting inconsistencies between scales.

Hydrological forecasting linked to real-time hydrodynamic simulations at the urban scale

While this approach potentially enables a fully hydrodynamic real-time simulation of rainfall, inundation and impact it remains an emerging computational capability. There are a number of models that could be used to generate forecasts for individual cities which have been proven to accurately model the inundation extent and impacts from past events. The surface water nowcasting example was well received by end users, however, without significant investment in computational resources, this approach cannot meet the scientific requirements of using ensembles to account for forecast uncertainty or provide forecasts with lead times of greater than 6 hours.

Table 1 Comparison of surface water flood forecasting approaches

	Operational examples reviewed in this report	Advantages	Disadvantages	Operational challenges	Suitability for Scotland
Empirical-based rainfall scenarios	Environment Agency / FFC Extreme Rainfall Alert (ERA) FFC Surface water flooding decision support tool (SWFDST) Met Office MOGREPS-W system to inform National Severe Weather Warning Service (NSWWS) SFFS Heavy Rainfall Alert (HRA) USA Flash Flood Guidance System Spanish radar-based early warning system Local trigger- / sensor-based warning systems	• Low development and running costs • Quick to use • Probabilistic approaches possible • Minimal computational requirements allow full use of convection-permitting NWP providing lead times of up to 5 days • Improvements to convection-permitting NWP immediately benefit therefore systems are becoming more trusted • Continual validation against observed events possible • At a local scale, can encourage community engagement • Simple automated operational systems can support multiple end-user needs	• Trigger-based systems using observed rainfall offer limited lead times • Systems using deterministic forecasts provide no account of uncertainty • Probabilistic systems are reliant on some form of post-processing that can make them difficult to interpret • Thresholds are static and do not take account of hydrological or hydraulic process or changes invulnerability	• Usually used alongside other approaches • Requires expert knowledge and experience to interpret	• The national system already in use and being continually developed • Provides a useful national-level overview • The current system is not suitable for providing detail of impacts at a city scale, but additional low-cost local scale trigger-based systems could be developed using existing or crowd-sourced rainfall data

Hydrological forecasting linked to pre-simulated impact scenarios (national scale)	Natural Hazard Partnership Surface Water Hazard Impact Model for the FFC French Vigicrues Flash Flood Forecasting Service	• A quick and integrated approach • Offers compromise between computation requirements, lead time and detailed assessment • Makes good use of existing available data • Allows consideration of probabilistic forecasts in a risk-based approach • Relatively low computational requirements allow full use of convection-permitting NWP providing lead times of up to 5 days • Accounts for spatial variability of rainfall, antecedent conditions and impacts • Suitable for providing information on regional level timings and impacts to support responders	• Reliant on quality of existing hydraulic modelling and inundation mapping • Limited lead times if only observed rainfall or nowcasts are used • Ensemble forecasts are required to take account of uncertainty for a fully risk-based system • Reliant on having a large enough library of pre-simulated scenarios to represent the forecast rainfall event • No direct accounting for real-time hydraulic processes or changes in vulnerability as the hydrodynamic model is pre-simulated • Challenging to aggregate between finer-scale detail of pre-simulated inundation and impact scenarios and regional scale reporting framework • Limited local detail	• Existing inundation mapping and impact assessments are at a finer resolution than can be justified by the uncertainty in rainfall forecasts • Consideration of appropriate reporting scales requires assumptions around aggregation of impacts • Remaining research needs to identify what information is needed from the system to support decision-making	• SEPA could adopt an approach similar to the FFC to support the provision of national scale surface water flood forecasts in the FGS • Further research would be required to establish appropriate impact thresholds and reporting scales for Scotland

	Operational examples reviewed in this report	Advantages	Disadvantages	Operational challenges	Suitability for Scotland
		• Becoming more widely used with widespread ongoing scientific programs to enhance capabilities			

	Operational examples reviewed in this report	Advantages	Disadvantages	Operational challenges	Suitability for Scotland
Hydrological forecasting linked to pre-simulated impact scenarios (regional scale)	Glasgow surface water flood forecasting pilot for the 2014 Commonwealth Games	• A quick and integrated approach • Designed to support city scale decision-making • Offers compromise between computation requirements, lead time and detailed assessment • Makes good use of existing available data • Allows consideration of probabilistic forecasts in a risk-based approach • Accounts for spatial variability of rainfall, antecedent conditions and impacts • Relatively low computational requirements allow full use of convection-permitting NWP providing lead times of up to 5 days (although this may not be justified scientifically) • Suitable for providing detailed information on location, timings and impacts to support responders	• Reliant on quality of existing hydraulic modelling and inundation mapping • Reliant on having a large enough library of pre-simulated scenarios to represent the forecast rainfall event • Ensemble forecasts essential to account for uncertainty in rainfall at city scale • May give more detail at the local scale than can be justified by science • Probabilities will remain low for small areas resulting in a communication challenge and potential inconsistency with national products • No direct accounting for real-time hydraulic processes or changes in vulnerability as the hydrodynamic model is pre-simulated	• Operational experience showed a high staff resource was needed to interpret and communicate the output	• SEPA could develop a similar approach to Glasgow in other cities making use of existing surface water flooding maps and utilising the recent improvements to MOGREPS UK • Requires consideration of how city scale forecasting would be integrated with the existing FGS and regional Flood Alerts

	Operational examples reviewed in this report	Advantages	Disadvantages	Operational challenges	Suitability for Scotland
Hydrological forecasting linked to real-time hydrodynamic simulation at the urban scale	Surface water nowcasting (Loughborough University)	• Designed to support city scale decision-making including providing detail down to the street level • Demonstrated to run fast enough to support real-time decision-making • Includes real-time hydraulic modelling component • Directly models spatial variability of rainfall on inundation and impact at city scale • Potential to set warning thresholds based on the velocity of flow • Surface water nowcasts already available on Resilience Direct (for some UK cities)	• Computational requirement challenging for useable lead times • Needs to be probabilistic to account for uncertainties in rainfall forecast and this has currently not been demonstrated in real-time • Requires flood forecasters to understand the modelling assumptions of new hydraulic modelling approaches • The existing surface water nowcasting approach provides limited options for supporting a broad range of end users needs due not using probabilistic forecast, limited impact data and short lead times	• Still an emerging capability • Computational run-time remains high • Benefits of approach (in terms of improvement to decision-making) compared to pre-simulated scenarios have not been demonstrated	• Offers potential support detailed city scale flood forecasting • The use would require considerable investment in GPU technology and/or computing resources • Requires consideration of how city scale forecasting would be integrated with the existing FGS and regional flood alerts

6 Concluding remarks

Surface water flooding is an important issue in Scotland (and increasingly becoming more so as the climate changes and we see more intense summer storms).

In this review, we show through a series of case studies that recent developments in computational power, convection-permitting NWP and hydrodynamic modelling mean that it is possible for SEPA to explore and build upon international best practice and 'state-of-the-art' surface water flood forecasts for Scotland. SEPA's current use of MOGREPS-UK through the Heavy Rainfall Alert is ensuring the best practice in convection-permitting NWP is currently being used to inform the FGS, however, rainfall threshold approaches do not take account of spatial/temporal variability in vulnerability. An opportunity therefore exists to learn from the examples presented in this review to extend this best practice to incorporate MOGREPS-UK into either a national- or city-scale pre-simulated approach as a balance between computation resources, lead time and fully risk-based approach.

Using each of the case studies reviewed in Section 3, there is an opportunity for SEPA to learn from international best practice and to identify parts of the system that could be useful in Scotland. In particular, we have identified the potential to provide targeted impact-based forecasts linked to specific receptors. In the Loughborough University surface water nowcasting approach, the original objective was to provide targeted advice to emergency responders trying to access the city during a flood event. This enabled a clear partnership to be developed between the users and the developers of the forecast resulting in a product that met operational needs and was quickly transferred from research to an operational tool. The Vigiecrues Flash application from France is another good example of a forecasting tool that is linked to specific at-risk vulnerable communities. This approach could be transferred to Scotland by focussing on PVA's, particularly those with a known high risk of surface water flooding. SEPA's existing approach using MOGREPS-UK in the HRA tool, combined with existing knowledge of catchment susceptibility, is already following international best practice for an early warning tool. However, this approach could be further improved with better post-processing and visualisation tools, such as the FloodAlert tool in Spain, which provides a good example of available visualisation techniques.

The iCASP project also demonstrates an effective way to explore the use of city-scale flood forecasts by decision-makers and to develop effective communication strategies. When it becomes available, the output from the iCASP project could be helpful to inform SEPA's decision making in this area. However, while city-scale real-time hydrodynamic approaches are useful as they can provide street-level detail, computationally it is not possible to run them at lead times greater than 6 hours.

There are also several examples identified in this review of programmes and initiatives that could potentially improve monitoring of surface water impacts in Scotland, either with an operational focus using platforms such as Global Flood Monitor (including potentially integrating Report-a-Flood into this), or making better use of crowdsourced data as demonstrated by use in The Netherlands.

Below, we conclude with some key considerations for SEPA for the improvement to surface water forecasting in Scotland, together with some more general challenges that are applicable to surface water flood forecasting.

Key considerations for the improvement to surface water forecasting in Scotland:

1. Determine if the priority is a national approach or a more localised approach for individual cities and at-risk vulnerable areas – this will guide the future of surface water forecasting in Scotland
2. Identify what level of detail is required for a range of decision-makers (e.g. lead time, spatial scale, impact assessment)
3. Establish if available research and techniques can meet these requirements and if so, what approach should be taken
4. If surface water forecasting requirements are already being met through existing products, determine if these could be improved by communicating forecasts more effectively to decision-makers (e.g. training for decision-makers on limitations of convection-permitting NWP, how to effectively use probabilistic forecasts, and how to improve visualisation tools)

General challenges to surface water flood forecasting improvement:

- Increase preparedness at longer lead times by making better use of other sources of supplementary information
- Effective post-processing of forecasts to address the issue of low probabilities for surface water events (especially at small spatial scales)
- Communicating the scientific limits of predictability and developing novel solutions to this that do not necessarily follow the approach used in fluvial and coastal forecasts, which should be done in partnership with stakeholders and end users
- Integration of national and local scale approaches may lead to consistency issues and communication challenges due to impacts being at different scales

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