Expert perspectives on the next generation of UK surface water flood warning services

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Introduction

Surface water flooding (SWF) – also referred to as pluvial or flash flooding – happens when rain from heavy storms overwhelms local drainage capacity. SWF has been recognised by the British government as a key risk and was added to the national risk register in 2016. The speed at which severe storms develop means that there is often limited time to take protective action before flooding occurs. SWF presents a threat to life, livelihoods and critical national infrastructure (DEFRA, 2018; NIC, 2022). For example, intense rainfall in London in 2021 led to many Londoners requiring rehousing as their homes were flooded with stormwater and sewage; '*It rendered critical infrastructure unusable with the closure or partial closure of 30 London underground stations and the evacuation of hospital wards and schools*' (Mayor of London, 2022). Analysis by the National Infrastructure Commission (NIC) concluded that the United Kingdom needs to be better prepared to manage SWF events (NIC, 2022). Severe flooding in 2021 in Germany, Belgium and the Netherlands (Szönyi *et al.*, 2022), New York (USA, Sullivan, 2021) and Zhengzhou (China, Chen *et al.*, 2022) also indicates the international importance of preparing for SWF in urban areas. As the climate changes, the convective rainfall events that typically lead to SWF will become more intense and slower moving (Fowler *et al.*, 2021). While some years may see more SWF in the UK, variability between years (Kendon *et al.*, 2023) will continue to make SWF a difficult risk to prepare for. Thus, there is an urgent need to build resilience to SWF underlain by evidence-based research and investment in resources (Climate Change Committee, 2023).

Flood forecasts and warnings are an essential component of resilient communities (WMO, 2022). When used effectively, flood warnings can save lives, reduce impacts and costs, and speed up recovery following flooding (Kuller *et al.*, 2021) by supporting individuals, communities and responsible organisations to take proactive action before flooding occurs. Flood warning systems for fluvial and coastal flooding in the UK are well established (Pilling *et al.*, 2016); however, the science supporting SWF warnings lags behind. Unique challenges include high uncertainties when predicting locations, timings, intensity and impact of localised SWF events (Speight *et al.*, 2021). Subsequently, SWF warning services are not as well developed compared to other geophysical hazards (Merz *et al.*, 2020) and the current operational systems do not meet all users' needs for targeted information to support decision-making before a flood event (Birch *et al.*, 2021).

To help readers understand the current system, a timeline of developments in SWF forecasting and warning provision in the UK is shown in Figure 1 (with supporting information provided in Table S1). In England and Wales, strategic national scale SWF warnings for government and responders are provided by the Flood Forecasting Centre (FFC) and in Scotland, the Scottish Flood Forecasting Service (SFFS) through the Flood Guidance Statement (FGS, Pilling *et al.*, 2016). The FGS is a partnership product that combines hydrological and meteorological expertise from the Met Office and Environment Agency (EA) or Scottish Environment Protection Agency (SEPA). The FGS is underlain by a range of forecasting tools, including convective permitting rainfall forecasts (Hagelin *et al.*, 2017; Tang *et al.*, 2013) which are post-processed to support the identification of areas at risk of SWF (Speight *et al.*, 2021), and the Surface Water Flooding Hazard Impact Model (SWFHIM, Aldridge *et al.*, 2020; Pilling *et al.*, 2023a,b). There is limited publicly available information on SWF beyond the National Severe Weather Warnings, which primarily provide rainfall rather than flood warning (Neal *et al.*, 2014); although SWF information is included in public facing Flood Alerts in Scotland.

Alongside the scientific challenges, the NIC has identified that due to the number of Risk Management Authorities involved, there is a lack of clarity around responsibility for SWF (NIC, 2022). The current arrangements for SWF management were implemented in the Flood and Water Management Act 2010, following recommendations from the Pitt Review (Pitt, 2008), which investigated the widespread flooding experienced over the summer of 2007. The Environment Agency has a strategic overview for all sources of flooding, which includes surface water. This is set out in the National Flood and Coastal Erosion Risk Management Strategy for England (FCERM Strategy, Environment Agency, 2020). Lead local flood authorities (LLFAs), which are unitary or county councils, have the principal role in managing flood risk from local sources such as surface water, ground water and small watercourses. Increasingly, LLFAs are turning to bespoke SWF models developed by consultants to support them in this role. Local monitoring and response is often led by community volunteers such as flood wardens (Forrest *et al.*, 2019) which makes the response unequitable. Expertise and level of service therefore vary widely between regions (Ochoa-Rodríguez *et al.*, 2018; Pilling *et al.*, 2023a; Maybee *et al.*, 2024).

Given the scientific challenges and number of Risk Management Authorities involved, it is unlikely that any single authority will have all the knowledge, skills, power or resources to solve the unique challenges of SWF by themselves. Doing so requires transformative thinking, interdisciplinary working and the development of innovative new tools and services. The paper presents the professional community's perspectives on priority areas for research and development to support the provision of effective SWF warnings based on a workshop held in Birmingham in January 2024. We adopt the terminology used by the World Meteorological Organisation (WMO) HiWeather project (Golding, 2022). A forecast is considered to provide information about the future state of the weather and resulting flooding, without consideration of its use. A warning provides information about flooding

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and resulting impacts with the aim of supporting an appropriate response. A decision-maker may be a user of a warning and a producer of a warning for someone else. The warning value chain (Figure 2) illustrates the components that support decision-making. The bridges between them represent the communication of expertise between different components.

Workshop: community perspectives and priorities for SWF warning

A workshop was co-organised by the Environment Agency and academics working in the field of SWF forecasting, warning and communication (the authors of this paper). The workshop followed previous EA engagement events to define the big issues around surface water flooding and capitalised on a period of commitment towards improving the provision of SWF forecasts and warnings in the UK (Environment Agency, 2024a). The workshop took a forward-looking approach, discussing potential solutions and how they should be prioritised. Bringing together forecasters responsible organisations and emergency responders (21), academics (15) and consultants (13), the day provided a valuable opportunity to begin to shape a unified approach to building resilience to this growing risk. While attendees were all based in the UK, the presentations and experiences of the group also enabled incorporation of overseas learning into the discussion.

The day comprised a mix of presentations on new research and operational capabilities (much of which is cited in this paper), alongside plenary discussion and two breakout sessions where delegates were split into groups of 5–8 people (Figure 3). The first breakout session asked delegates to consider designing a real-time surface flood warning service. The second session considered priority areas of the warning chain for future research and development and priorities and funding mechanisms. This paper reports on key themes arising in the workshop to inform future development of SWF warning capabilities; therefore, it does not represent the views or recommendations of any particular organisation, individual or author.

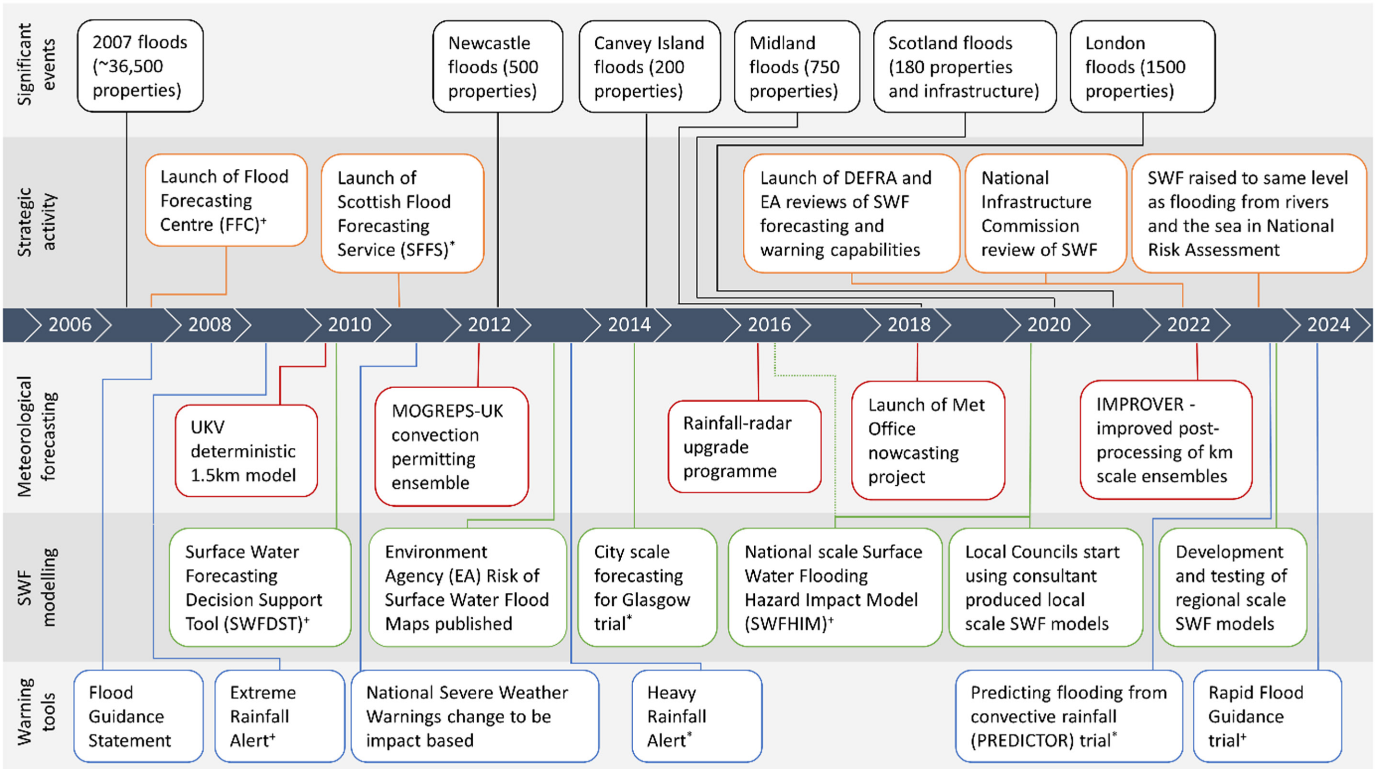

*Figure 1. Operational developments in SWF forecasting and warning since 2007. SWF models and warning tools differ between the SFFS and the FFC. Scotland only tools are indicated by *, England and Wales only tools are indicated by +. Interested readers are directed to the Supporting Information (S1) for further details of these developments.*

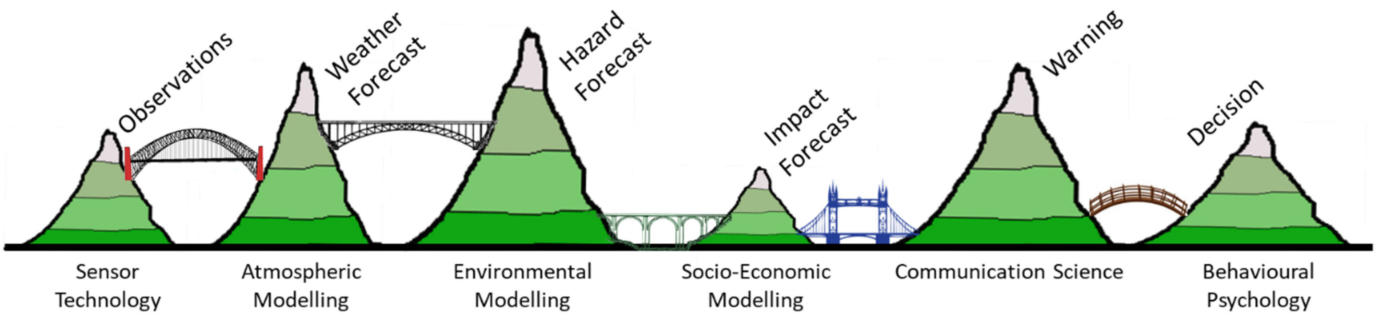

Figure 2. Example of a warning value chain from the WMO HiWeather project (Golding, 2022).

Figure 3. Participants at the SWF Workshop in Birmingham during plenary sessions and breakout groups.

What needs to be considered in designing a real-time surface water flood warning service?

It was widely acknowledged that existing flood warning service frameworks are unlikely to meet the needs of all users for future SWF events. Delegates were asked to think beyond the constraints of their normal ways of working to envisage what an effective SWF warning service could look like.

Users' perspectives

The provision of SWF warnings should reflect the different needs of different users, including emergency responders, infrastructure providers, community groups and the public who require information at different spatial and temporal scales with differing degrees of confidence. Future discussions with a diverse set of users are required to establish detailed user requirements (outcomes) for a SWF warning service. The range of expected needs and tolerances of risk makes it challenging to design a single system that meets all the potential requirements of all potential users (see 'Service Provision' section). Given the known limits of forecasting skill for SWF (Hagelin *et al*., 2017), a probabilistic approach that empowers individuals to make their own decisions based on their own risk tolerance was seen as essential. Such a system would make the best use of convective permitting Numerical Weather Prediction (NWP, Porson *et al*., 2020) and should provide transparent communication of forecast confidence based on ensemble postprocessing, clear messaging and a defined focus on the type of impacts being warned for (transport disruption, flooding of basement properties, loss of life).

Education and risk awareness

The public are often unaware they live or work in areas at risk of SWF as the hazard is not visible and occurs infrequently. SWF warnings must be delivered alongside wider action to increase education of risk and appropriate responses before flood events occur. More behavioural science research is required to understand how and why people respond (or do not respond) to warnings. Lack of awareness of the dangers was considered to contribute to risky actions such as driving through flood water. Education is also needed to help people interpret the information provided in warnings correctly and to understand key terminology. Based on previous experience of successful activities, or drawing ideas from other applications that could be successfully used with SWF, suggestions from delegates to raise awareness of locations at risk of SWF and the potential impacts included:

- Physically marking areas at risk, for example, with tape on buildings.
- Crowd sourcing flood images to translate into a flood history.
- Visualising historic or potential flood levels in a virtual reality environment.
- Routine installation of property level monitoring and warning systems (e.g. of water level in basement properties) or sensors in all at-risk properties which would improve access to impact data and raise risk awareness.
- Showing images of behavioural change on street infrastructure, for example, cars turning back from floodwater, cars not parking in areas known to flood.
- Integrating with services that are already familiar to the public, for example, indicating areas which have previously experienced impacts on online maps in the same way that speed cameras are shown.

Service provision

There was no single definition of what a successful SWF warning service should look like. As SWF is very different from flooding from rivers and the sea, any service offered (e.g. lead time, resolution, location accuracy, confidence) will significantly differ from other established services. Rather than adapting existing approaches, new and innovative methods are required. Participants acknowledged that while this is well understood by those working in the field, they did not believe that it is necessarily understood by all responders, and certainly not by the public. This raises issues of how to communicate often high-impact, low-likelihood SWF forecasts while maintaining trust in existing river and coastal warnings. The starting point should be identification of the outcomes required and a consideration of moving towards delivering these with current capabilities. It was concluded it was better to evolve the service over time, even if this means initially offering a service with much shorter lead times than those established for river and coastal flooding.

Despite being well regarded by responders, national systems such as the Flood Guidance Statement are not meeting all user needs (Pilling *et al*., 2023b; Maybee *et al*., 2024) and where they exist, local systems are considered more useful as they can provide more targeted information. Uncertainty in rainfall forecasts reduces at short lead times (0–6h) and users would like more information at this point. The 2024 Met Office and FFC trial of a Rapid Flood Guidance (RFG) product is a first attempt at meeting this need, proving shorter lead times and more localised warnings than the FGS (FFC, 2024). A review of the trial service will help inform future research directions. A strong consensus emerged throughout the workshop that a nested multi-scale system of SWF warning provision is required. Such a system should provide consistent messaging across multiple spatial and temporal scales by embedding local knowledge and decision-making within a national framework, thus enabling the provision of information that can be tailored to the multiple needs of individual users at different lead times and can flexibly integrate community knowledge and real-time flood observations from local sources. Such a system requires consideration of challenges such as how to encourage users to pay attention to long lead time, wide area and low probability warnings of potentially developing events, and how to include small villages and large cities within the same impact-based system.

Communication needs to come from trusted organisations (recognising that who is a trusted organisation or individual will vary for different groups of users). A nested system could support consistent communication of SWF warnings across all agencies. This should be further supported by work to develop trust and confidence in the system through transparent communication of validation and uncertainty. Given the speed of onset of SWF, partnerships with so-called Big Tech firms and integration with services that people are already familiar with (e.g. the Met Office weather app or online maps) have the potential to offer a means to quickly deliver forecast information to users.

What are the priority areas in the warning chain for future research and development?

The second breakout session used the warning value chain (Figure 2) as a framework to identify where further research or investment is needed to support the provision of SWF warnings.

Participants felt that there was not one clear area where improvement would solve the SWF challenge. A priority was to focus on bringing people together with different approaches and skills to develop innovative and imaginative solutions, including people who may not necessarily have a background in hydrometeorology, such as social and computer scientists. It is notable that given recent developments in convective ensemble forecasting (Hagelin *et al*., 2017; Porson *et al*., 2020), limited mention was made of improvements to weather forecasts. Discussions focused on improving the use of the forecast data that is currently available while acknowledging that the uncertainty in NWP and nowcasting is high when forecasting convective, localised storms. Interested readers are referred to Pilling *et al*. (2023a) for consideration of the potential value of future improvements in NWP for SWF warning.

Observations

Our limited capacity to observe SWF events reduces our ability to model, forecast and understand SWF impacts, particularly due to the small-scale and ephemeral nature of many events. Improved data collection and sharing is needed, such as access to rain gauge and rainfall-radar data, sewer and local drainage information and centralisation of SWF reports and observations. Green *et al*. (2024) provide an example of how dense observations from novel data sources across a city can be used to support dynamic flood risk assessment. Further opportunities to explore the potential uses of micro-sensors, drones, new satellites and traffic data should be prioritised alongside the use of machine learning (ML) techniques to support rapid post-processing of real-time observations to support SWF warning.

Modelling hazard

While it was acknowledged that the lack of observation and impact data makes model validation difficult and limits opportunities for innovation, greater transparency about which models and methods are best in different scenarios is needed. Established models may not be the most appropriate for use for SWF, and the modelling community needs to be flexible and open to new approaches. Models for SWF should be included in, and benefit from, the ongoing efforts to improve hydrological benchmarking, such as part of the Flood Hydrology Roadmap (Environment Agency, 2022) or the EA Flood Hydrology Improvements Programme (Environment Agency, 2024b).

The level of detail required for modelling SWF hazard remains an open question. The choice of hazard model resolution should be informed by an understanding of the uncertainty in the underlying NWP for SWF events, as well as the benefits of increased spatial detail. New technology and techniques (Guo *et al*., 2021; Ivanov *et al*., 2021) such as graphics processing units coupled with hydrodynamic modelling improvements (Xia *et al*., 2019; Ming *et al*., 2020) and machine learning (Hou *et al*., 2021; Li *et al*., 2021) are increasing the possibilities for modelling at street scale in real time and for static flood risk mapping. Higher resolution mapping enables understanding of at-risk locations in more detail. There is a need to evidence the value of hydrological/hydraulic modelling to inform emergency management planning, particularly for unprecedented events where there may be no existing knowledge of at-risk areas, or to provide additional information about risk due to high-flow velocities and interaction with debris. Despite this, concerns were raised that increased detail adds potential uncertainty; for example, a street scale urban model that includes detailed drainage systems would still struggle to take account of the stochastic uncertainty of blockages.

Understanding impacts

The impacts of SWF are poorly understood. The constant flux of urban environments means impacts will change over time (e.g. due to the increase prevalence of sustainable urban drainage schemes) and may vary across the day (e.g. during rush hour). The human response to SWF will affect the severity of impacts; understanding this requires greater knowledge of vulnerability and response.

Local councils and responders hold valuable expertise of locations that are particularly vulnerable to SWF and can combine this with broader scale forecasts to target local response. New approaches are required to improve the integration of this knowledge into regional and national systems. Storing information on impacts in a consistent digital format is important for developing risk matrices, along with understanding of how impacts may change over time or scale up in unprecedented events. Representing impacts at smaller scales than possible in the current national systems offers potential to deliver targeted warnings for different users. At a very local scale, this should be supported by property-level data collected from innovative micro sensors ('Observations' section).

Warning communication

The effective communication of warnings relies on improving understanding within the SWF community of behavioural science to explore how warning messages are received, interpreted, and acted upon. This includes how messages are re-communicated with family, wider communities and through social media. Acknowledging that professional partners and the public have very different needs and that there will not be a '*one size fits all*' solution, the story needs to be consistent across the multiple organisations who may deliver the information in different ways and at different lead times.

The nature of SWF means probabilistic warnings will be needed to account for the uncertainties in forecasting convective rainfall (Hagelin *et al*., 2017). Research shows that people can use probabilistic information effectively if consideration is given to how probabilities are presented in text and graphics (Ripberger *et al*., 2022). Communication scientists could provide valuable support in achieving the appropriate balance between clear science and messaging. The communication of low-probability high-impact events remains a challenge but would be improved by increased awareness ('Education and Risk Awareness' section) of historic or worst-case scenarios.

The rapidly changing nature of SWF events means communication should provide live information (e.g. by posting a link to a live widget rather than an outdated message). For life-threatening situations, messages should be communicated quickly using automated processes from existing familiar platforms. Very short lead time warnings may be useful at a personal level and for a very local area when they are delivered alongside direct recommended

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actions such as '*leave basement properties immediately*'. This would be a step-change from current approaches, but comes with different risks. Re-definition of legal duties and governance is required alongside careful consideration of potential unintended consequences of recommended actions is required before delivering messages of this nature.

Adaptation and decision-making

SWF warnings can contribute to building cities and communities that are more resilient to flooding. To achieve this, work is needed to shift attitudes, raise risk awareness and empower people to keep themselves safe by responding effectively to SWF warnings. This should include the following:

- Education and expectation setting when people sign up to SWF warnings to explain that they will not offer the same level or type of service as warnings for flooding from rivers and the sea;
- Developing flood plans that focus on more low-regret and preparatory actions, and ensuring responders and the public have the capacity to act;
- Providing more support for property-level protection from multiple organisations (e.g. insurers and water companies), particularly in areas that flood frequently;
- Stopping dangerous behaviour, such as driving through flood water.

Funding

The locally-held responsibility for SWF management by LLAs, and the valuable knowledge of impacts held by local organisations and communities would be best supported by a bottom-up approach to funding. This would allow Risk Management Authorities to co-develop SWF warning services that meet their needs, making the best use of existing data, knowledge and expertise while feeding into a consistent, national scale, strategic framework. To date, funding has been piecemeal, with some big cities benefiting from increased funding linked to key events (see Figure 1, e.g. Glasgow in advance of the Commonwealth Games in 2014 (Speight *et al*., 2018)), following high-profile floods (e.g. London after 2021 (Mayor of London, 2022)) or regional research initiatives and innovation programmes (e.g. the West Yorkshire Flood Innovation Programme – WYFLIP (n.d.) which led to the development and testing of regional SWF models (Birch *et al*., 2021; Maybee *et al*., 2024)), while others are without the means or capacity to make use of emerging capabilities. Funding for SWF warning development needs to be considered alongside secure funding for incident management, ongoing training of forecasters and responders and response capabilities to ensure appropriate action (such as clearing assets) can be taken on receipt of warnings. Given the level of risk, funding is a priority; waiting for the next big event to highlight weaknesses in the existing system is not appropriate. More effort needs to be put into presenting the value of emerging approaches to cities and communities and learning from other cities around the world.

Research funding for interdisciplinary work is challenging to secure. Previous large projects around surface water flood risk (e.g. the NERC funded Flooding from Intense Rainfall programme (FfIR, Flack *et al*., 2019)) worked well when integrated funding ensured direct links between different research disciplines and operational users, and where funding proposals were developed around operationally relevant research questions. The existing Natural Hazards Partnership (Hemingway and Gunawan, 2018) which supported the development of the SWFHIM, is a good example of proactive development of interdisciplinary approaches, but funding to do so has come through funding for individual projects. Questions remain about how to break down the big integrated needs of SWF into smaller projects that are easier to fund while still benefitting from inter/trans disciplinary approaches, and how to effectively utilise investments from other stakeholders such as insurance and private companies. Interdisciplinary research funding from UKRI, with funding available for non-academic partners, is key to developing the science required to deliver evidence-based solutions that increase resilience to SWF.

Conclusion and next steps

The workshop crystallised the urgency for increased resilience to SWF and the valuable contribution forecasts and warnings can make. Figure 4 provides a summary of

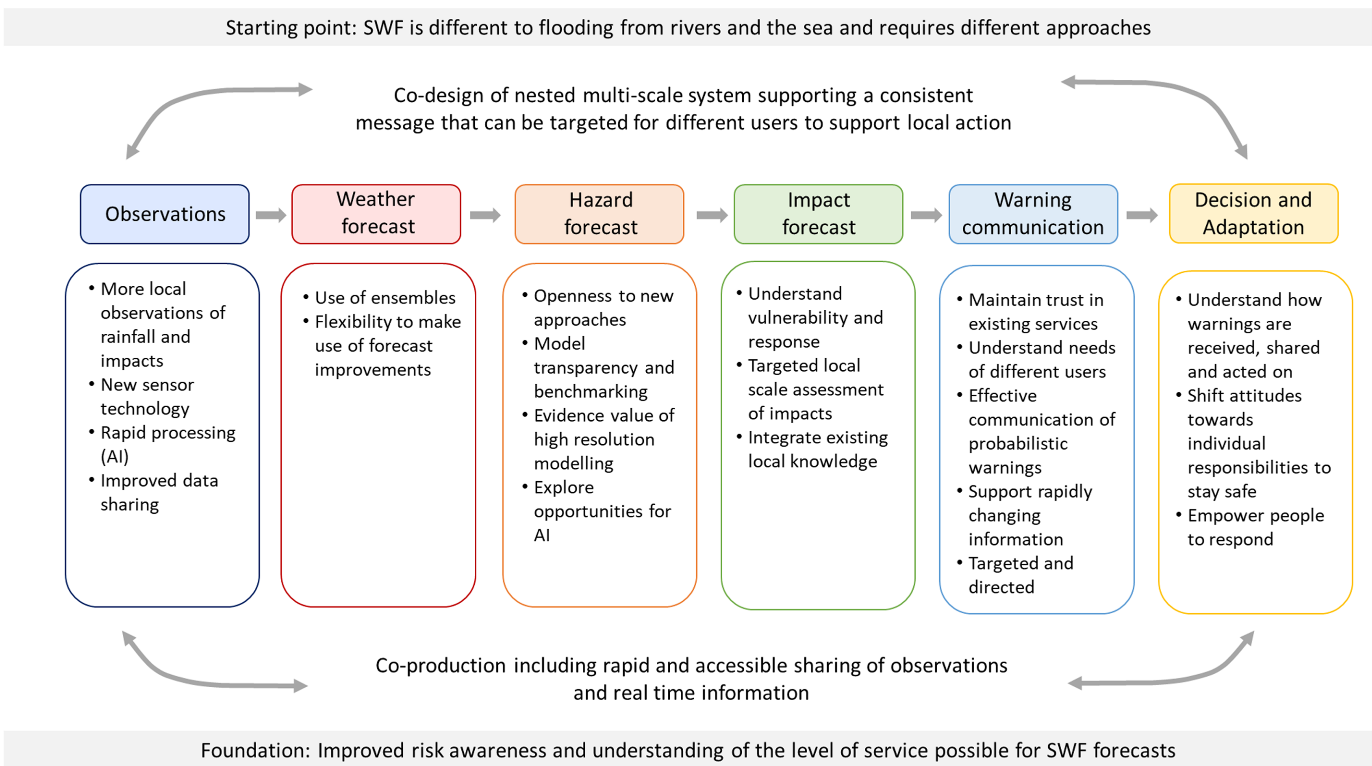

Figure 4. Summary of priority areas for research and development to support the provision of an effective SWF warning service.

the areas identified by workshop participants as priorities for further research and development to support the provision of an effective SWF warning service that meets the diverse needs of users.

Delegates envisaged a future SWF warning service that:

- Does not reduce trust in existing warning services for rivers and the sea;
- Is based on a bottom-up design reflecting the needs of multiple users;
- Uses a nested multi-scale system that supports the two-directional flow of national information into embedded local decision-making and sharing of local observations and real-time information;
- Would be delivered alongside increased education and risk awareness to support realistic expectations and effective decision-making, with warnings delivered by trusted organisations.

SWF is complex. As a forecasting community we need to be open to new models, methods and data sources to meet the multiple needs of different users. The workshop highlighted that despite the excellent developments in physically based science, understanding more about effective communication and managing uncertainty during SWF events is also a key priority. Behaviour and social scientists are essential to include in further discussion in developing effective services to help understand behaviours, mobility and thought processes that can reduce risk and improve response to warnings. Attendees at the workshop commented that the relaxed atmosphere and openness of participants to sharing thoughts and ideas was a promising start towards the collaborative solutions needed. It is essential that we continue to build partnerships to learn from each other, including internationally. Having a strategic vision and roadmap to join parts of the science together would help this process. Hopefully, developments in the provision of SWF services will act as a catalyst to improve forecasting and warnings in other areas too.

Following the workshop, the next steps to maintain the momentum of SWF science include the following:

- Using the learning from the symposium to inform the development of a possible new surface water flood incident management framework for England.
- Submitting '*big ideas*' to UKRI funding bodies to indicate where new science and interdisciplinary solutions are needed.
- Using the evidence gathered during the workshop and presented in this paper to support future research bids.
- Engaging appropriate behavioural and social scientists to improve the SWF community's understanding of impacts and response.

Everyone who attended the workshop, or reads this paper, is encouraged to continue to work together to build the effective partnerships needed to address the challenges of effective SWF warning.

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Author contributions

Linda Speight: Conceptualization; investigation; writing – original draft; writing – review and editing; visualization. **Cathryn E. Birch:** Conceptualization; investigation; writing – review and editing. **Katherine Self:** Conceptualization; investigation; writing – review and editing. **Sally Brown:** Conceptualization; investigation; writing – review and editing.

Conflict of interest statement

None.

Data availability statement

No new data have been generated as part of this research.

Supporting Information

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

Table S1. Further information on the strategic activity, events and forecasting and modelling tools included in Figure 1.

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