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Real-time flood impacts mapping

Technical report

SC120023/R1

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Professor Doug Wilson  
**Director, Research, Analysis and Evaluation**

# Executive summary

The Environment Agency's National Flood Forecasting System (NFFS) supports flood incident management by forecasting river flow and level at specific locations, which are linked to Flood Warning Areas. This project explores how maps could be linked to flood forecasts, of the type currently provided by the NFFS, and used to provide consistent, easy to understand information to flood incident managers and those at risk.

There is growing recognition of the need to provide maps of flood extents and impacts, in real-time, to support improved flood incident management. The Pitt Review (2008), Exercise Watermark (2011) and the Environment Agency's Flood Incident Management Plan (2015) have helped establish the high-level needs for this information. This project consulted users on their requirements and explored technical options that could be used to provide real-time flood impact mapping. Its main focus is fluvial flooding. Options to improve coastal flood forecasting are considered in 'Investigating Coastal Flood Forecasting' (project SC140007).

This project has generated the evidence required to inform the Environment Agency's strategic direction with respect to real-time flood extent and impact mapping.

## Main findings

- The main user needs are for maps of flooding and its impacts, with time-varying information as an event develops.
- Simulation libraries currently have the most potential to meet the user requirements. In this approach, flood extents, depths and impacts information are selected during an event from a library of pre-computed results.
- Real-time simplified fluvial modelling, in which models are run 'on demand' during an event, also has significant potential. These models would be of greatest benefit in situations too complex to represent using pre-computed scenarios.
- Both options could be implemented relatively efficiently on a national scale by reusing existing models and data held by the Environment Agency.

For the purposes of this project, the two main user groups of real-time flood extent and impact information were consulted:

- The Environment Agency's Flood Incident Rooms (interested in monitoring, analysing and disseminating live flood information).
- Gold and Silver Command staff (responsible for co-ordinating the response on the ground).

For both user groups, the overarching need is for maps of flooding and its impacts, with time-varying information, as an event develops. For Flood Incident Rooms, incident management tools must be easy to use, being suitable for use in the early hours whilst under pressure to deliver requests for information. For Gold and Silver Command staff, outputs must be easy to understand and accessible by non-technical decision-makers.

A shortlist of options was then drawn up by appraising a long list of technical options against their ability to meet user requirements in the near term. The long list of options were created through an Options Development Workshop and a literature review. They considered current best practice and future technological trends.

Next, 6 proof of concept experiments were designed and carried out. They allowed the key concepts from each of the shortlisted options to be tested against the following research questions, using currently available tools and data:

- What is the technical feasibility of the option?
- What information does the option provide?
- How does the option perform?

### Preferred options

Use of pre-computed simulation libraries is the preferred option for providing real-time flood impacts mapping in the future. Simplified fluvial models, run in real time, also have potential in situations too complex to simulate using pre-computed libraries. The table below provides a summary of the main benefits, risks and dependencies of the preferred options.

### Summary of the main benefits, risks and dependencies of the preferred options

Option	Benefits	Risks and dependencies
<b>Simulation library</b>	<p>Meets all user requirements.</p> <p>Efficient implementation – national coverage could be achieved by reusing models/data from the National Flood Risk Assessment (NaFRA) and the State of the Nation risk modelling project.</p> <p>Potential to incorporate local, detailed information where available. Future projects will address operational data sources.</p> <p>Fast, predictable run times – can be used to assess multiple scenarios (for example, forecast ensembles).</p> <p>Robust – does not depend on model stability and licences in real time.</p>	<p>More complex to implement where flooding is caused by multiple variables, which would difficult to relate to mapping for a specific scenario.</p> <p>Practical issues need to be overcome to incorporate different datasets alongside each other (for example, local detailed mapping, alongside broad-scale modelling).</p> <p>Look-up libraries and routines should be structured to make the most efficient use of data in real time.</p>
<b>Simplified fluvial modelling</b>	<p>Meets all user requirements.</p> <p>Depth, hazard and velocity mapping are is sufficiently accurate and detailed for the intended purpose of flood incident management.</p> <p>Run times are feasible for real-time use. The approach is preferred to running the Environment Agency’s current stock of detailed hydrodynamic models ‘on demand’ as these are not typically designed for real-time use.</p> <p>National coverage could be provided by reuse of existing models/data from the NaFRA and State of the Nation modelling.</p>	<p>Models are straightforward to set up, but some quality control may be required (for example, edits to Digital Terrain Models).</p> <p>May require non-standard IT to achieve viable run times.</p> <p>The PoC uses a simplified representation of channel–floodplain interactions. This is heavily dependent on data quality to specify bank/defence heights and other characteristics. Where possible, accurate and up-to-date information should be incorporated.</p>

More detail on the different stages of the project and the pro-formas produced for 5 of the 6 PoC experiments are provided in appendices to this final project report.

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# 1 Introduction

This is the final report for the joint Defra/Environment Agency R&D project, Investigating the Needs, Feasibility and Benefits of Real-time Inundation Mapping for Flood Incident Management (SC120023).

This chapter begins by discussing the wider context and drivers for this study, before explaining the project's specific aims and objectives. Finally, the structure of the rest of the report is outlined.

## 1.1 Context and drivers

Predicting when and where flooding will occur is of vital importance for flood incident management. It allows flood risk managers, emergency planners and responders to assess the potential consequences of flooding, enabling them to reduce risk and the damaging effects of floods. Reliable flood forecasting underpins much of this.

The Environment Agency's National Flood Forecasting System (NFFS) provides real-time information on the predicted magnitude, severity and timing of a flood to inform flood incident management before and during an event. The NFFS currently forecasts river flow and level at specific locations, which are linked to Flood Warning Areas, but does not produce detailed maps of flood extent or the consequences of flooding. Making maps of forecast data readily available in real-time could help provide consistent, easy to understand information for flood incident managers and those at risk.

Advances in science and technology are providing more accurate forecasts, better understanding of confidence in forecasts, faster models, better monitoring and more options for communicating and sharing information – including mapping. There is now a need to understand the options available for real-time mapping of flood impacts and how, when and where this information could help support the flood incident response.

In some respects, the high-level needs for real-time flood mapping are well established. The Pitt Review (Pitt 2008), which followed the widespread flooding of summer 2007, recommended that the Environment Agency should:

'work with its partners to progressively develop and bring into use flood visualisation tools that are designed to meet the needs of flood risk managers, emergency planners and responders' (Recommendation 37).

The review further advised that flood visualisation data should be:

'held in electronic map format, available online to Gold and Silver Command' (Recommendation 36).

The Pitt Review also recommended a national flooding exercise to test arrangements for responding to flooding and infrastructure emergencies (Recommendation 49). This led to Exercise Watermark in March 2011 (Exercise Watermark Review Team 2011). Lessons learnt from Watermark are important drivers for this project. The Environment Agency identified a need to prepare information in advance (such as best, worst and most likely scenarios) and make these data readily available to response staff, to reduce demands on their time during an incident. This creates a need for consistent data management and communication, including mapping and visualisation.

This project addresses these recommendations by investigating current and future needs for real-time flood mapping in more depth. It also identifies and tests a number of technical options that could be used operationally in the future.

The outcomes of this study support the 'Flood Incident Management Plan 2015 to 2020', which sets out the Environment Agency's ambitions for the service it will provide (Environment Agency 2015). Important flood incident management outcomes set out in the plan that are relevant to this project are summarised below.

- Make all flood risk information available in a central location for people to view and use in a way that they can easily understand (Outcome 1).
- Work with partners to target high risk locations, such as fords and arterial roads, to provide alerts and warnings (Outcome 3).
- Communicate probabilities when issuing forecasts (Outcome 3).
- Use maps and other visuals to represent forecasts and the areas expected to flood (Outcome 3).
- Include contextual information so that people know what impact the flooding will have (Outcome 3).
- Present forecasts online and through maps, communicating the confidence in them (Outcome 4).
- Support other responders to help them interpret forecasts (Outcome 4).
- Forecast different possible flood scenarios to help plan the response (Outcome 5).
- Introduce a consistent forecasting service for England and a single team approach to sharing forecasts and warnings (Outcome 6).

The next section explains how this project investigated user needs, identified potential technical options that could be used for real-time flood mapping, and evaluated the feasibility, benefits and constraints of the available options.

## 1.2 About the project

The main focus of this project is fluvial flooding. Options to improve coastal flood forecasting are considered in the joint Defra/Environment Agency R&D project Investigating Coastal Flood Forecasting (SC140007) (Environment Agency 2016).

NFFS helps the Environment Agency to provide an effective forecasting and warning service for both fluvial and coastal floods. In the case of fluvial flooding, NFFS primarily provides level and flow forecasts at discrete locations (normally river gauges) in river networks across England. Forecast locations are linked to Flood Warning Areas. Flood warnings are considered when river forecasts exceed pre-determined thresholds, which are associated with the level at which flooding impacts upon receptors in the Flood Warning Area.

But as discussed above, flood risk managers and emergency responders require more detailed information on the likely impact and consequences of flooding as an event develops. The Joint Programme Board therefore commissioned this R&D project to investigate:

- the needs of Flood Incident Rooms, Gold and Silver Command and other emergency responders in relation to real-time flood impact mapping

- the feasibility and benefits of options to derive flood impact mapping in real-time in a form that can be easily used by organisations responding to flooding.

Surface water flooding is also considered by this project for completeness; Lead Local Flood Authorities are responsible for managing the risk from surface water flooding, and the Environment Agency retains a strategic overview role in England. It also provides a useful comparison to ongoing work by the Natural Hazards Partnership Surface Water Flooding Hazard Impact Model (NHP SWF HIM) Programme to develop a prototype national scale surface water flood impacts forecasting system for the joint Met Office/Environment Agency Flood Forecasting Centre.

The activities carried out during the project are summarised below.

### **1.2.1 User needs and consultation (completed October 2014)**

The first stage of the project involved the development of a detailed understanding of user needs through consultation with Environment Agency staff and a cross-section of Local Resilience Forums, many of whom had been involved in managing the extensive winter flooding of 2013 to 2014. The User Requirements Summary Report (Appendix 1) describes the consultation.

A literature review was conducted to inform subsequent option development. This considered previous projects and consultations, emerging research and international best practice.

### **1.2.2 Technical options (completed May 2015)**

Based on the outcomes of the user consultation, the second stage of the study identified technical options that would meet some or all of the user requirements and which were considered feasible in the near to medium term. These are detailed in the Technical Options Report (Appendix 2). Longer term options were also considered, but were not pursued further in this project due either to limited data availability or challenges in implementing them on a large scale.

An appraisal process that scored each technical option on how well they aligned with user needs was developed and used to shortlist options to take forward to the next stage of the project.

### **1.2.3 Proof of concept test development (completed June 2016)**

The final stage of the work – and the main focus of this report – involved proof of concept (PoC) trials, with an emphasis on understanding the options available rather than developing operational software. The PoC tests assessed the technical feasibility of the options, how they could be used, and their wider benefits and limitations.

The findings from the PoC trials were presented to the Project Board in April 2016. Section 7 discusses the Board's preferred options and recommendations for future implementation.

## 1.2.4 Project implementation

Since the completion of this research project and its final write-up in 2017, findings have been used to help steer and influence major Environment Agency initiatives such as projects to improve to future flood forecasting systems (FFFS) and the New National Flood Risk Assessment 2 (NaFRA2). They have also helped confirm the validity of existing approaches and help underpin the general strategy of moving towards a precomputed lookup approach to flood risk mapping.

## 1.3 About this report

This report summarises all the work carried out for the project and the recommendations for the next steps. It describes the outcomes of the user consultation, appraises the available technical options against users' needs, and investigates the technical feasibility and benefits of the options taken forward for PoC testing. Existing modelling and data products were used to explore the technical options. No new software has been developed to implement the PoC tests.

Section 2 begins by describing the user consultation process and the identified user requirements. It then gives details of the long list of technical options and the appraisal process used to draw up a shortlist of options to progress to PoC test development.

Section 3 introduces the 6 options subjected to PoC testing, their data requirements and the outputs provided by each.

Section 4 sets out the research questions to be addressed by the project. It also introduces the available types of data and how these data were used to address the research questions. It provides details on how each option was assessed and how the information is reported.

Section 5 presents a series of case studies featuring different of flood events and the specific datasets available for each. These case studies were used to test the PoC experiments. For ease of reference, much of the detailed analysis of the PoC tests was compiled as standalone 'pro-formas' (see Section 4.2). These are provided as Appendices 4 to 8.

Section 6 discusses the project's findings, drawing out common themes across the PoC tests, before providing further details on the findings for each option.

Section 7 presents the Project Board's preferred options and recommendations for future implementation and further considerations.

Appendix 1 and Appendix 2 were produced during earlier stages of the project in order to document the user consultation and the initial assessment of technical options respectively. This final project report supersedes these reports, but they are included for completeness and to provide a description of the project team's early views/assessment of the technical options.

Appendix 3 describes future possible approaches to providing real-time information on flood impacts.

Note that all the appendices are available as separate downloadable files.

An independent peer review of this report by Professor Keith Beven of the Lancaster Environment Centre at Lancaster University is attached to this report as Annex A.

## 1.4 Flood likelihood terminology

The challenge of using consistent terminology to describe flood likelihood throughout this report should be acknowledged.

The Environment Agency's preference in technical documents is for flood likelihood to be expressed as a percentage and/or an annual chance. Where possible, this report uses percentage annual exceedance probability (AEP) terminology, which expresses the probability of a flood occurring in a given year. The standard of protection (SoP) offered by flood defences or other assets is also described in terms of AEP.

However, 'return period' terminology is fundamentally embedded in some models and data – for example, the National Flood Risk Assessment (NaFRA) and data and products from the European Centre for Medium-Range Weather Forecasts (ECMWF). It was difficult to reconfigure these third party outputs to use the preferred terminology as part of this project.

AEP terminology and their return period equivalents are shown in Table 1.1.

**Table 1.1 AEPs and equivalent return periods**

<b>AEP (%)</b>	<b>Return period (years)</b>
10	10
2	50
1	100
0.5	200
0.1	1,000

## 2 Consultation, user needs and shortlisting process

As discussed in Section 1, the driver for this project is the need for flood impact mapping that is straightforward for users to communicate and interpret while under the pressure of responding to a flood event.

The main themes that emerged from the consultation process are that any system:

- **‘must pass the 4am test’**. This refers to the need for incident management tools to be easy to use, given the scenario of dealing with a flood event at 4am, and under pressure to deliver information requested by flood incident management partners, the public or government.
- **‘must pass the 10-second test’**. Outputs must be communicated in ways that are easy to understand and accessible to all, particularly non-technical decision-makers.

However, the various partners involved in flood incident management have different practical needs. This section describes how different user groups and their requirements were identified, before developing a long list of options to meet those needs. Finally, details of a scoring system used to shortlist options for PoC trials are discussed. Details of these options are given in Section 3.

### 2.1 User requirements

#### 2.1.1 User groups

The users of real-time flood maps range from strategic decision-makers who need a high-level overview of flood risk, to emergency responders who require detailed local information.

Two main user groups were identified (see below). A third user group, central government (for example, Defra, the Ministry of Housing, Communities and Local Government<sup>1</sup> or the COBR Committee) requires a national overview during significant events. This group is not explicitly considered here, but is likely to have similar requirements to the Gold and Silver Command.

#### *Environment Agency’s Flood Incident Rooms*

Flood Incident Rooms are generally ‘producers’ of real-time forecasts. Their role involves monitoring unfolding events, running models and disseminating forecast information. Forecasts are disseminated to Flood Warning colleagues and professional partners who are involved in the response to flooding at a local, tactical level.

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<sup>1</sup> Formerly the Department for Communities and Local Government

## Gold and Silver Commands

Gold and Silver Commands are primarily ‘users’ of real-time flood information. They respond to unfolding events and co-ordinate the strategic and -tactical response on the ground. For example, police commanders might co-ordinate the Fire and Ambulance services, the Coast Guard, RAF rescue, RNLI, local authorities, and water, electricity and gas utilities.

### 2.1.2 Key requirements

To assess user needs, a short questionnaire was circulated to the user groups described above. Telephone interviews were also conducted. Consultation included Gold and Silver Command staff involved in the response to the widespread flooding of winter 2013 to 2014.

The questionnaire identified existing practices for assessing and communicating the predicted impact of flooding. It also sought suggestions on how these approaches could be developed to better support flood incident managers in future.

A total of 26 responses were received. These are collated in the User Requirements Summary Report (Appendix 1). The key requirements can be summarised as follows.

Flood incident room staff require:

- spatial and time-varying flood depths and velocities, which can be applied to assess hazard at the level of individual receptors
- an assessment of uncertainty at lead times up to 5 days
- access via resilient online systems (for example, web mapping)

Gold and Silver Command requirements are:

- broad-scale mapping of areas at risk of flooding, including temporal information
- predictions at long lead times for strategic planning, though single or deterministic outputs are preferred
- methods that work in an offline environment and which have limited training requirements

Table 2.1 and Table 2.2 provide further detail about the requirements of these 2 groups of users.

**Table 2.1 Summary of Environment Agency flood incident room user requirements**

Information required	Dissemination
<ul style="list-style-type: none"><li>• Hazard mapping needed to show <b>depth and velocities</b>, given that extents do not show the full picture.</li><li>• More accurate forecasting of <b>timing</b></li><li>• Must be able to communicate <b>uncertainty</b> as a range, rather than trying (and failing) to make accurate</li></ul>	<ul style="list-style-type: none"><li>• Can be easily communicated.</li><li>• Highly visual, map-based</li><li>• Information must be available on portable technologies (for example, <b>mobile devices and tablets</b>).</li><li>• Must be able to zoom in and out of an area to see the ‘most likely flood</li></ul>

Information required	Dissemination
<p>predictions to the nearest centimetre and metre.</p> <ul style="list-style-type: none"> <li>• <b>All sources</b> of flooding should be represented (if possible).</li> <li>• <b>Lead times of up to 5 days</b> are needed.</li> <li>• Must be relevant at the <b>property/ street scale</b>.</li> <li>• Other receptors must be considered (for example, individual roads).</li> <li>• Defence representation needs to be easily manipulated or changed to account for any temporary works/damages to defences/assets and/or any local issues that may change our impact mapping. For example, the ability to introduce a <b>breach</b> (of a certain size) in to a wall or coastal bank and to see a revised inundation map.</li> </ul>	<p>outline' and 'worst case scenario outline' (for example, <b>web mapping</b>).</p>

**Table 2.2 Summary of Gold and Silver Command user requirements**

Information required	Dissemination
<ul style="list-style-type: none"> <li>• Professional partners typically want to know: <ul style="list-style-type: none"> <li>- 'Will it reach this level?'</li> <li>- 'When will it reach this level?'</li> <li>- 'How many people will need to be evacuated?'</li> <li>- 'Where will they be?'</li> </ul> </li> <li>• Some <del>Good-Gold</del> and Silver Commands had <b>no queries in relation to depths, hazard and velocity maps</b>. Required information is more general – 'is there a risk to life or not'?</li> <li>• One of the most important pieces of information Silver Command wanted to know was the <b>time of travel</b> and <b>when the peak would pass certain locations</b></li> </ul>	<ul style="list-style-type: none"> <li>• <b>Prefer to limit the use of technology</b> – PDF files can be seen as the 'technological limit'</li> <li>• <b>Prefer not to rely on computers</b> – for example, some Silver Commands had experienced Wi-Fi that kept dropping out</li> <li>• Information must be usable '<b>round a table</b>'</li> <li>• Dealing with large file sizes is a problem</li> <li>• Some respondents used a geographical information system (GIS) dataset to show critical infrastructure (in point format) on a whiteboard in the incident room. During the incidents, they overlaid live GIS data but with limited success.</li> <li>• Information must be <b>brief and simplified</b></li> </ul>



## 2.2 Options for real-time flood impacts mapping

Following the user consultation, an Option Development Workshop in November 2014 developed a series of technical options for flood event modelling, flood impact mapping and communication/decision support.

Figure 2.1 summarises different options for deriving information to support flood incident management, with examples of current or future practice. Although the potential sources of flood impacts information are wide ranging, a number of broad categories present themselves. Figure 2.1 groups the options into:

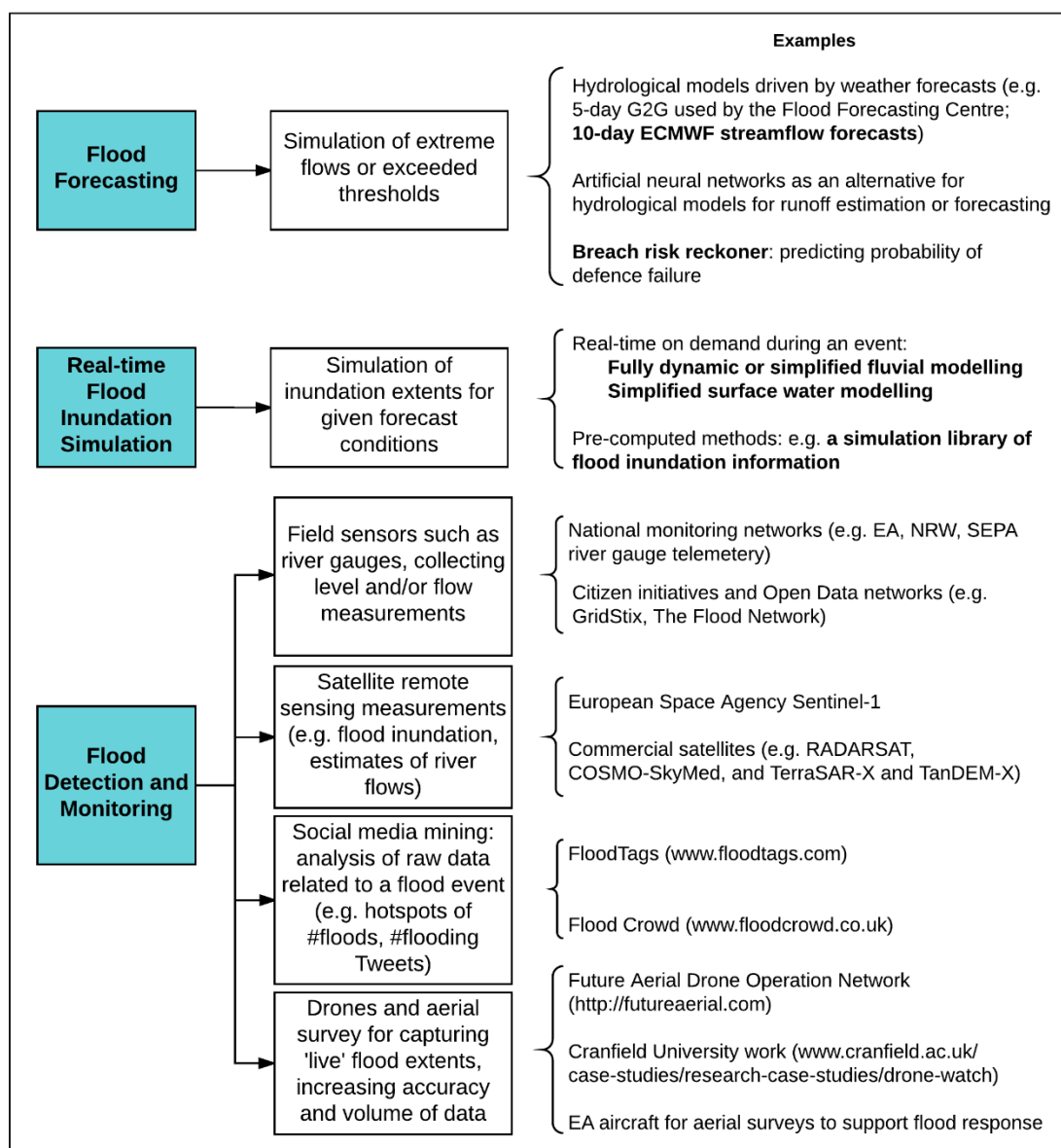
- **flood forecasting** of in-channel conditions, with up to several days' lead time prior to an event
- **real-time flood inundation simulation** driven by flood forecasts – might typically be applied at shorter lead times before an event, once there is an appropriate level of confidence in the flood forecasts
- **flood detection and monitoring** during and after an event (for example, via remotely sensed observations or data mining of social networks)

A Project Board meeting in March 2015 further refined the options to those that were feasible, on a national scale, within short- to medium-term timescales. Although longer range options may become viable in future, these were not pursued further in this project due either to data limitations or challenges in implementing them on a larger scale.

Technical option development during this project therefore focused on approaches that provide real-time flood extent and impacts mapping, driven by flood forecasts of the type currently available in NFFS.

Options that relate to flood detection and monitoring were not considered further due to challenges in obtaining data with sufficient geographical coverage. Remote sensing is dependent on satellite or aircraft availability during a flood event. Although these may provide large-scale mapping, long re-visit times mean that these may not capture the full duration of flooding. Conversely, data mining of social networks could offer information at greater temporal resolution, but does not directly provide mapping and coverage may be limited to densely populated areas. While such challenges could be overcome, these options are likely to be viable only in the longer term.

Appendix 3 provides further details of some of the long-term approaches that may be considered in future research.



**Figure 2.1 Alternative approaches to real-time flood impacts information**

Notes: Bold text denotes PoC tests developed by the project (see Section 3).  
 EA = Environment Agency; G2G = Grid-to-Grid; NRW = National Resources Wales; SEPA = Scottish Environment Protection Agency

## 2.3 Proposed technical options

The Option Development Workshop and subsequent Project Board meeting identified 14 options that were viable for further consideration. They can be broadly classified as:

- **pre-computed methods** that use current or forecast levels/flows to derive inundation extents for a given event, based on existing flood mapping products or outputs from new flood models, run offline
- **real-time methods** that run flood spreading models (and any other associated components) on demand during an event

In addition to the real-time mapping options, the project also assessed how broad-scale flood indices – based on numerical weather prediction (NWP) probabilistic forecasts

produced by the ECMWF – could be used to support improved flood incident management.

The final PoC experiments were designed with these 3 overarching classifications in mind and to test individual components and concepts from the preferred options using data and tools available at the present time.

Table 2.3 summarises the options, including the further category of breach options, set out in the Technical Options Report (Appendix 2). Detailed descriptions of all the options are not reproduced here; an outline of the shortlisted options is given in Section 3.

All the options are primarily concerned with mapping flood inundation. The derivation of flood impacts is then a straightforward intersection of inundation mapping and appropriate receptor datasets. **However, the challenging process – and the one given most attention in this report – is the initial process of deriving the inundation data in real time.**

**Table 2.3 List of technical options**

<b>Pre-computed</b>	<b>Real time</b>	<b>Breach options</b>
1. National simulation library using NaFRA models and data	5. Non-dynamic: real-time fluvial and coastal inundation modelling	11. Breach risk ready reckoner
2. National simulation library using commercial (fluvial) flood map products	6. Real-time surface water linked to G2G or NWP	12. Real-time breach inundation
3. Static groundwater maps linked to borehole telemetry and NWP	7. Real-time coastal modelling system	13. Pre-computed breach inundation
4. Updated Flood Map for Surface Water based simulation library linked to G2G run-off outputs	8. Real-time groundwater inundation using G2G	
	9. All-sources inundation modelling	
	10. Long-range ensemble warning system using NWP outputs	
	14. Fully dynamic: linked 1D–2D modelling <sup>1</sup>	

Notes: <sup>1</sup> Option added after the Technical Options Report (Appendix 2) was written to act as a baseline of 'best available information' to compare the other options against rather than as a preferred option.

1D = one-dimensional; 2D = two-dimensional

## 2.4 Option appraisal

Each of the technical options were assessed against user needs in order to derive a shortlist of options for further development as PoC experiments. The appraisal process can be summarised as follows.

1. Define a set of measurable acceptability criteria based on user needs (Section 2.4.1).
2. Evaluate each option's ability to meet the acceptability criteria (Section 2.4.2).
3. Calculate a numerical score for each option (Section 2.4.3).

### 2.4.1 Acceptability criteria

The user requirements were used to define acceptability criteria – a set of measurable criteria against which the options could be scored. Table 2.4 lists the criteria with commentary on each.

**Table 2.4 Summary of functional acceptability criteria**

Acceptability criteria	Sub-categories	Commentary
Flood source	<ul style="list-style-type: none"> <li>• Fluvial</li> <li>• Coastal</li> <li>• Surface water</li> <li>• Groundwater</li> <li>• All sources</li> </ul>	Coastal flooding is considered elsewhere (Environment Agency 2016).
Flood hazard	<ul style="list-style-type: none"> <li>• 1D water levels</li> <li>• 2D flood extents</li> <li>• 2D flood depths/water levels</li> <li>• 2D velocities and/or hazard rating</li> </ul>	Most approaches can generate floodplain depths or levels if a suitable digital terrain model (DTM) is available. Reliable prediction of velocity (and subsequent hazard calculations) generally requires approaches that solve the 2D shallow water equations.
Temporal information	<ul style="list-style-type: none"> <li>• Onset of floodplain inundation</li> <li>• Time of maximum inundation</li> <li>• Duration of flooding</li> <li>• Dynamic representation of floodplain wetting and drying</li> </ul>	Certain users may need to understand how the inundation extent will evolve – from onset, to peak, to recession. Others may only require information on the onset or maximum inundation.
Spatial coverage	<ul style="list-style-type: none"> <li>• Local scale (for example, town or river reach)</li> <li>• Regional scale (for example, county, catchment or river basin)</li> </ul>	Spatial coverage is the physical area that a given product could cover.

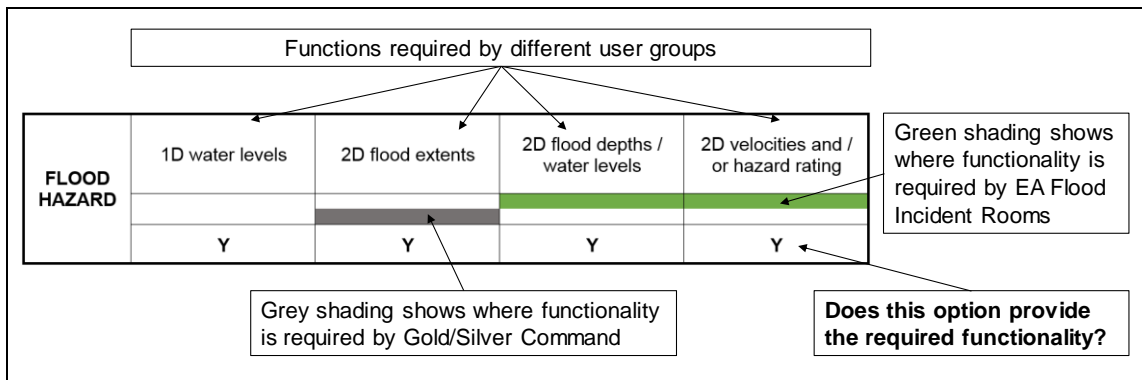
Acceptability criteria	Sub-categories	Commentary
	district) <ul style="list-style-type: none"> <li>National scale (that is, complete coverage across England)</li> </ul>	
Suitability	<ul style="list-style-type: none"> <li>Property</li> <li>Street to town</li> <li>Town to county</li> <li>County to national</li> </ul>	A flood map might have spatial coverage across the entire country, but not be suitable for property level assessments. For example, the NaFRA is a national product, but is available at 50m resolution and therefore less suited to analysis at the scale of individual properties.
Asset representation	<ul style="list-style-type: none"> <li>Flood defences</li> <li>Culverts and bridges</li> <li>Other structures (for example, gates, sluices, storage areas, pumping stations)</li> </ul>	Some existing mapping is undefended and therefore ignores the presence of flood defences. Some real-time modelling methods can include these defences but not represent smaller scale structures or blockage impacts.
Asset performance	<ul style="list-style-type: none"> <li>Breach inundation and/or overtopping: single asset failure</li> <li>Breach inundation and overtopping: multiple asset failure</li> <li>Within-event asset deterioration/failure</li> <li>Worst case breach inundation</li> </ul>	Has possibilities for incorporating defence failure or breach into the modelling.
Transparency	<ul style="list-style-type: none"> <li>Individual components can be interrogated/evaluated</li> <li>Closed system, simplified 'whole model' confidence statements only</li> </ul>	Can the various modelling components be interrogated so that weaknesses can be identified? Alternatively, have data been derived externally, so it is only possible to make generic confidence statements?

## 2.4.2 Evaluation matrix

Each technical option was then assessed in terms of its ability to meet the acceptability criteria. The appendices to this report present the findings as an 'evaluation matrix' for each option taken to PoC experiment stage.

Figure 2.2 explains the contents of the evaluation matrix, while Figure 2.3 shows the evaluation matrix for fully dynamic fluvial modelling (see Section 3.1) as an example.

- Each row of the table presents the **acceptability criteria** in terms of the functions required by different user groups. For example, a user group may require local, regional or national spatial coverage.
- The **user groups** are shown as coloured bars along each row of the table – Flood Incident Rooms are shown by green bars and Gold/Silver Commands are shown by silver bars. Shaded bars show that a given user group requires the given functionality.
- If the option provides a given function, it is assigned a ‘Y’. This process was preferred to a more subjective approach such as assigning a score from 1 to 5. However, it is acknowledged that an option rarely answers acceptability criteria in clearly binary terms. Some subjectivity therefore remains.



**Figure 2.2 Annotated example of an evaluation matrix**

F U N C T I O N A L R E Q U I R E M E N T S	<b>FLOOD SOURCE</b>	Fluvial	Coastal	Surface Water	Groundwater	All sources
		Y	Y	Y		
	<b>FLOOD HAZARD</b>	1D water levels	2D flood extents	2D flood depths / water levels	2D velocities and / or hazard rating	
		Y	Y	Y	Y	
	<b>TEMPORAL INFORMATION</b>	Onset of floodplain inundation	Time of maximum inundation	Duration of flooding	Dynamic representation of floodplain drying	
		Y	Y	Y	Y	
	<b>SPATIAL COVERAGE</b>	Local scale (e.g. town)	Regional scale (e.g. county)	National scale		
		Y	Y	Y		
	<b>SUITABILITY</b>	Property	Parcels of land to street	Street to town	Town to county	County to national
		Y	Y	Y	Y	Y
<b>ASSET REPRESENTATION</b>	Flood defences	Culverts and bridges	Other structures (e.g. gates, sluices, storage areas, pumping stations)			
	Y	Y	Y			
<b>ASSET PERFORMANCE</b>	Breach inundation and overtopping: single asset failure	Breach inundation and overtopping: multiple asset failure	Within-event asset deterioration / failure	Worst case breach inundation		
	Y	Y	Y	Y		
<b>TRANSPARENCY</b>	Individual components can be interrogated / evaluated	Closed system, simplified model-wide confidence statements				
	Y					

Figure 2.3 Example evaluation matrix: fully dynamic fluvial modelling

### 2.4.3 Scoring system

The evaluation matrices were then used to derive a numerical score for each option. Figure 2.4 provides a generic example of how the scores were calculated for each acceptability criteria category. The generic example also explains how each functional requirement was scored.

<b>FLOOD HAZARD</b>	1D water levels	2D flood extents	2D flood depths/ water levels	2D velocities and/or hazard rating
		Y	Y	

In this example, the option meets:

- One out of two flood hazard requirements for the flood incident room (green bars).
- One out of one flood hazard requirements for Gold/Silver Command (grey bar).

Assuming that the needs of each user group should be met equally, the score for this requirement is  $0.5 \times (1/2 + 1/1) = 0.75$ .

#### Figure 2.4 Generic example of score calculation

This process was repeated for each acceptability criteria category. An average score was then calculated for each option, across all acceptability criteria and user groups.

Finally, the scores were assigned a weighting corresponding to the number of properties affected by the given type of flooding (Table 2.5). The weightings were based on property numbers, as these are readily available from the Long-term Investment Strategy (LTIS) 2014 (Environment Agency 2014). However, potential economic damage and disruption may also vary by the type of flooding.

The purpose of the weightings is to enable the scoring to reflect the potential benefits of the option in question. For example, a groundwater option might score highly in all aspects, therefore receiving an overall score comparable with a surface water option. However, the benefits of implementing a surface water forecasting system will be wider reaching; in England, nearly 10 times the number of properties are at risk from surface water flooding than from groundwater flooding (Environment Agency 2014).

**Table 2.5 Weighting factors applied to option scores**

Flood source	Weighting	Explanation
Fluvial and coastal	2.4	2.4 million properties are at risk from fluvial and coastal flooding in England <sup>1</sup>
Surface water	3.0	3 million properties are at risk from surface water flooding in England <sup>1</sup>
Groundwater	0.3	~290,000 properties are at risk of groundwater flooding in England (BGS 2015)
All sources	0.6	600,000 properties are at risk from fluvial, coastal and surface water. <sup>1</sup> These properties could therefore benefit directly from combined, rather than individual, systems.

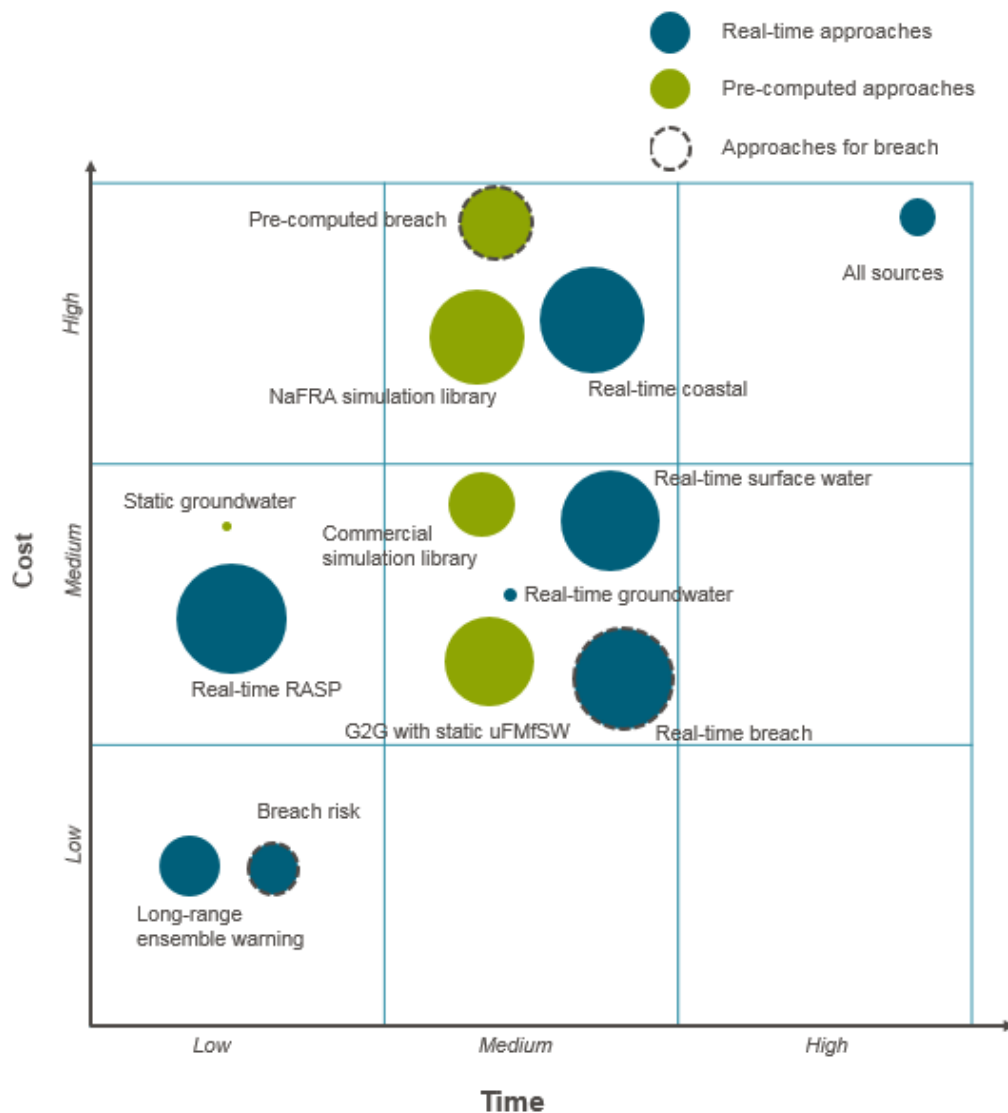
Notes: <sup>1</sup> Environment Agency (2014)

## 2.5 Results of the appraisal

The results of the scoring process are presented as a cost–time diagram (Figure 2.5). This provides an overview of the weighted score assigned to each option (shown by the size of the circles in the diagram) alongside the investment of time and cost required for their development.

Detailed scores and a commentary on each option are given in Table 2.6.





**Figure 2.5 Cost–time diagram**

Notes: RASP = Risk Assessment for Strategic Planning; uFmFSW = updated Flood Map for Surface Water

The most important findings are summarised below.

- There are obvious outliers. For example, the all-sources option has high cost and time requirements, but provides limited benefit because there are fewer properties that would benefit directly from a combined system (see Table 2.5). Conversely, real-time RASP could be a relatively quick win option and achieve considerable benefit.
- Many options score reasonably – meaning that they require medium time/cost inputs while providing moderate to large benefits.
- Groundwater options offer particularly low benefits. This is predominantly a result of the weighting process (penalising options that benefit fewer properties), but is an important conclusion.
- There are 2 quick win, low-cost options that provide reasonable benefits – breach risk (option 11 in Table 2.3) and long-range ensemble warning system (option 10).

Two options had been assessed by other projects and were therefore not considered further by this study.

- Option 4 (updated Flood Map for Surface Water based library linked to G2G run-off outputs). This scored highly, but had already been prototyped as part of the NHP SWF HIM programme and, at the time of writing, testing of the prototype system was ongoing. The NHP project will also consider findings from this study in relation to real-time surface water modelling.
- Option 7 (real-time coastal modelling system). Existing coastal forecasting systems generally use look-up based approaches. Coastal look-ups are not therefore been proposed here as they already exist, if not in a nationally consistent form. At the outset of this project, no work had explored the value of transitioning to a fully real-time system or which components of the system might benefit most from being run in real-time. These questions were addressed by project SC140007 (Environment Agency 2016), alongside a comprehensive assessment of coastal forecasting and therefore were not considered further in this study.

Table 2.6 shows the ranked position of the technical options, their overall score and a commentary that elaborates on each option. The table also highlights those shortlisted to be progressed to the PoC experiment stage of the project (see Section 3).

**Table 2.6 Scoring and commentary for options ordered by overall ranking**

Option		Rank [weighted score]			Commentary
		Overall	FIR	GSC	
5	Real-time RASP for fluvial and coastal inundation modelling	1 [2.02]	1 [2.12]	2 [1.92]	<ul style="list-style-type: none"> <li>Ranks highly across all groups</li> </ul>
7	Real-time coastal modelling system	2 [1.92]	3 [1.99]	3 [1.86]	<ul style="list-style-type: none"> <li>High cost</li> <li>Benefits gained by using a real-time system over what is currently available are not clear; further scoping recommended</li> <li><b>Not taken forward to PoC experiments</b> – considered by project SC140007 (Environment Agency 2016)</li> </ul>
12	Real-time breach inundation	3 [1.81]	2 [2.08]	6 [1.53]	<ul style="list-style-type: none"> <li>Ranks highly overall and particularly for FIR</li> <li>Potentially better if implemented within ‘real-time RASP’ option rather than on its own</li> </ul>
6	Real-time surface water linked to G2G or NWP	4 [1.76]	4 [1.95]	5 [1.58]	<ul style="list-style-type: none"> <li>Ranks highly across all groups</li> <li>High benefit versus cost–time</li> </ul>
1	National simulation library using NaFRA models and data	5 [1.70]	6 [1.27]	1 [2.12]	<ul style="list-style-type: none"> <li>Ranks highly for GSC but likely to be very expensive (requires the national NaFRA re-run MDSF2 and modifications to model)</li> </ul>
4	Updated Flood Map for Surface Water based simulation library linked to G2G run-off outputs	6 [1.61]	5 [1.76]	8 [1.45]	<ul style="list-style-type: none"> <li>Ranks highly across all groups</li> <li><b>Not taken forward to PoC experiments</b> – already trialled by NHP, so no value added by repeating here; provides a useful comparison to option 6</li> </ul>
13	Pre-computed breach inundation	7 [1.32]	8 [1.11]	6 [1.53]	<ul style="list-style-type: none"> <li>Potentially very high cost but with low benefits</li> <li>Difficult to envisage how such a large pre-computed modelling task could be completed efficiently and how key assets would be identified.</li> <li><b>Not taken forward to PoC experiments</b> – would require computation of many thousands of combinations of asset locations, asset failure states and water level loadings. This in turn would require large volumes of data storage for the pre-computed flood maps, especially if carried out on a national scale.</li> <li>Real-time assessment of breach risk is considered elsewhere (option 11).</li> </ul>

Option		Rank [weighted score]			Commentary
		Overall	FIR	GSC	
2	National simulation library using commercial (fluvial) flood map products	8 [1.16]	7 [1.16]	9 [1.16]	<ul style="list-style-type: none"> <li>Lack of defended scenarios and inability to consider breach makes this option unappealing at present.</li> <li>Otherwise a viable look-up alternative to using the NaFRA – scores equally among both groups</li> </ul>
10	Long-range ensemble warning system using NWP outputs	9 [1.11]	11 [0.46]	4 [1.76]	<ul style="list-style-type: none"> <li>Strong option for GSC; weak option for FIR</li> <li>Very quick win with low cost–time requirements</li> <li>Provides a different type of long-range output in comparison to all other options</li> </ul>
11	Breach risk ready reckoner	10 [0.92]	9 [0.82]	10 [1.02]	<ul style="list-style-type: none"> <li>Scoring artificially lowers score of this option (given that it does not directly generate inundation data).</li> <li>Strong case if coupled with ‘real-time RASP’ option</li> <li>Quick win</li> </ul>
9	All-sources inundation modelling	11 [0.55]	10 [0.58]	11 [0.53]	<ul style="list-style-type: none"> <li><b>Not taken forward to PoC experiments</b> – benefits not clear given the expense of combining inundation modelling of multiple flood sources.</li> </ul>
8	Real-time groundwater inundation using G2G	12 [0.15]	12 [0.17]	12 [0.14]	<ul style="list-style-type: none"> <li>In some areas that have historically experienced groundwater flooding, the Environment Agency provides a groundwater alert service. However, the benefits of extending this approach to derive national-scale groundwater flood mapping in real-time are unclear.</li> <li><b>Not taken forward to PoC experiments</b> – limited benefit provided to real-time flood incident management by implementing forecast groundwater flood maps on a national scale</li> </ul>
3	Static groundwater maps linked to borehole telemetry and NWP	13 [0.13]	13 [0.15]	13 [0.11]	
14	Fully dynamic fluvial modelling	NA	NA	NA	<ul style="list-style-type: none"> <li>This option was added to act as a baseline against which the PoC tests could be compared. An accepted and calibrated flood model is the best information currently available; the limitations of such models are relatively well understood compared with the other options.</li> <li>PoC experiment added after scoring and evaluation to act as a baseline of ‘best known information’.</li> </ul>

Notes: Ranking is from 1 highest to 13 lowest.  
Shading indicates the technical options shortlisted to be progressed to the PoC experiment development stage.  
FIR = Flood Incident Room; GSC = Gold and Silver Command; NA = not applicable

# 3 Proof of concept experiments

Section 2 details the long list of technical options considered by this project and discusses the rationale behind the shortlist selection (Table 2.6). This section introduces the PoC experiments based on this shortlist which were trialed to understand:

- their technical feasibility
- how they could be used
- their ability to accurately predict flood extents

Although the long-listing process (Section 2) identified examples of specific datasets that could be used in a forecasting system, the PoC experiments explored the options in a more generic way and considered alternative datasets, approaches and concepts where relevant. Although efforts were made to test all the key concepts from the preferred options, from here on the report refers to the overarching themes of the PoC experiments rather than specific shortlisted options. The PoC experiments are:

- fully dynamic fluvial modelling
- simplified fluvial modelling
- simulation library
- 10-day lead time NWP products
- simplified surface water modelling
- breach risk ready reckoner

Apart from simplified surface water modelling, all the PoC experiments relate to fluvial flooding.

Although each option was treated separately for the purpose of analysis, future operational systems could consist of a combination of options, in which different approaches are applied in different circumstances.

A brief technical summary of each PoC experiment is provided below. Full details are given in the pro-formas, provided as in Appendices 4 to 8 of this report (a PoC experiment was not produced for the breach risk ready reckoner – see Section 6.2.6 for a discussion of this option).

## 3.1 Fully dynamic fluvial modelling

This option applied linked 1D–2D hydrodynamic models to generate maps of flood extent and depths. River channels were simulated in 1D and dynamically linked to a 2D model of the floodplain.

Flow time series were applied at model boundaries. In the PoC experiments, observed time series at gauging stations are used to provide model boundary conditions. Operationally, forecast flows from the NFFS or G2G could be used instead. In some circumstances, level time series might also be required, for example, at a tidal downstream boundary. However, none were tested by this study.

1D–2D modelling is widely used by the Environment Agency and other organisations to produce detailed floodplain mapping. It is arguably the most detailed flood mapping

product that is routinely available to the Environment Agency, as it includes high levels of flow process representation (1D or 2D shallow water equations) and topographic detail (in-channel structures and floodplain features).

In this project, outputs from 1D–2D models were used as a baseline against which other options can be compared. All the case studies use existing models, which have been calibrated, validated and accepted for use by the Environment Agency. Although 1D–2D models can of course still be incorrect (depending on their input data, calibration, configuration and so on), they are considered the best available data (i.e. not necessarily the correct answer, but the best we have for the range of flood magnitudes and scenarios).

## 3.2 Simplified fluvial modelling

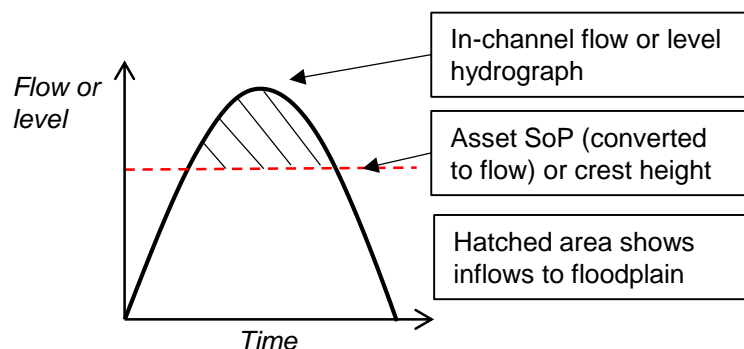
This option used suitably fast flood spreading models to derive depths and extents on the floodplain. To demonstrate the approach, this project used a fast, graphics processing unit (GPU) accelerated 2D hydraulic model, based on the shallow water equations. The main difference between this approach and fully dynamic fluvial modelling is that it applies a simplified representation of the channel–floodplain system. In-channel areas are not explicitly modelled and there is no dynamic link between channel and floodplain.

Inflows to the floodplain were based on predictions of:

- in-channel flows or levels
- asset crest heights or standard of protection

Figure 3.1 shows, in conceptual terms, how these data are used. Inflow volumes were derived as per the specific RASP methods implemented within the Modelling and Decision Support Framework (MDSF2). The full set of equations is described in Environment Agency (2005) and can be easily implemented outside of the MDSF2 software.

In this approach, inflows are derived on a per defence basis or, in undefended areas, lengths of high ground. The volumes are calculated using a simplified form of the broad crested weir equation and a number of simplified relationships that vary with asset type.



**Figure 3.1 Conceptual diagram of inflow calculations for simplified fluvial modelling**

One advantage of this approach is that inflow volumes can be calculated for both breached and non-breach cases.

River gauges do not, by themselves, provide sufficient spatial density to accurately represent in-channel conditions at every location where floodwater could overtop onto the floodplain. This project used 1D–2D hydraulic models to predict in-channel flows and levels. However, there are a number of alternative approaches such as NFFS forecasting models, G2G or interpolation of AEPs along the river network. These are discussed further in Section 4.1.2.

### 3.3 Simulation library

The simulation library option used pre-computed floodplain depth grids to estimate the depth and extent of flooding that might be expected for in-river conditions in a given event.

A set of look-up tables was pre-computed using the State of the Nation MDSF2 baseline models. These were run offline to obtain a ‘defences in place and none fail’ set of floodplain depth grids for each of the 40 NaFRA return periods ranging from 1 in 1 year to 1 in 1,000 years. In real-time, the look-up tables can then be used as surrogates for running the R Flood Spreading Model (RFSM) within MDSF2 for in-river conditions.

In-river flow or level estimates (from river gauges or forecast locations, as used in the NFFS) can be converted to return periods based on local flood frequency analysis. These can be interpolated more robustly along the river network than the flow/level measurements themselves. An approach was developed within the joint Defra/Environment Agency R&D project, Spatial Coherence – Risk of Widespread Flooding (SC060088). This method interpolates return periods along the watercourse using a comparison of the centroids of the catchment area upstream of each interpolation point with those at river gauges where design flow has been estimated.

Return periods are then allocated to the individual NaFRA assets. At this point, the depths can be read (and interpolated where necessary) from the look-up tables to give the flood depths and extent for the event being simulated. As such, the option provides only a ‘snapshot’ of flood inundation for a particular set of flow/level observations, although it can be run at multiple instances throughout an observed/forecast time series.

The State of the Nation MDSF2 baseline models provide a robust national set of models on which to build a complete set of operational forecasting models. The models have been subject to an intensive programme of data and method improvements, and the input data have been reviewed and updated where necessary by local, knowledgeable Environment Agency staff. Other advantages of using the State of the Nation baseline models include consistency of approach between the risk and forecasting models, and extremely fast run times for real-time use.

However, outputs from MDSF2 models can be inconsistent with flood risk information based on local detailed modelling. Any subsequent operational implementation will therefore need to consider how to incorporate local data better where these are available.

### 3.4 10-day lead time NWP products

This option makes use of 10-day lead time NWP ensemble (probabilistic forecast) products, which are run at the ECMWF in collaboration with the European Commission’s Joint Research Centre (JRC). Data for assessing this PoC experiment were kindly provided by the ECMWF and JRC.



The ECMWF derives a number of flood indices based on NWP products. This project assessed how 2 of these could be used to support real-time flood impact mapping. They were:

- Extreme Run-off Index (ERI) – currently a research product (Alfieri et al. 2013)
- European Flood Awareness System (EFAS) – an operational forecasting system hosted by the ECMWF (<https://www.efas.eu>)

The Environment Agency is an EFAS partner and is therefore able to access the real-time forecasts from these products free of charge.

The outputs of the flood indices based on ECMWF modelling are predictions of exceeded return periods (provided by ERI) and modelled flows (EFAS). The PoC experiment assessed how these could be used operationally by comparing ERI and EFAS to return periods derived using standard flood frequency techniques or observed flow time series respectively. Regression relationships were built between the modelled and observed products. Testing was then carried out into how these could be used to inform long-range planning and linked to flood impacts.

These outputs could be further combined with pre-computed libraries of flood impacts to estimate the potential consequences. For example, a postcode-level dataset of properties at risk could be pre-computed for given pre-defined flows or AEPs. This could be compiled from existing mapping with national coverage, for example, Risk of Flooding from Rivers and Sea (RoFRS) and/or commercial flood mapping. Forecast flows could then be compared with this dataset to estimate flood impacts, with interpolation between the pre-computed impact assessments as necessary.

Alternatively, the approach could be coupled with a 2D inundation model (for example, the simplified fluvial modelling PoC tested in this study) or the pre-computed simulation library PoC experiment. The final output from this process would therefore be a broad-scale long-range ‘hotspot’ map of likely flood impacts.

There is likely to be much uncertainty in these approaches and considerable further work would be needed around model set-up and performance (infiltration rates for example). In addition, known forecasting shortfalls associated with the NWP (under specific situations) should be further investigated.

### 3.5 Simplified surface water modelling

The updated Flood Map for Surface Water provides high resolution surface water flood mapping with national coverage. The underlying models are fast, GPU-accelerated 2D hydraulic models, which can receive rainfall or flow inputs and are used to predict flood depths and velocities. Environment Agency (2013) gives details about the models and methods used to produce the updated Flood Map for Surface Water.

The PoC experiment re-runs existing updated Flood Map for Surface Water hydraulic models in real-time, driven by G2G surface run-off grids. This type of direct rainfall modelling has been successfully implemented to produce surface water flood maps at all spatial scales and is widely accepted as an appropriate method for analysing higher magnitude, lower probability storms, where subsurface drainage systems are likely to be overwhelmed and/or inlet capacities exceeded (Defra 2010).

The ongoing NHP SWF HIM programme is developing a prototype surface water flood forecasting system, with national coverage. The approach is based on linking G2G surface run-off forecasts with libraries of flood impacts pre-computed using updated Flood Map for Surface Water outputs.

The PoC experiment produces equivalent outputs to the pre-computed approach. However, its main advantage is that it avoids having to relate a limited set of pre-computed flood outlines (3–9 scenarios), based on design rainfall, to G2G run-off estimates that vary spatially and over time. The NHP project will further evaluate the benefits of real-time versus pre-computed surface water modelling. The testing for this project will help to inform this work.

### 3.6 Breach risk ready reckoner

Fragility curves – available for both coastal and fluvial assets – are used in MDSF2 to determine the probability of defence failure given an asset's type, condition grade and loading (that is, overtopping rate or water level).

In fluvial settings, these curves can be combined with telemetered/forecast water level information – either available directly from NFFS or through the same river network interpolation look-up approach that underpins the simplified fluvial modelling and simulation library PoC experiments – to identify where particular assets have an increased probability of failure during a flood event. Individual flood defences can then be categorised by probability of failure (for example, Low, Medium, High) and combined with pre-computed, per asset risk data (for example, relative/absolute contributions to the NaFRA estimated annual damages) to provide indicative information on the likelihood and impact of breaching at these locations.

The PoC experiment can be implemented very efficiently by reusing software modules and data from MDSF2 and the State of the Nation risk modelling project respectively. As is the case for all of the other options investigated, important flood defence parameters (for example, crest level and condition grade) could also be updated during an event where suitable telemetry or local knowledge is available.

# 4 Methods and data for testing shortlisted options

This section outlines the approach used to develop the PoC experiments. The aims of the PoC testing are summarised by a series of research questions, which are discussed below. Details about the available data and the methods used to evaluate the options are also provided. Section 5 presents specific case studies and the datasets provided.

All the PoC experiments are based on datasets, models or systems that the Environment Agency already holds or can access readily. Where numerical models have been used, these are based on existing models and software that have been accepted by the Environment Agency for operational use. This project therefore does not assess the detail of how individual models have been set up (for example, model parameterisation). Rather its purpose is to explore how these datasets can be used in different context (that is, to provide flood impacts mapping in real-time).

Detailed findings for each PoC experiment are provided in a pro-forma (see appendices). Section 4.2 outlines how the information is presented in a pro-forma.

## 4.1 Assessing the options

### 4.1.1 Research questions

Earlier stages of the project identified user requirements and shortlisted a number of technical options with the potential to meet those needs. This phase of the project explored each option in more detail, leading to the development of 6 more generic experiments to take forward for PoC testing (see Section 3).

The scope of the project was to understand how the options can be used rather than developing operational software, and is analogous to assessing 'functional requirements' in the software development process. The project's objectives are summarised in 3 research questions (Table 4.1). These questions also provide evidence to support future considerations about implementing the options (see Section 7).

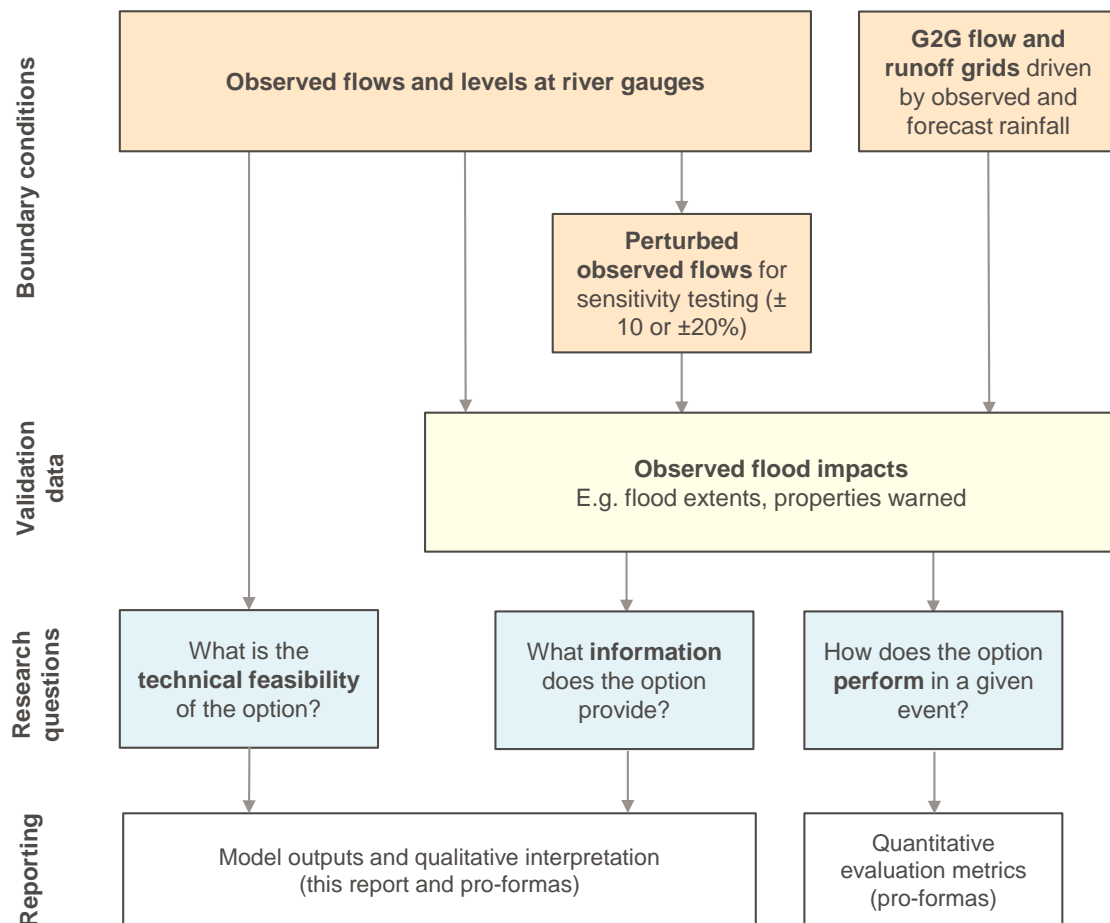
**Table 4.1 Research questions summarising the project's objectives**

Question	Objectives
<b>1. What is the technical feasibility of the option?</b>	<ul style="list-style-type: none"><li>• Developing the methods required to implement the option</li><li>• Understanding the data requirements at each stage in the process</li><li>• Uncovering technical barriers or challenges (for example, model run times)</li></ul> <p>Future projects will address operational software needs and compatibility with existing forecasting platforms (non-functional requirements) – these will</p>

Question	Objectives
	be defined by the Environment Agency.
<b>2. What information does the option provide?</b>	<ul style="list-style-type: none"> <li>• Assessing how the information provided by the option could be used operationally, including its fit to user requirements</li> </ul> <p>Future projects will evaluate specific data sources for implementation in operational systems.</p>
<b>3. How does the option perform?</b>	<ul style="list-style-type: none"> <li>• Evaluating the performance of the option in case studies (by comparing with observations of past flood events) – this included quantitative metrics that summarise model performance in terms of accuracy, overprediction and underprediction</li> <li>• Testing how the options could be combined with different types of forecast input (based on forecasts of the type provided by NFFS or G2G)</li> <li>• Testing the sensitivity of the option to boundary condition specification (for example, how variability introduced by forecast uncertainty propagates to flood extents)</li> </ul>

The flow chart in Figure 4.1 shows the overall approach to testing the PoC experiments. The flow chart sets out how various boundary condition datasets (introduced in Section 4.1.2) were used to drive the PoC experiments. This allowed outputs from the PoC experiments to be compared with observations of flooding (Section 4.1.3) and flood receptors (Section 4.1.4) and so to address each of the research questions. Section 4.1.5 explains the methods used to assess the PoC experiments.

An overview of the available data is given below. Section 5 details the case studies and the specific data available in these flooding events.



**Figure 4.1** Flow chart summarising the methodology used for PoC testing

## 4.1.2 Boundary conditions

All the fluvial PoC experiments require accurate prediction of in-channel flows or levels to drive the derivation of floodplain mapping. Existing fluvial forecasting systems (NFFS) already provide river forecasts, normally at river gauges, which are linked to Flood Warning Areas. However, NFFS does not provide maps of flood extent, and forecast locations or river gauges are rarely of sufficient spatial density to infer flows or levels at any point in the catchment. Accurate floodplain mapping requires predictions of in-channel conditions throughout the river network.

This project considered a number of approaches to derive the boundary conditions required by the PoC experiments in order to link each option to forecasts of the type currently provided by NFFS. Each approach is discussed in turn below. All are based on models or datasets that are readily available to the Environment Agency. In all cases, the boundary conditions provide time series of flow or level for a given location in the river network. The purpose of the PoC experiments is to receive these time series as the boundary condition to generate floodplain mapping.

Surface water flood modelling requires different boundary conditions to the fluvial options. In this project, the PoC experiments were tested using surface run-off grids from the G2G hydrological model. This is discussed further below.

Flood indices based on 10-day lead time NWP products do not produce detailed flood extent mapping and are instead driven by probabilistic rainfall forecasts. The pro-forma for the NWP PoC experiment gives specific details of its boundary condition requirements.

### *Observed flows and levels*

Where the PoC experiment explicitly models the river channel (for example, 1D–2D hydraulic modelling), boundary conditions were provided by observed flow time series at river gauges. The PoC experiment itself then routes flows through the river network.

Using observed data demonstrates the simulation performance of the PoC experiment, isolating its performance from uncertainties introduced by forecast datasets (for example, uncertainty in rainfall forecasts).

As a separate test, these data were also adjusted by arbitrary amounts ( $\pm 10\%$  or  $\pm 20\%$ ) to test the sensitivity of the PoC experiments to boundary conditions.

### *Hydraulic modelling*

Apart from fully dynamic fluvial modelling, the PoC experiments do not explicitly model the river channel. However, most of them still require flows or levels to be derived locally.

In the PoCs tested in this study, 1D–2D dynamically hydraulic models were used to route observed flows through the river network to calculate local in-channel flows and levels. The models consist of schemes that solve the 1D or 2D shallow water equations. These schemes provide the most detailed representation of river channel and floodplain flow routing that is widely available to the Environment Agency.

Other options that could be considered operationally include lower complexity 1D only hydraulic models or flow routing models. Both types of model are currently used within NFFS to provide flood forecasts.

### *G2G surface run-off and flow grids*

The G2G model developed by the Centre for Ecology and Hydrology is a forecast product used by the joint Met Office/Environment Agency Flood Forecasting Centre. Operationally, it receives the outputs of NWP-based rainfall forecast models. It predicts run-off and flow routing at 15-minute time-steps for a 1km x 1km grid of the UK. The Environment Agency aim to embed G2G outputs within future flood forecasting systems and so it will have the potential to drive the PoC experiments where there are no local forecasting models such as hydraulic models.

Because G2G is driven by probabilistic rainfall forecasts (such as a 12- or 24 member ensembles), it provides probabilistic flow forecasts. This study used the variability between different ensemble members to demonstrate how uncertainty in forecast boundary conditions propagates to modelled flood extents.

G2G river flow or surface run-off grids were available for each case study. Fluvial PoC experiments were driven by flow grids, while surface run-off grids were the main input to the simplified surface water modelling PoC experiment. Each G2G dataset is based on the rainfall forecast product that was available at the time of the event. Note that improvements in rainfall forecasting since the time of the case study events –

particularly in the spatial and temporal resolution of the data available – will increase the quality of forecasts derived from G2G in the future.

The main limitation of this approach is that G2G outputs are relatively coarse (1km resolution). Some subjectivity also remains in assigning outputs from a given G2G grid cell to the boundaries of a PoC experiment. Nonetheless, the use of G2G in testing the PoC experiments demonstrates how broad-scale forecasts can be ‘downscaled’ to guide local tactical responses to a flood event.

### *National Fluvial Flows Database and National Fluvial Levels Database*

Interpolation of return periods along the river network provides many possibilities for real-time flood mapping. The method was developed by the joint Defra/Environment Agency R&D project, Spatial Coherence – Risk of Widespread Flooding (SC060088) and was applied in the H21 Evidence Update for National Risk Assessment 2016.

This approach is more robust than interpolating the actual flow/level values along the river network, It is also more straightforward to implement on a wide scale than local hydrodynamic modelling (although hydrodynamic models provide accurate modelling of flows/levels along watercourses). The approach developed by the SC060088 project converts flows/levels (at a river gauge) to an AEP, interpolates the AEP along the river network and then looks up the local flow/level value.

Interpolated return periods can be linked to look-up databases to provide local estimates of flow or level. National coverage is already available through 2 datasets:

- National Fluvial Flows Database – provides estimates of flow for 9 return periods at approximately 1km intervals throughout the river network (based on the Environment Agency’s Detailed River Network dataset). Flow estimates and hydrograph shapes are based on Flood Estimation Handbook catchment descriptors and rainfall–run-off methods. The H21 Evidence Update for National Risk Assessment 2016 provides national coverage. Flows are estimated for the 50, 20, 10, 4, 2, 1.33, 1, 0.5 and 0.1% AEPs.
- National Fluvial Levels Database – provides estimates of level for 40 return periods (as applied in the NaFRA) at 100m intervals along Environment Agency designated Main River and Critical Ordinary Watercourses. The dataset is recognised and maintained by the Environment Agency and is currently being updated by the ongoing State of the Nation risk modelling project.


In future, these datasets could be updated with local detailed modelling where available.

### **4.1.3 Validation data**

All the case studies considered by this project (see Section 5) have several sources of spatially distributed observations of flood extents and impacts. These data range from point-based local measurements to coarse resolution datasets, with wide spatial coverage. The main datasets are listed in Table 4.2.

The evaluation of the PoC experiments involved comparing their outputs with the available validation datasets for a series of past flood events. Section 5 gives specific details of the data available in each case study.

**Table 4.2 Validation data**

Data	Scale
<ul style="list-style-type: none"> <li>• Georeferenced photos and point measurements of water depth (in the Morpeth case study these were interpolated to provide a map of depths – see Section 5.1.1)</li> <li>• Aerial photographs or LIDAR, subsequently digitised into outlines of flood extent</li> <li>• Observed flood extents, based on wrack mark survey and reports of flooding</li> <li>• Records of Flood Warnings issued by the Environment Agency, for individual Flood Warning Areas</li> <li>• Media-based impacts data created by mining media reports of flooding</li> </ul>	<p>Point-based local</p>  <p>Coarse resolution, wide coverage</p>

Notes: LIDAR = light detection and ranging

#### 4.1.4 Receptor data

Deriving maps of flood inundation was the main focus of PoC test development. However, once flood inundation mapping is available, understanding impacts is a comparatively straightforward process which involves intersecting inundation maps with spatial information about flood receptors.

This project used properties within the flood extent to illustrate how the PoC experiments could be used to understand flood impacts. The Environment Agency's National Receptor Dataset was used as the source of property data and all property points (residential and non-residential) were considered.

Operationally, there is no technical reason why the analysis could not be extended to assess flood impacts on other receptors such as transport networks or critical infrastructure.

#### 4.1.5 Evaluating the options

The performance of the PoC experiments was evaluated by comparing their outputs with observations of flood events. Results were expressed in terms of differences in:

- flood extent and depth (where available)
- flood impacts (in this project, residential and non-residential properties within the flood extent) between modelled and observed datasets

This section describes the approach used to evaluate the options and a series of quantitative model evaluation metrics. Examples of figures and maps are presented in this section solely to illustrate how the results are presented; no interpretation of the model results is given here. Section 4.2 explains the results and interpretation, which can be found in the pro-forma appendices to this report.



## Model outputs

The pro-formas present modelled outputs from each PoC experiment for a series of case studies. In most cases, this takes the form of a map of modelled depths, annotated with a qualitative interpretation of the model results. These annotated maps provide a quick, visual presentation of the information that the PoC experiment provides and allow the user to interpret how the results could be used in practice. Other case studies provide results at specific point locations within the area of interest, where point-based observations were available (for example, photographs).

## Comparison of extent flooded (Test A1)

The first quantitative metric is a comparison of modelled and observed area flooded. This is calculated at the scale of the entire model domain. In locations where Flood Warning Areas have been delineated, however, the calculation is repeated for each Flood Warning Area. This allows more targeted assessment of the performance of the PoC experiment in distinct geographical areas; Flood Warning Areas are used to delineate the floodplain to identify where flood receptors are and the different communities at risk of flooding.

Results are presented as:

- **absolute values** of area flooded in modelled or observed outlines
- **percentage of Flood Warning Area flooded** in modelled or observed outlines, calculated for each Flood Warning Area (FWA) using Equation 4.1

$$\text{Percentage flooded} = 100 \times \frac{\text{Area flooded}}{\text{Area of FWA}} \quad (4.1)$$

## Model performance (Test A2)

Model performance scores were used to quickly assess:

- how well the modelled flood extent corresponded to observations
- whether there was systematic overprediction or underprediction

These metrics were again calculated for the entire model domain and each individual Flood Warning Area.

The scores are based on a contingency table (as in Table 4.3), in which the areas of observed and forecast outlines are compared to show whether the model predicts flooding correctly.

**Table 4.3** Contingency table for model performance

		Observed	
		Yes	No
Forecast	Yes	Correct wet (correct positives)	Overprediction (false alarms)
	No	Underprediction (misses)	Correct dry (correct negatives)

The following metrics were calculated:

- **Correct wet** – percentage of flood extent that is correctly predicted by the model
- **Overprediction** – percentage of flood extent that is overpredicted by the model
- **Under**— percentage of flood extent that is underpredicted by the model
- **Skill** – a single measure of model accuracy, calculated using Equation 4.2. The calculation is the same as for ‘correct wet’ above, but scores are presented on a range from 0 to 1, where 1 is a perfect match between the area shown as flooded in modelled and observed outlines.

$$SKILL = \frac{Area\ Correct\ Wet}{Area\ Correct\ Wet + Area\ Overprediction + Area\ Underprediction} \quad (4.2)$$

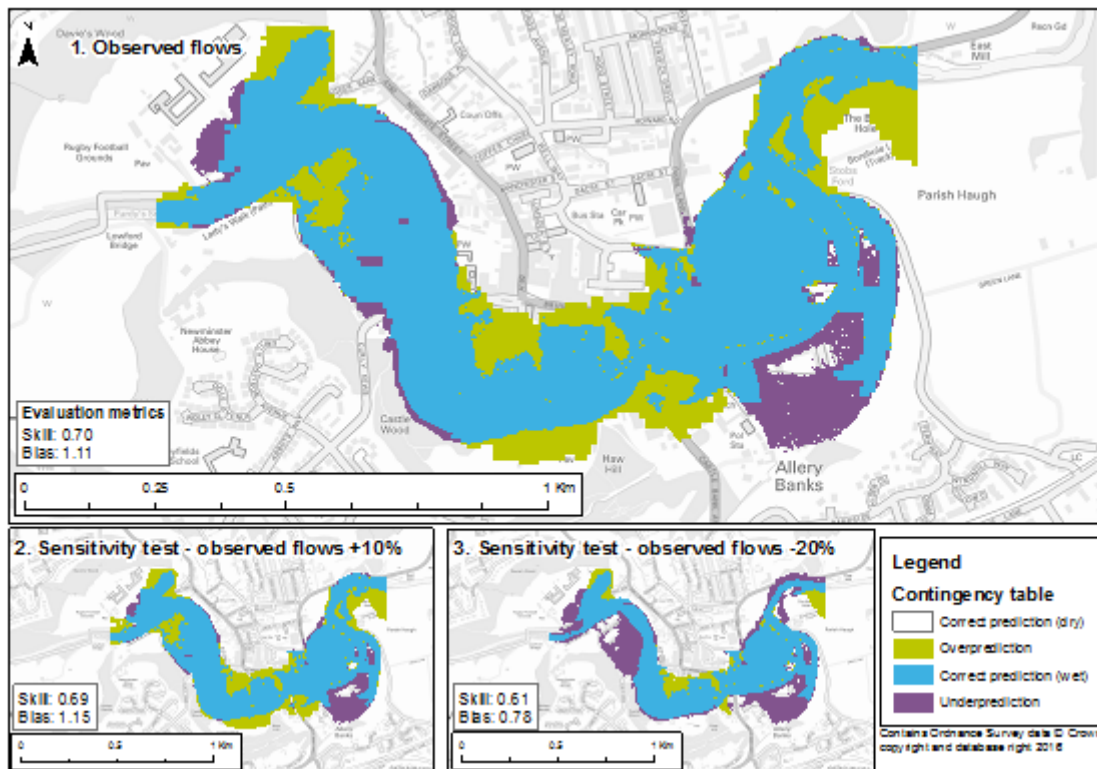
- **Bias** – a measure of systematic overprediction (values >1) or underprediction (values <1), calculated using Equation 4.3

$$BIAS = \frac{Area\ Correct\ Wet + Area\ Overprediction}{Area\ Correct\ Wet + Area\ Underprediction} \quad (4.3)$$

NB ‘Correct dry’ areas are never included in the scores, as this is heavily dependent on the outer extent of the model domain, defined during the model build.

The method was varied for the simplified surface water modelling PoC experiment, where maps of observed flood extent were not available. Instead, results were corroborated with those from a different hydraulic model to assess whether different modelling approaches predicted consistent patterns of flooding. Section 5.2.1 gives further details in relation to a surface water flood event in Newcastle upon Tyne in June 2012.

Maps are also presented to allow model performance to be viewed geographically. An example is shown in Figure 4.2.



**Figure 4.2 Example of model performance plots**

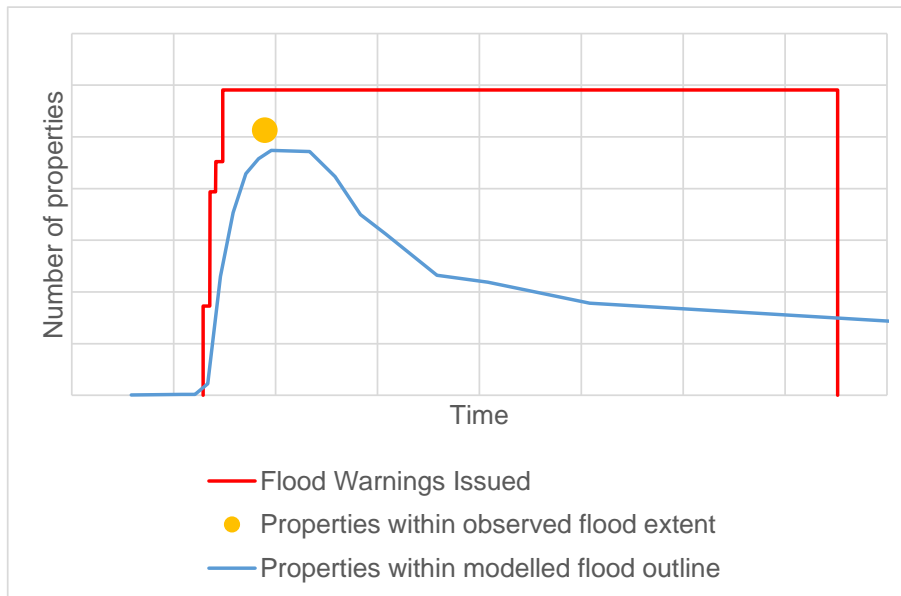
Notes: The maps show correct prediction (blue), model overprediction (green) and model underprediction (purple). Skill and bias scores are shown in the bottom left of the maps. The smaller inset maps show model performance in sensitivity tests. In this example, the boundary condition flows have been scaled by +10% and -20% respectively.

### *Property counts (Test B)*

Counts of the number of properties within the flood extents were derived by intersecting flood outlines with property point data from the National Receptor Dataset. The analysis was repeated for modelled and observed outlines. As before, numbers are reported for both the entire model domain and each Flood Warning Area.

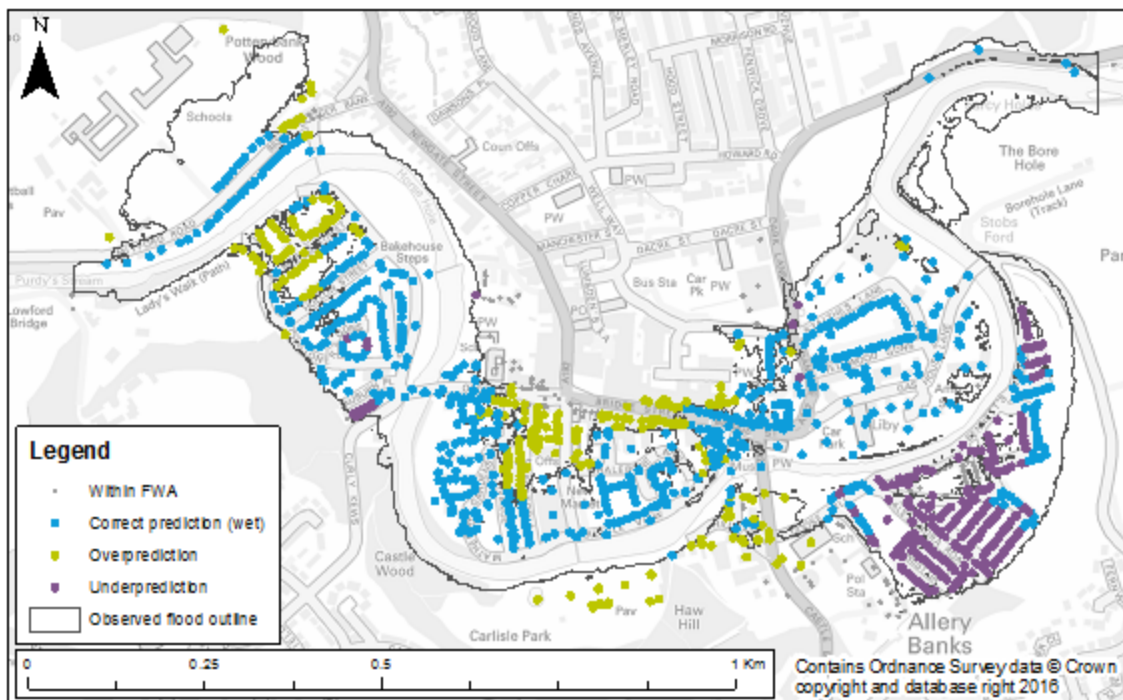
Figure 4.3 shows how numbers of properties were compared over the course of an event. The maps show correct prediction (blue), model overprediction (green) and model underprediction (purple). Skill and bias scores are quoted in the bottom left of the maps. The smaller inset maps show model performance in sensitivity tests; in this example, the boundary condition flows have been scaled by +10% and -20% respectively.

Operational decisions over the issue and withdrawal of flood warnings are, however, based on more information than model results alone and often require local expertise.



**Figure 4.3 Example of property counts as a time series**

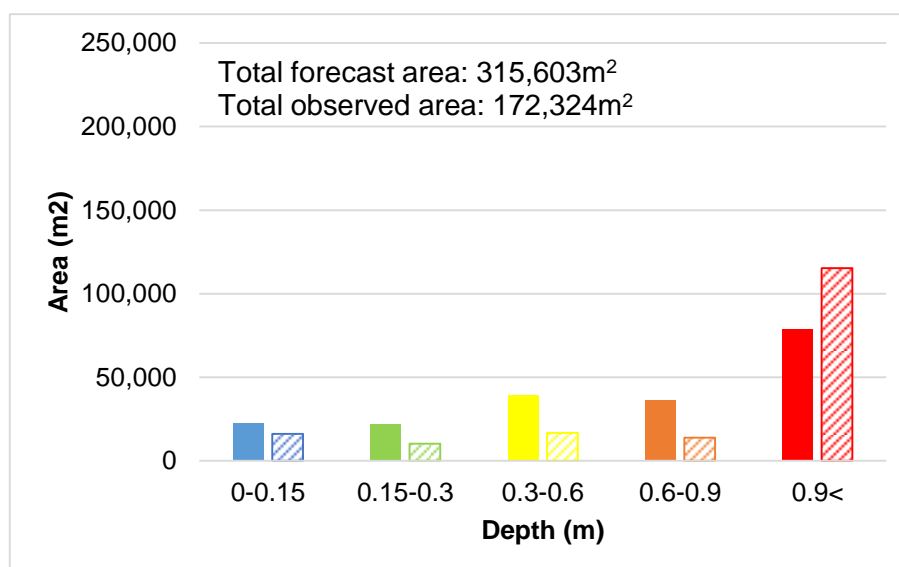
Properties were also mapped and colour-coded according to whether they fell within an area of the model domain that correctly, overpredicted or underpredicted, as in the example in Figure 4.4.



**Figure 4.4 Example of presentation of properties themed by model performance**

### *Depth analysis (Test C)*

Depth, hazard and velocity mapping were among the user requirements discussed in Section 2.1. Where the datasets allow, the distribution of modelled depths was presented as a histogram. Figure 4.5 shows an example which compares modelled depths (solid bars) with observed depth mapping (hatched bars).



**Figure 4.5 Example of how depth analysis is presented**

Notes: Solid bars indicate modelled depths and hatched bars indicate observed depth mapping.

Depths were banded into 5 categories (as shown on the x-axis of Figure 4.5), which are intended to aid the interpretation of flood impacts. Table 4.4 lists the categories and the potential impacts of flooding to this depth. The categories correspond to those used for the updated Flood Map for Surface Water, based on feedback from Lead Local Flood Authorities (Environment Agency 2013).

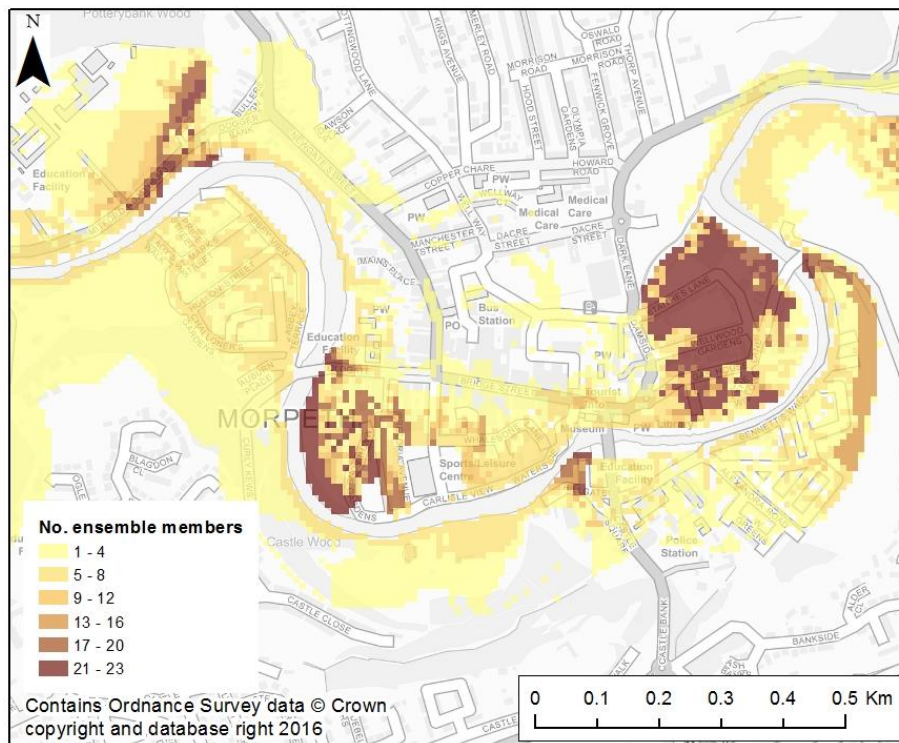
**Table 4.4 Depth categories**

Depth (m)	Potential impacts
0–0.15	Flooding has limited impact.
0.15–0.30	Flooding exceeds kerb heights on roads. At properties, water levels are likely to exceed the level of a damp-proof course.
0.30–0.60	Property flooding is likely based on average flood threshold levels, unless property level protection measures are in place.
0.60–0.90	Property level flood protection measures are typically effective up to 0.60m above floor level. However, as floor levels vary, flood protection measures may still be effective in some circumstances in the range from 0.60m to 0.90m.
>0.9	Flooding is likely to exceed property level flood protection measures.

### *Model outputs using G2G ensembles*

Where data were available and the run times computationally tractable, PoC experiments were run using G2G ensemble members. This demonstrates how G2G could be used to drive real-time flood mapping and the sensitivity of the PoC experiment to different boundary conditions. Results are presented as a map of modelled outlines, as in the example in Figure 4.6. Darker colours on the map show where greater numbers of ensemble members identify the same location as flooded.

Although not explicitly considered in this work, the ensemble information could be used in future to attribute flood receptors (for example, properties) with different likelihoods of flooding.



**Figure 4.6 Example of presentation of model outputs when driven by G2G ensemble members**

Notes: Darker colours on the map show where greater numbers of ensemble members identify the same location as flooded.

### *Approaches applied in specific PoC experiments*

In some cases, the nature of the available observed data required particular approaches to evaluate the PoC experiments. The PoC pro-formas in the appendices to this report describe specific approaches in detail.

Broad-scale outputs from 10-day lead time NWP products do not generate detailed flood mapping. However, they do provide estimates of river flow or event rarity. These were compared with flow time series at river gauges and corresponding estimates of AEP. See Appendix 7 for details.

The simplified surface water modelling option was evaluated by comparing model outputs to point-based photographs, depth measurements and more generalised anecdotal reports of flooding (for example, flooded roads), where available. It is rare to find comprehensive maps of the observed extent of surface water flooding. See Appendix 8 for details.

## 4.2 Reporting the outcomes of PoC testing

Section 6 of this report presents a summary of the findings for each PoC experiment. Here, the main points in relation to the technical feasibility, information provided by each option and model performance are discussed.

However, much of the detailed analysis is provided in a pro-forma for each PoC experiment. These are included as appendices to this report, with the intention that they provide a standalone reference document for each PoC experiment. Table 4.5 provides an overview of the structure of the pro-formas and where key pieces of information can be found.

**Table 4.5 Overview of the contents of the pro-formas**

<b>Pro-forma section number</b>	<b>Pro-forma section title</b>	<b>Description</b>
1	Summary	<ul style="list-style-type: none"> <li>• Gives an executive summary of the findings for the PoC experiment</li> </ul>
2	PoC overview	<ul style="list-style-type: none"> <li>• Describes the PoC experiment and how it meets user requirements</li> <li>• Provides technical details about how the option works</li> </ul>
3	PoC testing	<ul style="list-style-type: none"> <li>• Explains how the PoC has been tested in this project</li> <li>• Lists the case studies and evaluation tests that were applied</li> <li>• Includes details of model set-up, constituent files, run times and other information</li> </ul>
4	PoC evaluation	<ul style="list-style-type: none"> <li>• Presents the results – outputs from the PoC, evaluation metrics and interpretation of the results are presented in a subsection for each case study</li> </ul>
5	Implementation considerations	<ul style="list-style-type: none"> <li>• Notes items that should be considered if implementing this option in future, including a commentary of any major issues that were encountered during the PoC development</li> </ul>
6	Scope for further development	<ul style="list-style-type: none"> <li>• Provides details of how the option could be developed further or, in turn, may be affected by future developments (for example, updates to the datasets that provide boundary conditions)</li> </ul>

# 5 Case studies

This section describes past flood events that were used as case studies for PoC testing (3 fluvial events and 2 surface water events). All the case studies are relatively recent, high profile events, with widespread and readily available observations of flood extent and impacts.

Table 5.1 summarises the case studies and the data available for each. Further details about each case study and the available data are introduced in Section 5.1 (fluvial) and Section 5.2 (surface water).

**Table 5.1 List of case studies and available data**

Event	Boundary conditions	Validation data
<b>Fluvial events</b>		
Morpeth (6 September 2008)	Observed flows  G2G flow estimates, based on observed and ensemble rainfall forecasts	<ul style="list-style-type: none"> <li>• Surveyed flood depth maps (7) throughout the event, incident report (Parkin 2010) and georeferenced photos (courtesy of Newcastle University)</li> <li>• Record of Environment Agency Flood Warnings issued</li> </ul>
Cockermouth (19–20 November 2009)	As above	<ul style="list-style-type: none"> <li>• Aerial photography (single inundation snapshot)</li> <li>• Recorded Flood Outline (maximum extent)</li> <li>• Record of Environment Agency Flood Warnings issued</li> </ul>
Thames (9–13 February 2014)	As above	<ul style="list-style-type: none"> <li>• Aerial photography and satellite imagery</li> <li>• Recorded Flood Outline (maximum extent)</li> <li>• Record of Environment Agency Flood Warnings issued</li> </ul>
<b>Surface water events</b>		
Newcastle (28 June 2012)	G2G run-off estimates, based on observed and ensemble rainfall forecasts	<ul style="list-style-type: none"> <li>• HiPIMS model, georeferenced photos (Newcastle University)</li> <li>• Post-event measurements of observed depth</li> <li>• Media-based impacts database (Health and Safety Laboratory (HSL), King's College London (KCL) and the Flood Forecasting Centre, via the NHP SWF HIM project)</li> </ul>
Canvey Island (20 July 2014)	As above	<ul style="list-style-type: none"> <li>• Media-based impacts database (HSL/KCL/FFC via the NHP SWF HIM project)</li> <li>• Section 19 Flood Incident Report (Essex County Council 2014)</li> </ul>

Notes: HiPIMS = High-Performance Integrated Hydrodynamic Modelling System



## 5.1 Fluvial flood events

### 5.1.1 Morpeth, September 2008

The town of Morpeth in Northumberland has a long history of flooding from the River Wansbeck. One of the most severe events occurred on 6 September 2008, when about 1,000 properties were affected by flooding from the Wansbeck following 2 days of heavy rainfall (Parkin 2010).

After the event, flood levels were surveyed throughout the town. These were generally based on:

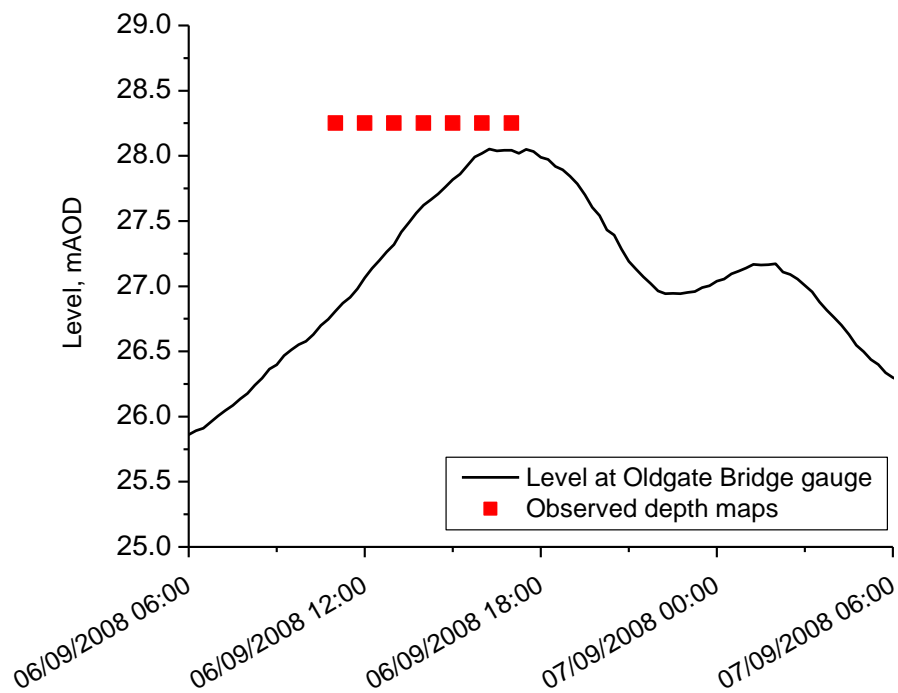
- wrack (debris from flooding)
- high water marks on buildings
- reports of flooding from residents

Together this information provides an estimate of maximum water levels and extent. However, the Morpeth event is unusual in that observations of floodplain water levels are also available throughout the event, based on photographs taken at known times and locations during the flood.

Parkin (2010) provides full details of the process by which around 2,000 photographs, videos and other records were used to quantify water levels. In summary, photographs were used to identify water levels against measurable features such as buildings. Where the time and location of a photograph was known, the location was visited and relevant measurements were collected to estimate flood depth. The resulting point measurements were then interpolated to provide a 2m resolution grid of flood depths at hourly intervals from 11:00 to 17:00 Greenwich Mean Time (GMT) (the event peak was around 17:00). Water levels were then calculated by adding the observed depth grids to a DTM based on 0.25m LIDAR.

The flood incident report compiled by Parkin (2010) also captures anecdotal evidence of flood mechanisms based on reports from residents. Taken together, the available observations enable the ability of different PoC experiments to accurately predict flood mechanisms and temporal evolution during the Morpeth event to be evaluated.

Figure 5.1 shows the times at which the depth maps fell in relation to the observed level hydrograph (at Oldgate Bridge gauge in Morpeth) during the event. Most of the observed depth maps are on the rising limb of the flood, with the final depth map falling around the peak.



**Figure 5.1 Morpeth, September 2008: observed depth maps and event hydrograph**

#### *Input data available*

- Observed flow and level time series at Mitford gauge (River Wansbeck) at 15-minute intervals
- G2G surface run-off and flow grids, driven by observed rainfall and UKV rainfall forecasts (24 members)

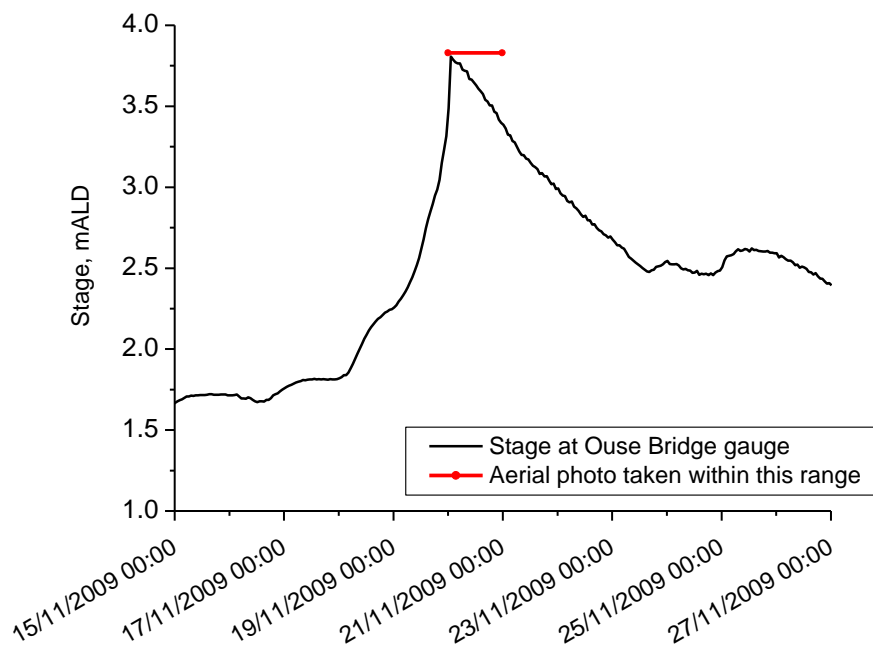
#### *Validation data available*

- Hourly depth maps (7 one-hourly intervals between 11:00 to 17:00 GMT inclusive)
- Environment Agency recorded Flood Outline
- Georeferenced photographs taken during the event
- Flood incident report (Parkin 2010)
- Environment Agency record of Flood Warnings issued during the event (for context only) – information was extracted from the Flood Warning Validation Database

### **5.1.2 Cockermouth, November 2009**

The north-west of England experienced prolonged heavy rainfall from 18 to 20 November 2009. The event was severe; at the time, Seathwaite in Cumbria observed the UK's highest rainfall for any 24-hour period, with 316mm of rainfall recorded on 19 November (Met Office 2016).

The event followed a lengthy period of wet weather, which meant that river catchments were already saturated and therefore generated high proportions of run-off. A number of towns were severely affected by the resulting river flooding, including Cockermouth at the confluence of the Rivers Derwent and Cocker, where an aerial photograph taken during the event shows the widespread extent of flooding. Figure 5.2 shows where the aerial photograph falls in relation to the event hydrograph at Ouse Bridge gauge (around 13.5km upstream of Cockermouth). The photograph was taken during the day on 20 November 2009 – no other specific time information was available. However, high water marks are visible in the photograph and so it is likely that it was taken shortly after the event peak.



**Figure 5.2** Cockermouth, November 2009: aerial photo and event hydrograph

Compared with Morpeth, the floodplain at Cockermouth is flatter and more expansive. Flood extents are therefore more sensitive to level than in Morpeth, where the floodplains are bounded by steeply rising high ground. The Cockermouth event therefore offers further rigorous testing of the ability of each PoC experiment to accurately predict flood extent.

### *Input data available*

- Observed flow and level time series at Ouse Bridge gauge (River Derwent) and Southwaite Bridge (River Cocker) at 15-minute intervals
- G2G surface run-off and flow grids, driven by observed rainfall and rainfall forecasts from the Met Office Global and Regional Ensemble Prediction System (24 ensemble members) (the data supplied for this project make use of the Met Office Global and Regional Ensemble Prediction System (MOGREPS) product available at the time of the event)

### *Validation data available*

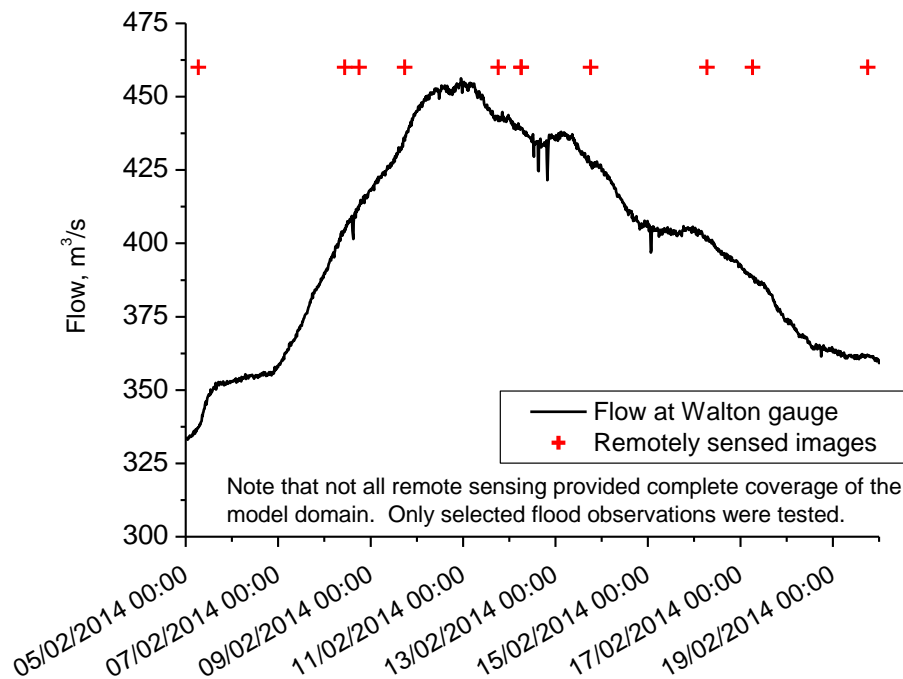
- Aerial photograph taken 20 November 2009, just after the peak

- Environment Agency recorded Flood Outline
- Environment Agency record of Flood Warnings issued during the event (for context only)

### 5.1.3 Thames, February 2014

A succession of storms throughout January and February 2014 resulted in widespread and prolonged flooding in the south of England, with at least 6,000 properties affected (Met Office 2015). The River Thames flooded along large parts of its length from Oxfordshire to Surrey. The event is notable for the long duration of flooding.

The case study focuses on a reach of the River Thames from Marlow in Buckinghamshire to Hammersmith in London. It tests the PoC experiments across a large catchment with multiple, interacting watercourses. Aerial photographs, LIDAR and satellite imagery (optical and radar) provide observations of flood extents over a wide area. Figure 5.3 shows the aerial photographs were taken just after the peak of the event, shown by the observed hydrograph at Walton gauge (Walton-on-Thames is towards the downstream extent of the model domain).



**Figure 5.3** Thames, February 2014: aerial photo and event hydrograph at Walton-on-Thames

#### *Input data available*

- Observed flow and level time series (15-minute intervals) at numerous river gauges and gauge stations along the Thames including those at Addlestone, Chertsey Bourne, Kingston, 'Maidlow',<sup>2</sup> Reading, Staines, Staines Moor, Staines Trading Estate, Thorpe, Walton, Weybridge and Windsor Park.

<sup>2</sup> A combination of flows from the Maidenhead and Taplow sluices

### *Validation data available*

- Flood outlines based on aerial photographs and LIDAR (taken 12 February 2014)
- Environment Agency recorded Flood Outline
- Environment Agency record of Flood Warnings issued during the event (for context only)

## 5.2 Surface water flood events

### 5.2.1 Newcastle, June 2012

On 28 June 2012, intense convective thunderstorms delivered, in parts of the city of Newcastle, up to 50mm of rainfall in 2 hours – this was equivalent to the 1% AEP storm (Newcastle City Council 2013a). This rain fell onto ground that was already saturated by high rainfall accumulations throughout June 2012 (Environment Agency 2012). Alongside run-off from extensive impermeable urban land cover, this resulted in large volumes of surface run-off that flooded over 500 properties. Much of this flooding occurred within one hour (Newcastle City Council 2013b). The scale of the event – combined with the rapid onset of flooding – left people with little time to react and caused significant disruption to the city.

The nature of surface water flooding – and the rapidity of this event – means it is rare to find conventional records of flood extent and depth (for example, gauge data, aerial photographs and wrack marks). This event, which began at around 15:00 GMT in a busy, urban area, was well documented by members of the public through large numbers of photographs and other eyewitness reports of flooding. Much of this information was collated and georeferenced by Newcastle University, and the project team is grateful to the university for providing the data to this project.

Ongoing work by Newcastle University also tested a GPU-based flood spreading model, HiPIMS. The model receives spatially distributed radar rainfall and solves the 2D shallow water equations to predict depths and velocities. Liang and Smith (2015) provide further details of the underlying software.

Model outputs from HiPIMS were compared with the results from the PoC experiment. The limitation of this comparison is that both models will only approximate observed 'real-world' flooding. However, corroborating the results shows where consistent patterns of flooding are predicted by the 2 different modelling approaches.

Media data were also mined for records of flood impacts. A database was provided by HSL/KCL/FFC via the NHP SWF HIM project. This was derived by searching media reports of flood impacts and, where possible, georeferences to this information at points (34 exist for Newcastle), polylines (that is, roads) and polygons (broad-scale impact information).

### *Input data available*

- G2G surface run-off grids, based on the Short Term Ensemble Prediction System 2 (STEPS-2) and UK4 blended ensemble rainfall forecasts (12 member ensemble)

### *Validation data available*

- Georeferenced photographs taken during the event
- Point-based observations depths, measured after the event based on water levels visible in photographs
- HiPIMS model outputs (depth and velocity grids at 10 minute intervals from 12:10 to 17:50 on the day of the event)
- Media-derived flood impacts database

## **5.2.2 Canvey Island, July 2014**

Canvey Island has a history of coastal and surface water flooding. One of the largest surface water events recorded occurred on 20 July 2014, when intense rainfall – estimated as a 0.3% AEP storm – resulted in substantial flooding to properties and infrastructure (Essex County Council 2014).

As with the Newcastle surface water event described above, conventional observations of flood extent are sparse. The main records available to assess this event are the media database provided via the NHP SWF HIM project (see Section 5.2.1).

### *Input data available*

- G2G surface run-off grids, based on STEPS-2 and MOGREPS-UK blended ensemble rainfall forecasts (24 member ensemble)

### *Validation data available*

- Section 19 Flood Investigation Report (Essex County Council 2014)
- Flooded roads, provided as polylines within an ArcGIS shapefile
- Media-derived flood impacts database

# 6 Findings

This section discusses the feasibility and benefits of the 6 PoC experiments identified in response to user requirements and summarised in Section 3.

Section 6.1 contains an overview of the findings which presents:

- the key overall findings
- a comparison of the PoC experiments
- common implementation considerations

Section 6.2 sets out in turn the findings for each PoC experiment in relation to the 3 research questions set out in Table 4.1, that is:

- its technical feasibility
- the information it provides
- its performance in the flood event case studies presented in Section 5

Important considerations for the option's future implementation are also discussed.

Much of the detailed analysis for the PoC experiments is provided in pro-formas provided [ds](#) in appendices to this report.

Section 7 presents the preferred options and key considerations for their implementation.

## 6.1 Overview

### 6.1.1 Key overall findings

- The PoC experiments demonstrate methods to generate real-time maps of flood inundation. Real-time modelling and pre-computed approaches are technically feasible using existing or readily available datasets and models. They meet some or all of the user requirements (see Section 2.1) for time-varying maps of flood extents and, in many cases, depth, velocity and hazard.
- Options with national coverage are possible through the reuse of models and data from previous NaFRAs, the ongoing State of the Nation risk modelling project and the updated Flood Map for Surface Water.
- Flood impact information can be readily generated by intersecting flood extents and/or depths with data on flood receptors. The PoC experiments demonstrate this by assessing properties (residential and non-residential) within the flood extent. The method could be extended for other receptors such as transport, infrastructure or sites of environmental significance in future.
- Reliable mapping of floodplain depths, velocity and hazard requires approaches that solve the 2D shallow water equations. Existing 1D–2D models based on the shallow water equations are generally not designed for real-time use and it would be difficult to reuse these models in the near

future. However, 2D flood models based on the shallow water equations, with a simplified representation of the channel–floodplain system, can achieve practical run times for real-time modelling, although non-standard hardware (GPUs) may be required.

- Pre-computed simulation libraries would be relatively efficient to implement, especially as national coverage of the prerequisite models is already available through the State of the Nation update to the NaFRA. This could also be supplemented with information from local, detailed mapping studies (where available), although future implementation would need to consider how to integrate multiple datasets (for example, to avoid abrupt step changes at the boundaries between datasets). Fast run times mean that simulation libraries are well suited to running multiple scenarios in real-time, such as probabilistic forecast ensembles.
- Interpolation of AEPs between gauges – an approach developed by Environment Agency R&D project SC060088 (Risk of Widespread Flooding) – provides many opportunities to derive event-specific flood mapping in real time. The Risk of Widespread Flooding project found that interpolating AEPs and then looking up local values of flow or level was more straightforward than modelling the actual flow/level values along the river network. Look-ups between the AEP and in-channel flow or level are already available with national coverage through the H21 Evidence Update and State of the Nation projects respectively. This approach has the potential to link the PoC experiments to the NFFS by interpolating forecasts of in-channel conditions between existing forecast locations.
- G2G forecasts can be downscaled to guide a local tactical response by using G2G flow or run-off as inputs to 2D hydraulic models or pre-computed libraries in real time.

### 6.1.2 Comparison of PoC experiments

Three PoC experiments provide detailed fluvial flood maps that meet all the user requirements:

- fully dynamic fluvial modelling
- simplified fluvial modelling
- simulation library

Results across these 3 options are compared in Figure 6.1 for the Morpeth and Cockermouth case studies. The results are presented for PoC simulations driven with observed flows to obtain a consistent comparison; results for level-driven variants of each option are not shown, but further detail can be found in the pro-forma appendices (Appendices 4 to 6). The maps in Figure 6.1 show modelled depths. Where in-channel results are not predicted by an option, the channel is shown by a cross-hatched area. Results for the Thames are not displayed in Figure 6.1 due to the large size of the model domain, but full details are given in the pro-formas.

Lower complexity options, with coarser grid resolutions, have faster run times. Run times for simplified fluvial modelling are feasible for real-time use, given an appropriate number of GPU cores (it is possible run this option across multiple processors, meaning that run times can be reduced by adding further GPUs). However, the simulation library has the fastest run times (around 2 minutes in each case study), without a requirement for non-standard hardware.



Model performance is relatively consistent across the PoC experiments, despite differences in the level of process representation contained in the various options. For the Morpeth case study, the simplified fluvial model and simulation library have lower model skill scores compared with fully dynamic fluvial modelling. However, the difference is small (skill scores range from 0.76 to 0.66 across the 3 options) and all the PoC experiments predict consistent patterns of flood extent and depth. As a tool to support improved flood incident management, users should therefore consider whether the different outputs would result in different operational advice being issued.

For the Cockermouth case study, the flood extent predicted by the simplified fluvial modelling PoC experiment is noticeably larger than the other options (note that the model domain is truncated to the north of Cockermouth, as this is the extent of the observed data). This is caused by inaccuracies in asset SoP data, which results in high calculated inflows to the floodplain, rather than an inaccuracy in the method itself.

### 6.1.3 Implementation considerations common to all options

This section introduces the main items that should be considered if implementing the PoC experiments within an operational flood forecasting system.

The following considerations are common to all PoC experiments. Section 6.2 provides option-specific details.

- **Selection of appropriate boundary condition datasets to drive the models.** As discussed in Section 6.1.1, interpolation of AEPs along the river network offers many possibilities to drive real-time flood mapping and link to existing forecast locations in the NFFS.
- **Acceptable model run times for use in operational forecasting.** Larger or more complex models will take longer to run and may limit the use of a given option to particular geographical areas of high risk. Hybrid approaches that combine with pre-computed flood mapping may offer a solution where run times are prohibitive.
- **Transfer of model results** – output files can be large and might require the transfer of large volumes of data across networks, particularly if map outputs are required at regular intervals as well as simulation maximums.
- **Integration with forecasting systems** (for example, general adapters or application programming interfaces, APIs) will be required to populate model boundaries and to execute the model run(s).
- **Post-processing of model runs** will require GIS routines to combine outputs (potentially from multiple models) and to extract flood extent polygons. Subsequent analysis will be required to intersect modelled outlines with receptors such as properties.

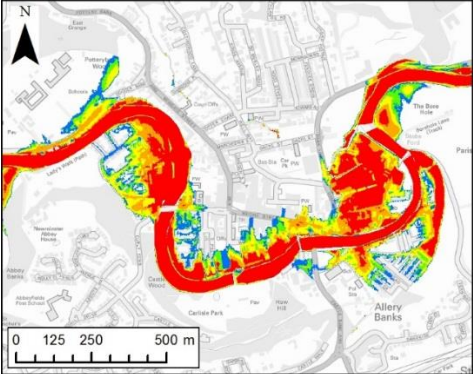
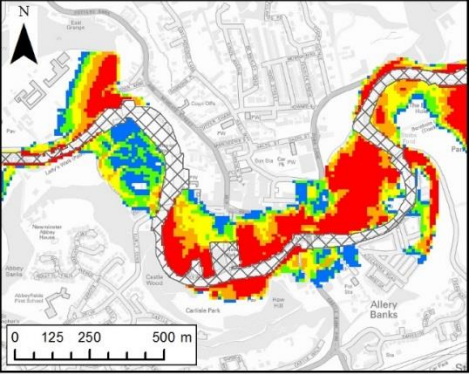
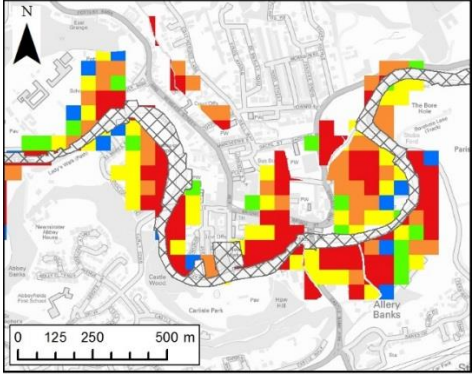
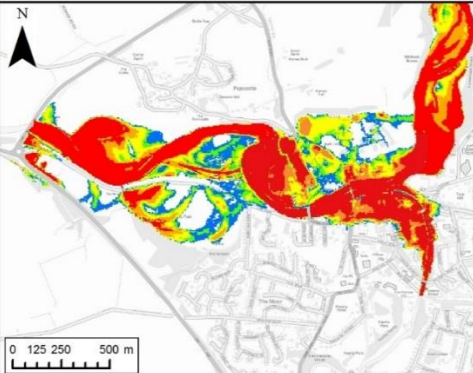
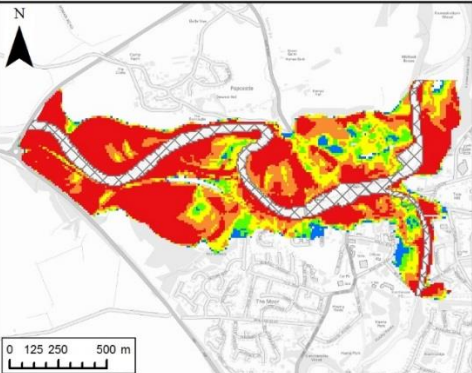
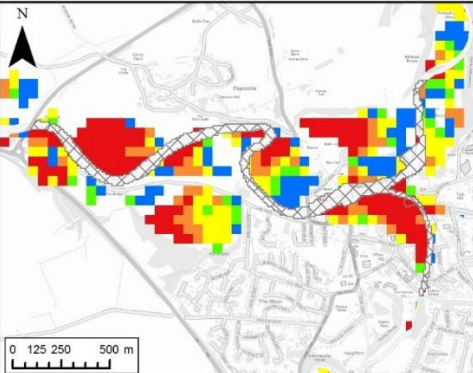
	Fully dynamic fluvial modelling	Simplified fluvial modelling	Simulation library
Morpeth			
	Resolution of outputs: <b>2m</b> Skill <b>0.76</b> ; Bias <b>0.87</b> Run time: <b>22.90 hours</b>	Resolution of outputs: <b>10m</b> Skill <b>0.70</b> ; Bias <b>1.11</b> Run time: <b>1.5 hours on a single GPU core</b> (3 GPU cores could achieve runs <30 minutes)	Resolution of outputs: <b>50m</b> (in future, could incorporate detailed modelling where available) Skill <b>0.66</b> ; Bias <b>1.10</b> Run time: <b>2 minutes</b>
Cockermouth			
	Resolution of outputs: <b>5m</b> Skill <b>0.83</b> ; Bias <b>0.90</b> Run time <b>15.64 hours</b>	Resolution of outputs: <b>10m</b> Skill <b>0.78</b> ; Bias <b>1.21</b> Run time: <b>6.8 hours on a single GPU core</b> (15 GPU cores could achieve runs <30 minutes)	Resolution of outputs: <b>50m</b> (in future, could incorporate detailed modelling where available) Skill <b>0.72</b> ; Bias <b>0.88</b> Run time <b>2 minutes</b>

Figure 6.1 Comparison of key metrics for 3 PoC experiments using results from the Morpeth and Cockermouth case studies

## 6.2 Individual PoC experiments

Although this section discusses each PoC experiment in turn, the different options and their sub-components are not mutually exclusive. Future systems could combine the options in different ways as appropriate to a given forecasting situation.

### 6.2.1 Fully dynamic fluvial modelling

#### *What is its technical feasibility?*

Detailed flood maps and high run times characterise the fully dynamic fluvial models tested in this study.

Fully dynamic 1D–2D models are widely used to provide floodplain mapping. The approach explicitly represents the river channel and so could be run using boundary conditions from river gauges or forecast locations in the NFFS. Additional interpolation of in-channel conditions throughout the river network is not a prerequisite to running the model.

However, real-time flood forecasting is rarely a consideration during the development of detailed flood mapping models. Most 1D–2D models currently held by the Environment Agency are primarily designed for offline, detailed flood mapping. All the models tested by this study have long run times, which would preclude their use in operational forecasting. As a result, reusing these existing models in the near future will be challenging. In this study, the long run times also limited the number of ensemble members that could be run using the models.

Long run times are not an inherent limitation of the software, as run times are heavily dependent on computing speed and the level of detail (for example, topography) incorporated in the model. In the future, faster run times could be achieved if models were built with real-time use in mind. For example, the Environment Agency could specify different types of model build from the outset of model development.

Adapters for the Flood Early Warning System (FEWS), the forecasting software that underpins the NFFS, are already available for many hydraulic model software packages including ISIS/Flood Modeller, TUFLOW (Two-dimensional Unsteady Flow), MIKE11/21 and HEC-RAS (Hydrologic Engineering Center’s River Analysis System).

#### *What information does it provide?*

Fully dynamic fluvial models offer some of the most detailed, widely available floodplain mapping. Such mapping is routinely used by the Environment Agency and other organisations to support a range of applications including:

- better understanding of flood risk
- optioneering for flood defence schemes
- economic appraisals

Flow processes are represented using the shallow water equations. River channels and floodplain are dynamically linked, with the models typically including a high level of topographic detail (both in-channel and on the floodplain). In this respect, the PoC can

meet all the user requirements for time-varying maps of flood depth, velocity and hazard.

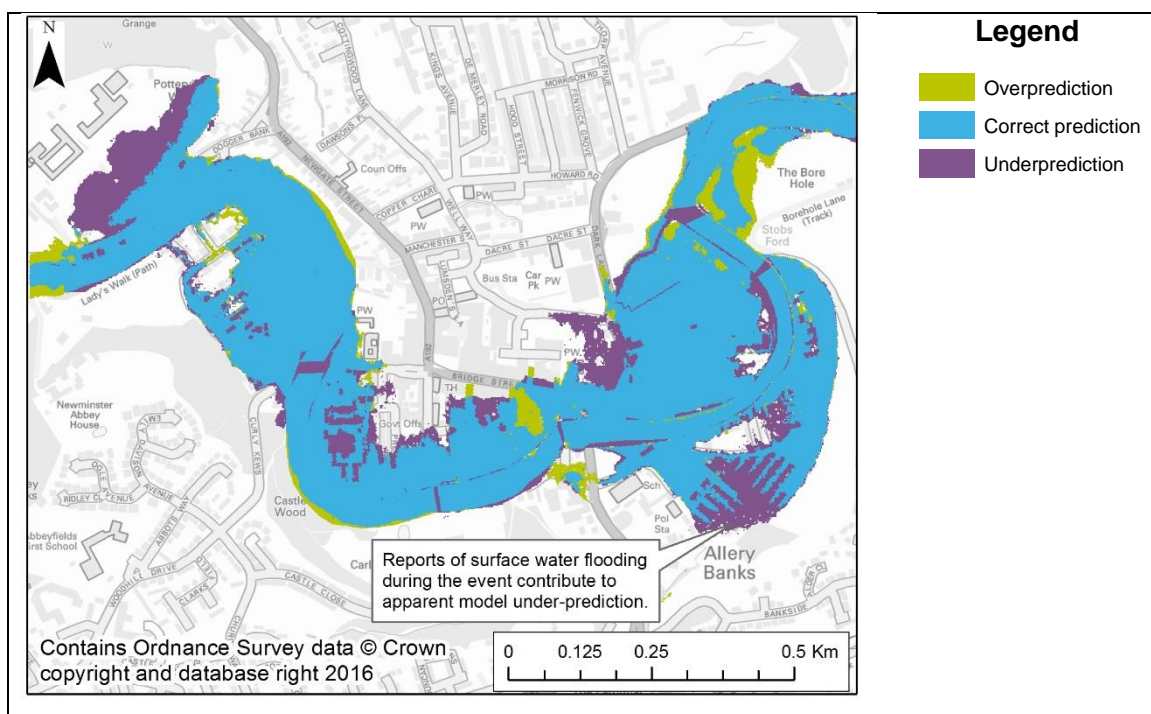
1D–2D models also provide in-channel predictions of flow and level. These were used as boundary conditions to some of the other PoC experiments (see below).

### *How does it perform in a given event?*

In the case studies tested, the models provide accurate predictions of flood extent. Model skill is high, generally scoring above 0.8 (when fed with observed inflows) and there is little evidence of bias. The model appears to perform less well for the September 2008 event at Morpeth (overall skill score of 0.76). However, surface water also contributed to the observed flood extent in this event – a source of flooding that is not modelled by this option, in the way it has been implemented here. Figure 6.2 maps model performance in different areas of the floodplain in the Morpeth event.

Results for the Thames event (presented in Appendix 4) appear to show large areas of model overprediction. However, the widespread nature of the flooding, difficulties in obtaining observations at the peak of the event and challenges in identifying flooded areas from satellite imagery all contribute to a high level of uncertainty associated with the observed flood outlines. The project team is confident that the modelling provides accurate predictions of flood extent and, like all the fully dynamic fluvial models used by this study, the model has been calibrated and accepted for operational use by the Environment Agency.

In this project, the fully dynamic fluvial models therefore formed a baseline against which other PoC experiments were compared.



**Figure 6.2** 1D–2D linked hydrodynamic model performance, Morpeth 2008 event

## *Implementation considerations*

- Faster run times that are feasible for flood forecasting could be achieved if real-time use were considered or specified from the outset of new model development. This may allow 1D–2D modelling to be applied in targeted geographical locations in the future.
- Data volumes of the outputs from 1D–2D models can be large and might require the transfer of significant volumes of data across networks. Implementation of this option should consider the infrastructure required to support post-processing and dissemination of model outputs.
- Model stability in extreme events should be considered during model development. It is possible that, as a forecasting tool, there may be model instabilities in events that are higher than those tested during the model build.

### **6.2.2 Simplified fluvial modelling**

#### *What is its technical feasibility?*

This option consists of a fast 2D inundation model of the floodplain driven by in-channel predictions of flow or level. The feasibility of this option depends largely on the availability and quality of datasets to provide boundary conditions. There are several options readily available with national coverage, but future consideration should be given to the most appropriate source of data for operational use.

In testing this PoC experiment, boundary conditions were provided by:

- hydraulic models to derive in-channel flows and levels
- G2G flow grids which provided flows throughout the river network

Operationally, however, interpolation of AEPs along the river network provides many possibilities for driving this option. This approach would involve the following steps.

1. Convert forecast levels or flows to an AEP value based on pre-computed frequency analysis at a given forecast location (for example, a river gauge).
2. Interpolate the AEPs along the river network.
3. Obtain a look-up table that links AEP to local estimates of in-channel conditions. Look-ups are available with national coverage for both flow and levels (National Fluid Flows Database and National Fluvial Levels Database; see Section 4.1.2), although only the former is recognised and maintained by the Environment Agency at present.
4. Use the information on SoP and crest levels held in the Environment Agency's Asset Information Management System (AIMS) to obtain estimates of local flow/level thresholds to take account of channel capacity and/or the protection offered by raised defences (where they exist).

The results are heavily dependent on the quality of the crest height and asset SoP information held in AIMS and the flow/level to AEP look-up tables. Maintaining up-to-date and accurate datasets is thus an important consideration for implementation of this option.

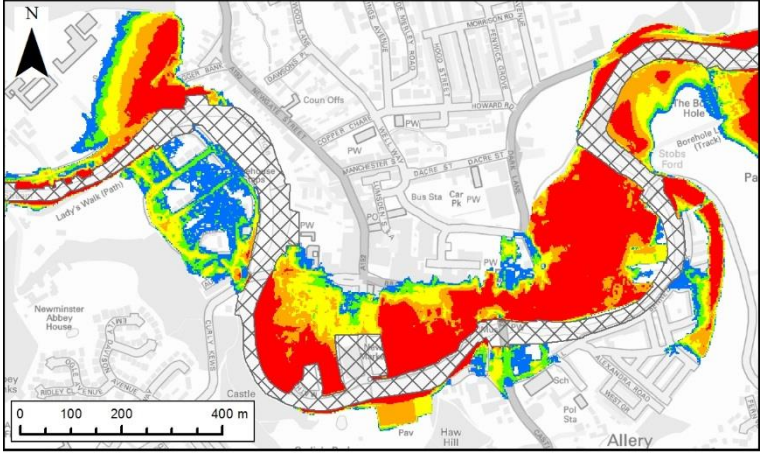
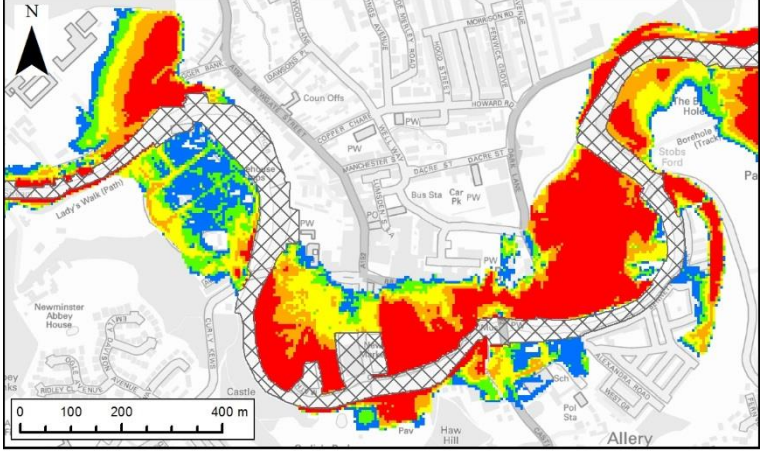
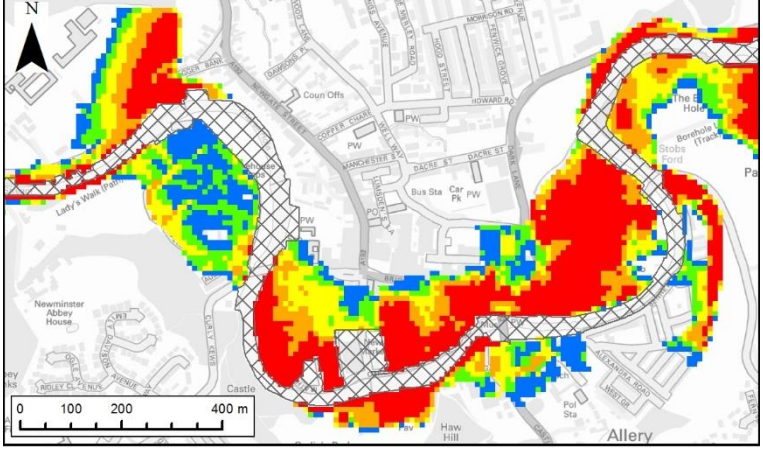
The PoC experiment demonstrates that model run times are viable for real-time forecasting use at 10m and 5m grid resolutions (though run times are dependent on model domain size). Non-standard hardware, however, such as GPUs may be required to run models based the shallow water equations in real time.

### *What information does it provide?*

Like the fully dynamic 1D–2D models, simplified fluvial modelling meets the user requirements for the mapping of floodplain depths, velocity and hazard.

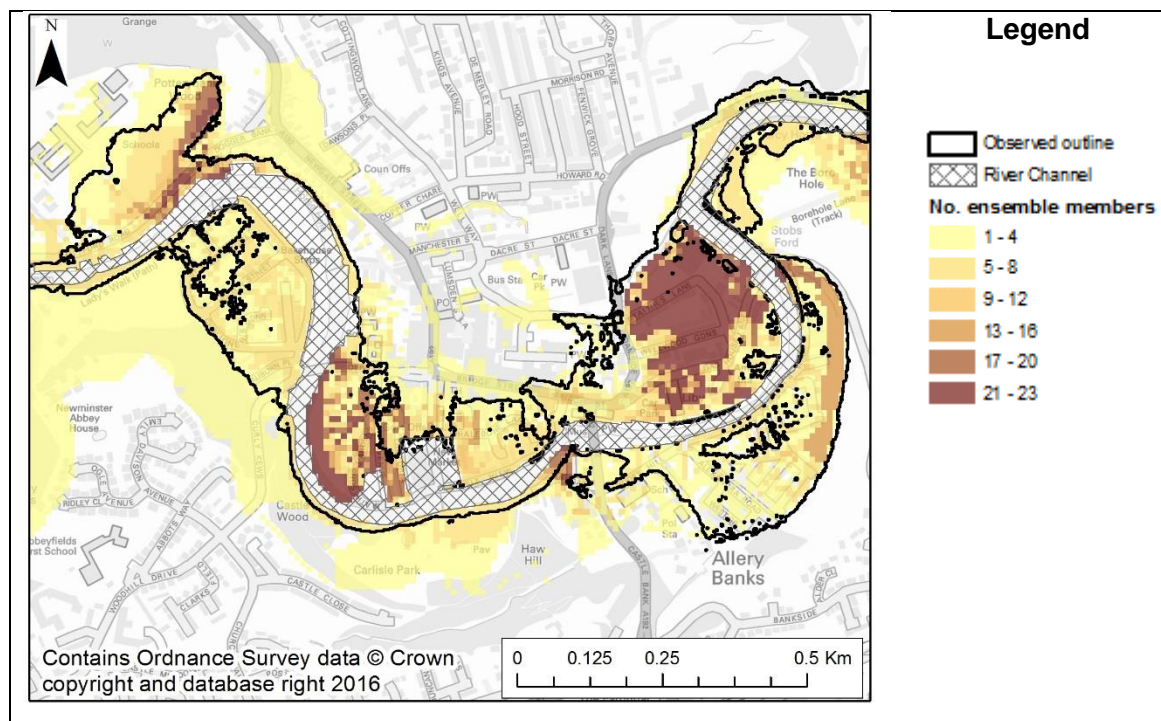
Detailed flow paths are more time-consuming to resolve. To achieve feasible run times for real-time use, some compromise may be required in the amount of topographic detail included in the model. However, in the context of operational flood forecasting, this does not necessarily detract from the usefulness of the information that the models provide.

As an example of topographic detail, 2m, 5m and 10m resolution model grids were tested. Run times were significantly higher for the finer grid resolutions. General patterns of inundation extent and depth were broadly consistent between the different model runs (Figure 6.3). The coarser 10m × 10m resolution grids, however, still provide relatively detailed mapping that would support planning and response to a flood incident at a scale relevant to individual receptors.

Grid resolution	Run time on a single GPU core	Map of modelled depths													
2m  (run times <30 minutes could be achieved with 80 GPU cores)	21.8 hours														
5m  (run times <30 minutes could be achieved with 20 GPU cores)	5.4 hours														
10m  (run times <30 minutes could be achieved with 3 GPU cores)	1.5 hours														
<div data-bbox="167 1720 391 1982" data-label="Table"> <table border="1"> <thead> <tr> <th colspan="2">Legend</th> </tr> <tr> <th colspan="2">Modelled depths, m</th> </tr> </thead> <tbody> <tr> <td style="background-color: blue; width: 20px;"></td> <td>0.00-0.15m</td> </tr> <tr> <td style="background-color: green; width: 20px;"></td> <td>0.15-0.30m</td> </tr> <tr> <td style="background-color: yellow; width: 20px;"></td> <td>0.30-0.60m</td> </tr> <tr> <td style="background-color: orange; width: 20px;"></td> <td>0.60-0.90m</td> </tr> <tr> <td style="background-color: red; width: 20px;"></td> <td>&gt;0.90m</td> </tr> </tbody> </table> </div>	Legend		Modelled depths, m			0.00-0.15m		0.15-0.30m		0.30-0.60m		0.60-0.90m		>0.90m	<p>The map is scaled to show central Morpeth and the extent of data used in model evaluation. The river channel is not explicitly modelled by this option, and so is shown by the grey hatched area. Run times are quoted for a single GPU core. However, faster run times can be achieved if multiple cores are available.</p> <p>Contains Ordnance Survey data © Crown copyright and database right 2016.</p>
Legend															
Modelled depths, m															
	0.00-0.15m														
	0.15-0.30m														
	0.30-0.60m														
	0.60-0.90m														
	>0.90m														

**Figure 6.3** Outputs from simplified fluvial modelling for Morpeth, September 2008: driven by in-channel flows

A much greater source of variability in the model outputs was the uncertainty introduced by forecast rainfall. Figure 6.4 demonstrates the range of flood extents predicted by 24 G2G ensemble members. Darker colours on the map show where a greater number of ensemble members predict the same locations as flooded.



**Figure 6.4** Outputs from simplified fluvial modelling for Morpeth, September 2008 event: driven G2G ensemble members

### *How does it perform in a given event?*

The method developed for this study depends heavily on the quality of data used to specify:

- in-channel flows or levels
- defence SoP or crest heights

In testing this PoC, in-channel conditions were provided by fully dynamic hydraulic models; although not without uncertainty, they are the best available local predictions of in-channel flows and levels readily available (see Section 6.2.1). Defence information was derived from AIMS. The main finding was that this option will significantly benefit from improvements to the accuracy of defence data.

When driven by in-channel flows, model results were broadly consistent with observations of flooding. The skill scores of 0.70 for the Morpeth event and 0.78 for the Cockermouth event are slightly lower than those achieved by the 1D–2D fully dynamic model. Bias scores of 1.11 (Morpeth) and 1.21 (Cockermouth) suggest slight overprediction. The lack of a dynamic link between channel and floodplain is likely to contribute to this. This means that, once on the floodplain, water is not able to drain into the channel, which may cause model overprediction, particularly on the recession of an event.



Much more varied results were found when the model was driven by in-channel levels. For example, the skill score of 0.58 and the bias score of 1.52 obtained for the Morpeth event suggests significant overprediction by the model – much more so than when the model was driven by observed flows. This was generally because crest levels (derived from AIMS) were too low compared with detailed 1D-2D models (based on topographic survey) and a LIDAR DTM. In this case, model overprediction is an implementation and data issue rather than a methodological issue with the PoC experiment.

The models are straightforward to set up, but quality control such as edits to the DTM may be required. Detailed floodplain flow routes (for example, beneath bridges) may not otherwise be represented.

### *Implementation considerations*

- This option can be implemented efficiently on a national scale by reusing NaFRA and State of the Nation models and data. The models are straightforward to set up, but some quality control (for example, edits to the DTM) may be required.
- Breaching can be incorporated through simple adjustments in defence standards of protection, crest level or fragility curve models such as RASP.
- Non-standard hardware such as GPUs or multi-central processing unit (CPU) systems may be required to run models based on the shallow water equations.
- Future development in hardware (for example, GPU speed) may reduce run times for large models that are currently limited by processing speed. However, if runs of many smaller models were required, run times are more likely to be limited by other software or hardware limitations (for example, network speeds).
- Data quality used to specify asset standards of protection and crest heights should be assessed and, where possible, these should incorporate accurate, up-to-date information. The performance of the PoC experiment relied heavily on the accuracy of asset data held in AIMS.
- In future, a fuller description of the channel–floodplain system could be incorporated into this option. For example, representing the river channel in 2D would enable feedback between the channel and floodplain to be simulated. However, the benefits this approach should be considered alongside the fully dynamic fluvial modelling approach (see Section 6.2.1), in which the channel is represented in 1D.

### **6.2.3 Simulation library**

#### *What is its technical feasibility?*

The simulation library looks up floodplain depth mapping based on in-channel flow and levels. This option shares a common basis for establishing boundary conditions with the simplified fluvial modelling approach (see in Section 3.2). Its technical feasibility is, likewise, dependent on the availability of accurate predictions of in-channel conditions.

Reusing existing State of the Nation models and data, the simulation library would be quick to implement with national coverage. However, the data in the look-up libraries would be subject to the same method and data restrictions as the underlying MDSF2 models used to produce them. The look-up libraries could be supplemented with local, detailed information where available, although operational implementation would need to consider how this could be done in practice.

This PoC experiment has low hardware requirements and no step changes in technology (for example, CPUs to GPUs) would be required to implement it. Fast, predictable run times mean that it is feasible to link this option to different input such as ensemble forecasts. In the case studies tested, runs took around 2 minutes on a desktop PC.

At present, the PoC experiment considers fluvial settings only. Further work is required to extend the approach to tidal and coastal areas. In particular, the look-up library approach is less suited to areas where flooding is driven by multiple variables. For example, in estuarine areas, flooding may be driven by a combination of tidal and fluvial forcing. Similarly, in coastal areas there may be multiple offshore and nearshore parameters to consider. In these situations, a look-up approach to deriving flood maps in real time would need both a larger library of pre-computed runs (for different combinations of variables) and more complex look-up routines to select appropriate flood mapping.

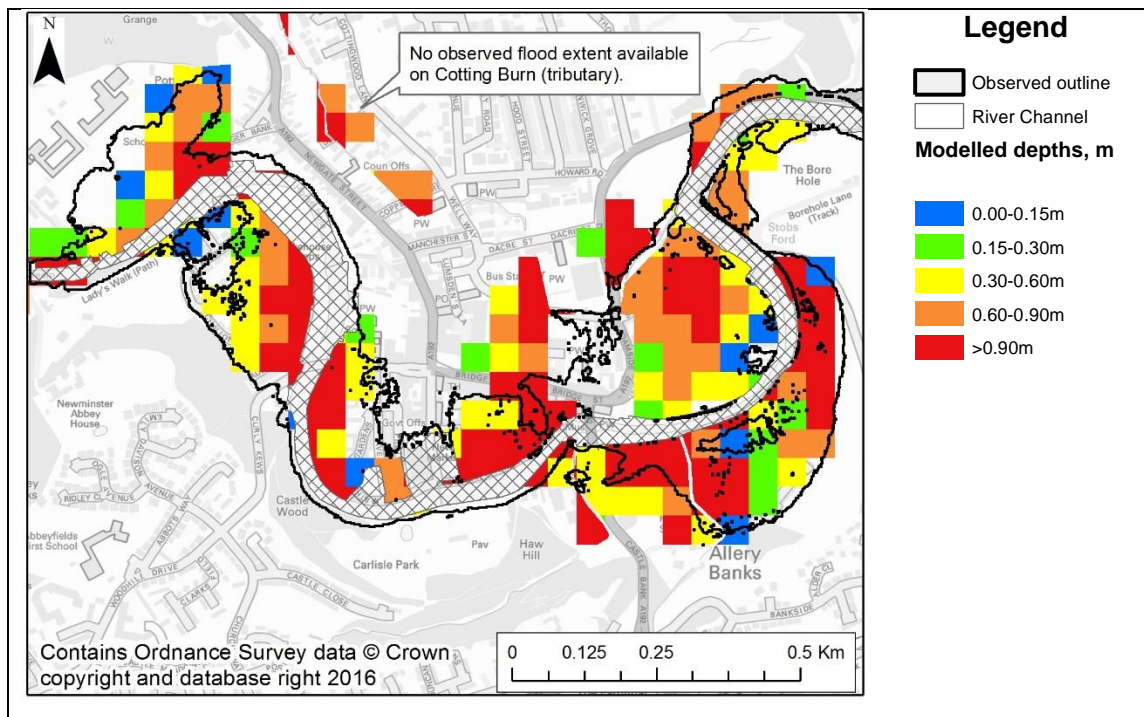
One of the most important limitations of the current simulation library approach is that the same return period must be assigned to all assets in a given Flood Area (a fundamental assumption of the underlying MDSF2 model). The assumption of uniform return period is very unlikely to be realistic for larger Flood Areas; for example, one Flood Area in the Humber catchment covers over 118km of Main River, including fluvial and tidal sources of flooding within reaches of the Rivers Aire, Calder, Don, Ouse and Went, as well as 12 other becks and drains. In these situations, running models in real time may be preferred.

### *What information does it provide?*

This PoC experiment provides flood extents and depths on a relatively coarse 50m × 50m resolution grid (this is the resolution of the MDSF2 Impact Cells used for NaFRA modelling). In future, there is the potential to attribute the cells with other receptor information to assess flood impacts. The lower complexity of this option means that it should be quicker to intersect results with different receptor datasets.

The simulation library provides a snapshot of inundation at a given time rather than a continuous model output. However, pre-computed, coarse resolution outputs are quick to access in real-time (around 2 minutes for each event tested in the case studies) and so the approach could be used to create multiple snapshots throughout an event. It is also well suited to running multiple ensemble members or experimenting with different scenarios. For example, the method could be readily extended to consider defence failure by the inclusion of 'what-if' scenarios in the pre-computed library of runs.

The coarse nature of the grid used to test the PoC experiment means that this option currently has limited ability to resolve detailed floodplain flow routes, although general patterns of flooding are still provided at a scale relevant to flood receptors (see, for example, the Morpeth 2008 event in Figure 6.5). However, higher resolution model results could be incorporated in the future into this option, where available.



**Figure 6.5** Outputs from simulation library for Morpeth, September 2008 event

### *How does it perform in a given event?*

In the case studies tested, the model accurately replicates the observed flood extents despite the coarse resolution of the outputs. The model has relatively high skill scores (0.66 in Morpeth, 0.72 in Cockermouth) and limited evidence of bias (up to 1.11 in Morpeth, 0.88 in Cockermouth). Inaccuracies in the distribution of flood depths are likely to result from limitations in the topographic representation within MDSF2.

The quality of simulation library outputs is largely governed by:

- the quality of the available data and the underlying models used to produce the maps (that is, State of the Nation MDSF2 models)
- accurate estimates of return periods for a given event, which are used to select corresponding flood depths from look-up tables

Based on a pre-computed look-up, the approach is robust (low probability of model failure) and offers predictable run times.

### *Implementation considerations*

- As with the simplified fluvial modelling option, the simulation library option could be implemented efficiently on a national scale by reusing State of the Nation MDSF2 models.
- Implementation of this option should consider how local detailed mapping can be incorporated into the simulation library, alongside datasets that provide national coverage.
- The structure of look-up libraries and routines should also be considered to make the most efficient use of these data in real time. For example, look-up libraries can potentially be large depending on the simulation extent.

However, data sizes could be managed efficiently in an operational system by evaluating flood depths on a Flood Area by Flood Area basis.

- The hardware requirements of this option are relatively low, as it is based on a look-up of pre-computed outputs. However, there may still be significant volumes of data that require transfer and access across networks.
- The simulation library concept is being considered as one potential option for replacing the current NaFRA. Should this be taken forward, the requirements for supporting real-time forecasting should be considered in parallel.

## 6.2.4 10-day lead time NWP products

### *What is its technical feasibility?*

This PoC experiment assessed how flood indices and systems developed by the ECMWF and JRC could be used to provide real-time flood mapping. Two indices (ERI and EFAS) were considered. The Environment Agency is an EFAS partner and can freely access these outputs. ERI is currently a research product and is also available to the Environment Agency. If implemented operationally, some thought would need to be given to how ECMWF forecast outputs (for example, river discharge and flood severity maps) could be made readily available to the Environment Agency during an event.

Development of this PoC experiment required an investigation of how broad-scale flood indices based on 10-day lead time NWP products could be used to meet the user requirements for flood impacts mapping. The flood indices were derived by ECMWF and JRC, which kindly provided the data to this project.

In terms of technical feasibility, difficulties in defining a relationship between the indices and flood impacts currently limit the use of this option in operational flood forecasting. However, the information it provides has the potential to support long-range planning. This is discussed further below.

### *What information does it provide?*

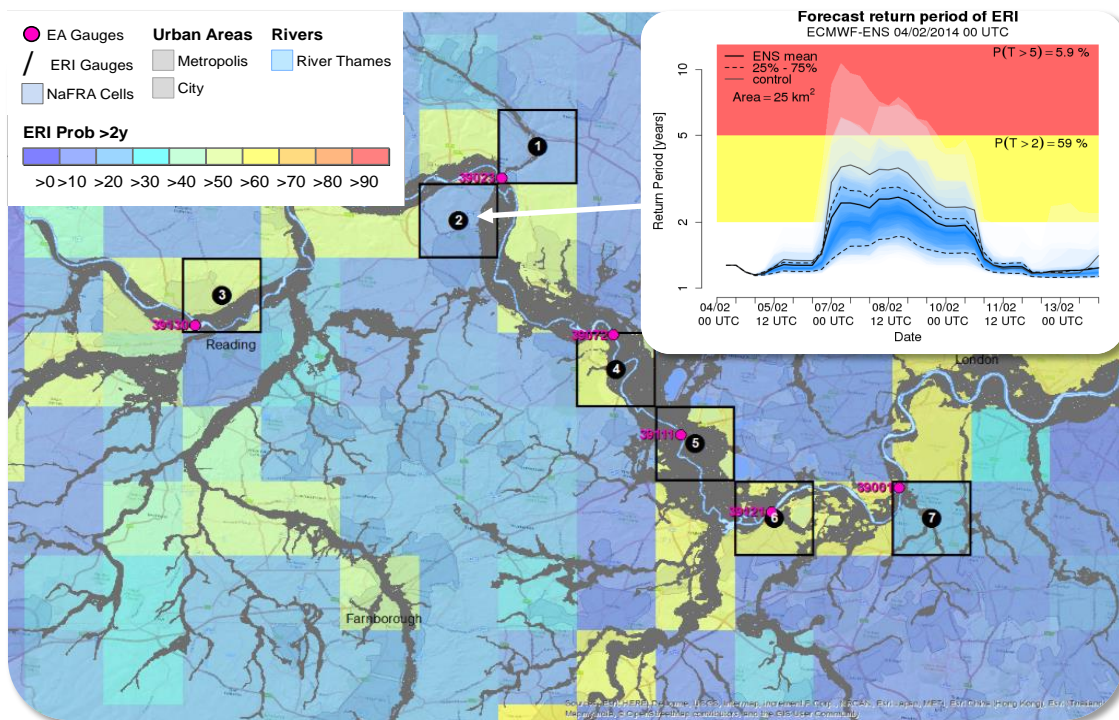
The main output provided by the ECMWF is an estimate of the rarity of a forecast event on a European-wide 5km × 5km grid. Using a 51 member NWP ensemble, the approach provides probabilistic forecasts at 10-day lead times. This is an extension to the lead times available at the moment; for example, the Flood Guidance Statement currently provides a 5-day outlook for flood risk. Although a large amount of forecast uncertainty exists at a 10-day lead time, the outputs from NWP products could be used for long-range, strategic planning activities (for example, planning the distribution of resources, rostering of duty staff, preparation of incident rooms and public awareness).

These outputs could be further combined with other options tested in this project, such as the simulation library or simplified fluvial modelling, to estimate the potential consequences of flooding. However, the estimates of event rarity derived from 10-day lead time NWP products are not compatible with conventional AEPs used in other options in this study (a detailed discussion can be found in the pro-forma presented in Appendix 7). Further research is required to create a robust link between ECMWF flood indices, based on NWP products, and existing flood impacts mapping (for example, the

property counts and economic damages information contained in the detailed RoFRS data).

As an example, Figure 6.6 shows the outputs from the ERI for the River Thames in February 2014. Grid cells are colour-coded by the probability of flows exceeding the 50% AEP event. The inset shows a probabilistic time series plot of that information for a 10-day window in a single grid cell. In this example, the graph shows that the ensemble mean (solid black line) exceeds the 50% AEP for about 3 days. Extreme ensemble members also exceed the 20% AEP.

It is important to note that the ERI method calculates both the event rarity and the probability of flows exceeding it. The 50% AEP expressed by the ERI (and shown in Figure 6.6) is therefore not equivalent to AEPs calculated using standard flood estimation guidelines (for example, the Flood Estimation Handbook). Full details of the ERI method are given by Alfieri et al. (2014): the scope of this project is to investigate whether the approach can be employed in real-time flood impacts mapping.



**Figure 6.6** Outputs from the ERI for the River Thames, February 2014 event

### *How does it perform in a given event?*

In the Thames case study, the flood indices suggested that a high flow event was likely, up to 10 days in advance. The approach performed less well in the Cockermouth event. Floods in smaller, faster responding catchments, such as the River Derwent at Cockermouth, are more challenging to capture many days in advance.

However, as discussed above, further research is required to link NWP-based flood indices to flood impact datasets that are evaluated for more conventional flood probabilities so as to assess flood impacts in real time. In the case of an event such as the Thames (a relatively large, slow responding catchment), ECMWF's flood indices could be used to provide a broad-scale early warning that a flood was likely to occur. Challenges remain in relating this information to local flood impacts at specific times.

## *Implementation considerations*

- Mechanisms would need to be developed by which NWP forecast outputs can be transferred from the ECMWF to the Environment Agency. The ERI flood index, for example, is updated every 6 hours.
- Further research is required to link flood indices, such as ERI, to flood impact information evaluated using conventional flood probabilities. At present, the approach provides an estimate of event rarity which is not directly compatible with detailed flood mapping and impact information.

### **6.2.5 Simplified surface water modelling**

#### *What is its technical feasibility?*

Surface water flood models with national coverage are provided by the updated Flood Map for Surface Water. The approach would be relatively efficient to implement in real time, as it reuses existing updated Flood Map for Surface Water models with appropriate real-time surface run-off forecasts such as G2G.

Operationally, this option could be directly driven with rainfall forecasts derived from rainfall radar. Direct rainfall modelling is conceptually straightforward and widely accepted as an appropriate method for analysing higher magnitude, lower probability storms where subsurface drainage systems are likely to be overwhelmed and/or inlet capacities exceeded.

Alternatively, G2G surface run-off grids could be used. This approach was taken to demonstrate the PoC. Using G2G run-off predictions accounts for antecedent conditions and removes the need for losses assumptions within the hydraulic modelling (since these processes are simulated by G2G).

Updated Flood Map for Surface Water models are run at 2m × 2m grid resolution, using GPU-accelerated hydraulic models. This is currently at the limit of feasibility for real-time applications, with run times of around 1 hour for the 6km × 6km model domains used in the updated Flood Map for Surface Water.

The value of real-time surface water flood modelling is currently being assessed alongside the ongoing NHP SWF HIM programme.

#### *What information does it provide?*

Based on the 2D shallow water equations, the existing updated Flood Map for Surface Water models that were applied in this PoC experiment provide time-varying maps of flood depth and velocity, meeting many of the user requirements. However, surface water flood forecasting and warning is currently beyond the Environment Agency's remit.

The PoC experiment demonstrates that it is feasible to run all ensemble members through a high resolution inundation model. This allows some of the uncertainty in the rainfall and hydrological forecasts to be cascaded through to the flood hazard footprint and affected receptors.

However, run times are relatively high for real-time applications. The approach could therefore target high risk areas (for example, where the impact on flood receptors is likely to be high), with model runs triggered by high rainfall or surface run-off forecasts.

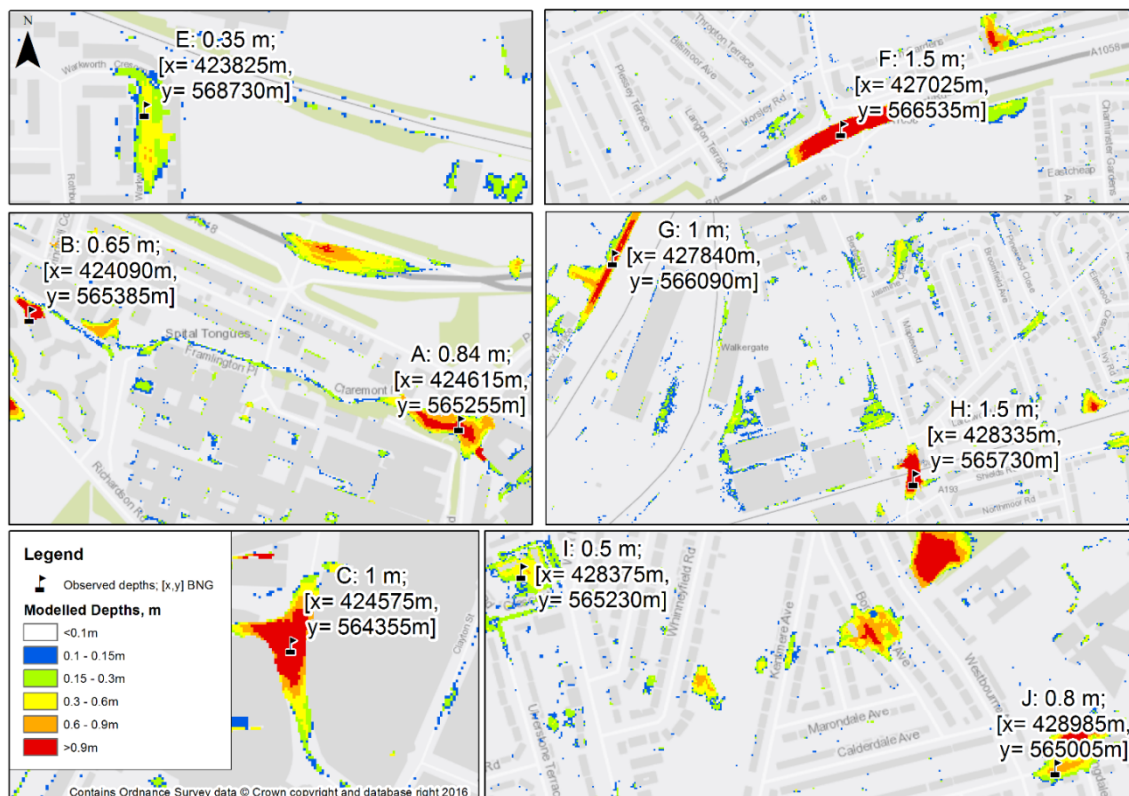
Lower grid resolutions could reduce run times, but would compromise representation of flow pathways, buildings and roads compared with the updated Flood Map for Surface Water. Future work could consider appropriate grid resolutions required for real-time planning and flood incident response.

### How does it perform in a given event?

When run with observed rainfall, the outputs of this PoC experiment provide a good fit to observations such as photographs, eyewitness reports and post-event measurements of depth (see Figure 6.7).

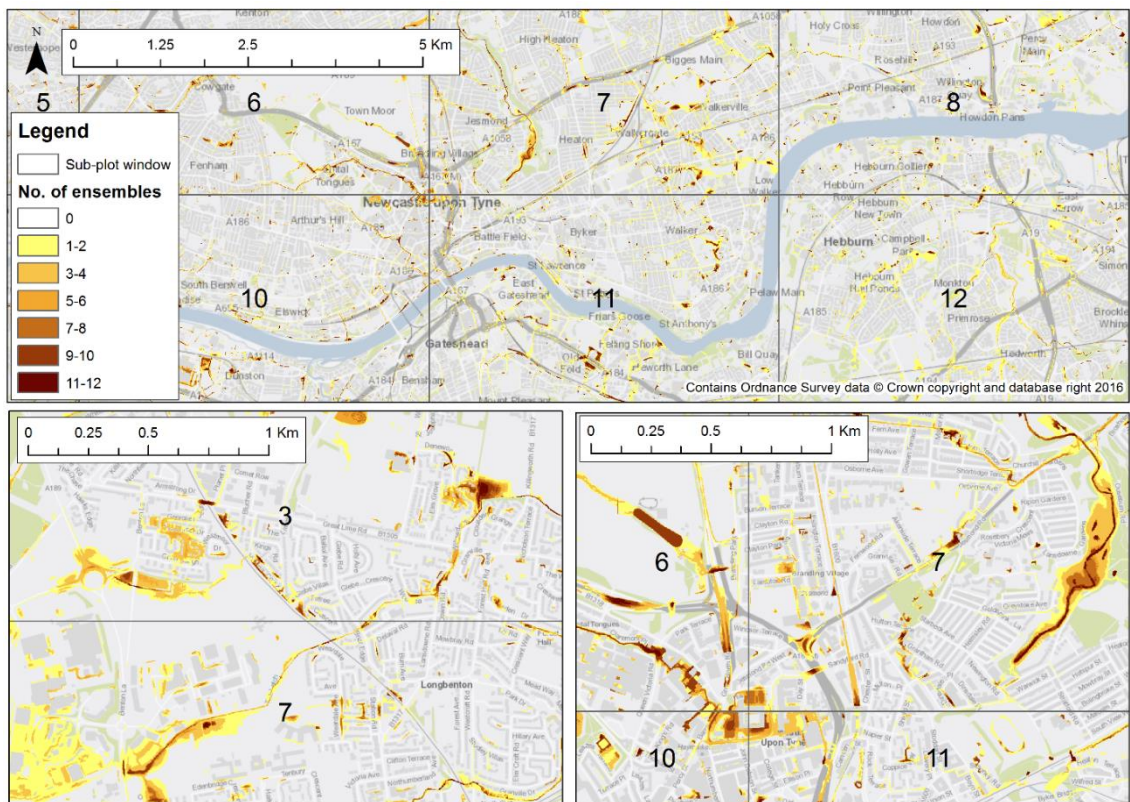
In the case of the Newcastle event (June 2012), the results from the updated Flood Map for Surface Water models were also corroborated with another hydraulic model, HiPIMS (Newcastle University). Most of the differences in model predictions were explained by different configurations (for example, edits to the DTM that were carried out in one model but not the other). Where the underlying data were comparable, the 2 modelling approaches gave similar predictions of flood extent.

When forecast rainfall was used as an input to the PoC experiment, there is a large variability in flooding across ensemble members. In short duration, high intensity convective thunderstorms such as the Newcastle 2012 event, it is more challenging to forecast rainfall timing and intensity to a high level of certainty. Real-time surface water modelling may therefore offer greater uncertainty or shorter lead times in this type of event. However, areas that are predicted to flood by multiple ensemble members generally correspond well to observations (Figure 6.8).



**Figure 6.7 Depth comparison between JFlow and point observations for the Newcastle, 28 June 2012 event**

Notes: The point observations were provided by Newcastle University.



**Figure 6.8** JFlow ensemble-based flood likelihood maps for the Newcastle, 28 June 2012 event

### *Implementation considerations*

- Reuse of existing updated Flood Map for Surface Water models would allow this option to be implemented on a national scale relatively efficiently.
- Implementation of this option would need to consider acceptable model run times for use in operational forecasting. Although this may limit use of real-time direct rainfall modelling across large areas within a single model domain, multiple smaller models could be launched to cover wide areas where significant rainfall and/or surface run-off is forecast.
- As with simplified fluvial modelling, non-standard hardware (GPUs) may be required to re-run existing updated Flood Map for Surface Water models. The existing models run on a 2m grid resolution and are based on the 2D shallow water equations.
- Appropriate sources of real-time boundary conditions should be assessed. This option could be fed with rainfall radar or G2G surface run-off estimates. Use of the latter would account for antecedent conditions and remove the need for assumptions about drainage rates within the hydraulic modelling.
- This option should be considered alongside the NHP SWF HIM programme, which has developed an approach for selecting the most appropriate pre-computed surface water flood map and associated impact library on a 1km x 1km basis.



## 6.2.6 Breach risk ready reckoner

A PoC experiment for the breach risk ready reckoner was not developed as part of this project because:

- no evidence of breaching was available for the chosen case study events
- key MDSF2 software modules could not be utilised within the budget constraints of the project

The research questions for this project are therefore answered below from a hypothetical perspective.

### *What is its technical feasibility?*

The fragility curve concept is well established and has been part of the RASP flood risk calculation process, which underpins NaFRA, since 2008. The required software tools are already embedded within MDSF2 and the fragility curves themselves have recently been reviewed (and updated where necessary) as part of the State of the Nation national risk modelling project.

In the majority of locations where observed/forecast water levels are not available directly from the NFFS, the prerequisite water level boundary conditions can be provided by return period interpolation look-up approaches (like the simplified fluvial modelling and simulation library PoC experiments).

As such, the breach risk ready reckoner is certainly technically feasible.

### *What information does it provide?*

During an event, individual flood defences can be categorised by the probability of failure (for example, Low, Medium, High) and combined with pre-computed, per asset risk data (for example, relative/absolute contributions to NaFRA estimated annual damages) to provide indicative information on the likelihood and impact of breaching at these locations.

### *How does it perform in a given event?*

For the reasons set out above, it was not possible to test the performance of this PoC experiment as part of this project.

### *Implementation considerations*

- This PoC experiment could be implemented very efficiently by reusing software modules and data from MDSF2 and the State of the Nation national risk modelling project respectively.
- Revised fragility curves have been developed as part of State of the Nation project in response to evidence suggesting that previous curves overestimated embankment failure.
- All the flood defence data required to implement this PoC experiment are stored and maintained with AIMS.

- Flood defence parameters (for example, crest level and/or condition grade) can be updated during an event where suitable telemetry or local knowledge is available, or to test 'what-if' scenarios.
- The option can be considered a 'quick win' as it is conceptually straightforward, and relatively cheap and quick to implement.
- The option could be incorporated into other options (for example, fully dynamic and simplified fluvial modelling) to enable a real-time indicative assessment of breach risk.

# 7 Recommendations and next steps

## 7.1 Preferred options

Based on the initial evidence presented here, the Project Board identified **pre-computed simulation libraries** as the option with most potential to meet current user requirements and future flood risk management aims.

**Simplified fluvial modelling** also has potential to provide real-time flood maps in situations that are too complex to simulate using pre-computed libraries. For example, coastal areas, where flooding is driven by multiple nearshore and offshore variables, may be technically challenging to model in real-time using a look-up library approach.

The main benefits of these options are as follows.

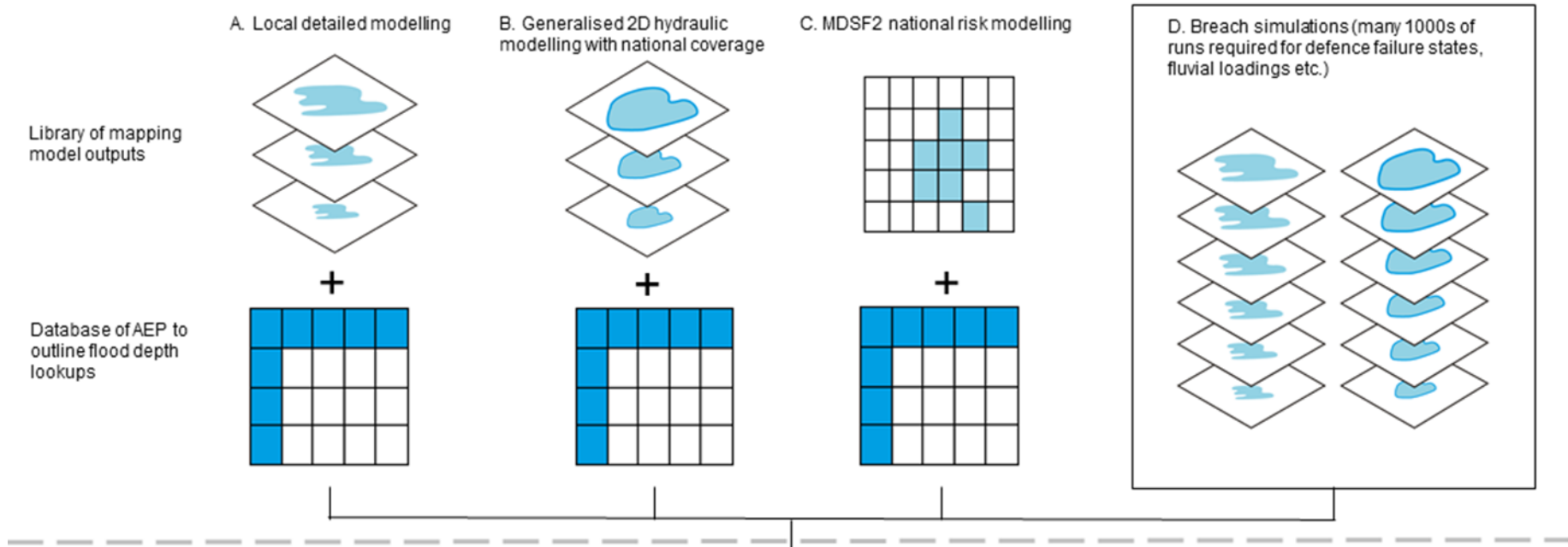
- They can be implemented efficiently using existing Environment Agency datasets and models.
- There is consistency with existing flood risk models and data (the simulation library is based on them).
- They are low risk, as no new technology is needed.
- Run times are quick. In the case of the simulation library, fast run times give this option the potential to be used with forecast ensembles in future.
- They can be tested offline.
- They can be coupled with other types of boundary condition information in the future (for example, G2G).
- They can be improved over time as new data become available. For example, the simulation library can be built on with the addition of local detailed mapping.

Details of the model set-up and real-time operation of the 2 preferred options are shown in Figure 7.1.

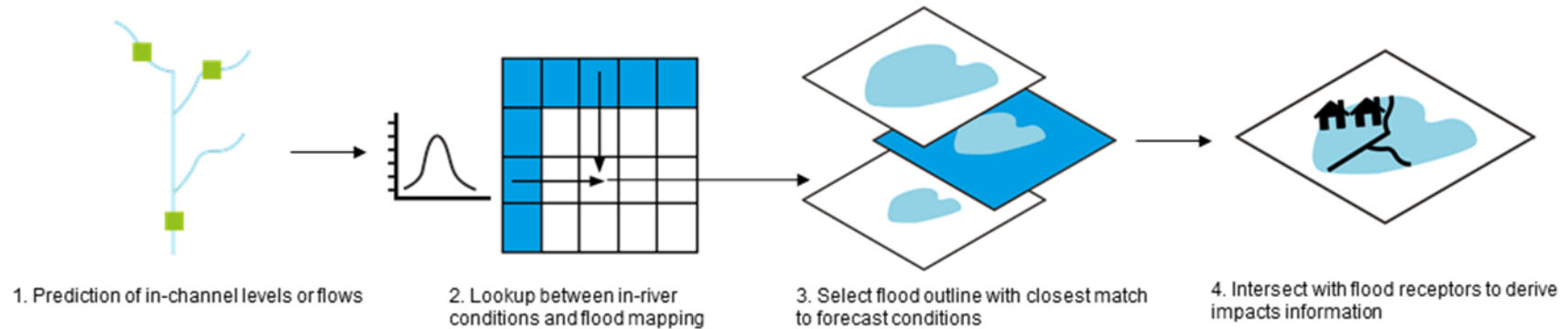
**Preferred Option 1:  
Simulation Library**

**MODEL SET UP**

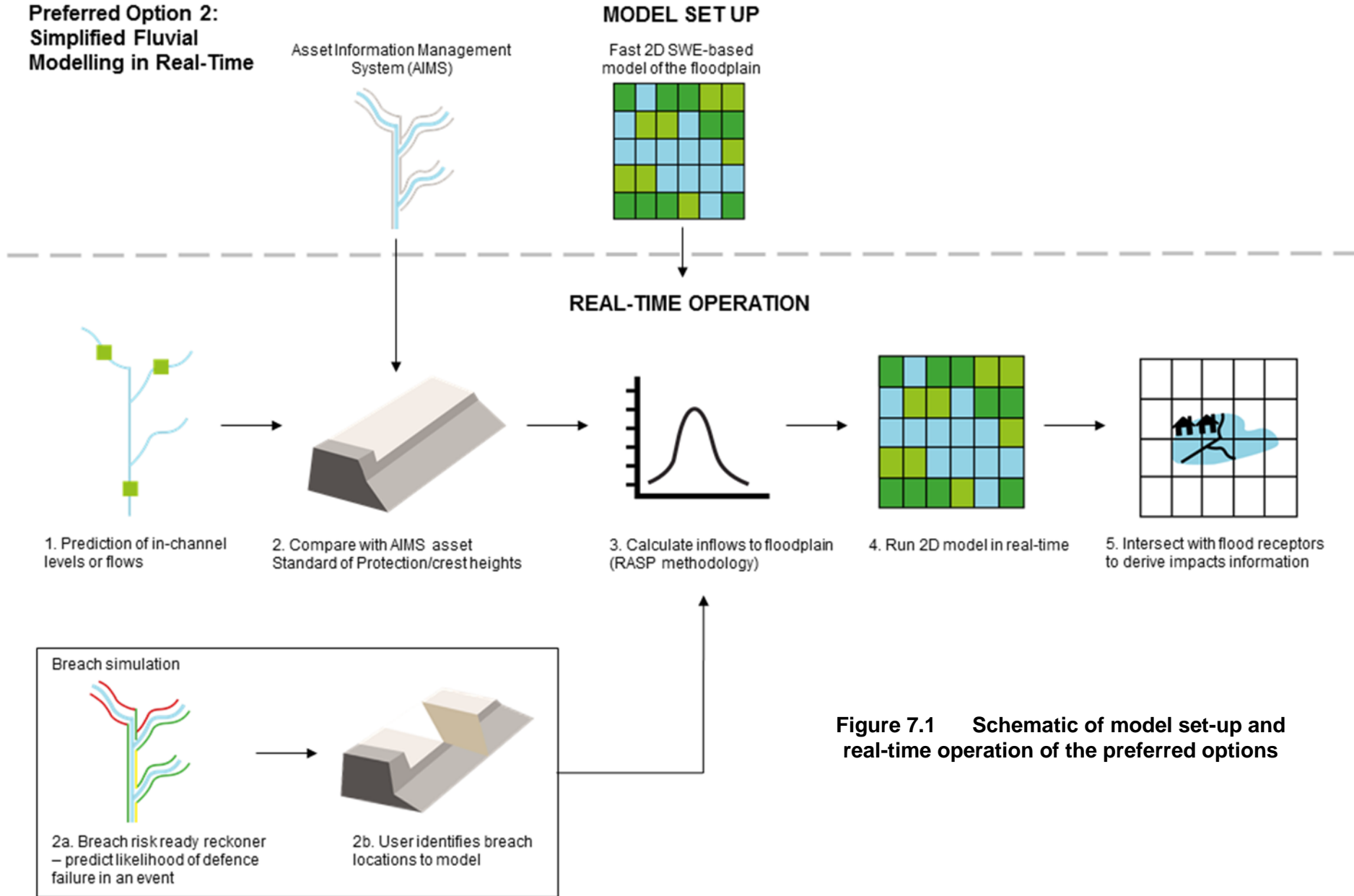
Lookup library – options for data sources and structure to be resolved by future projects



**REAL-TIME OPERATION**



**Preferred Option 2:  
Simplified Fluvial  
Modelling in Real-Time**



**Figure 7.1 Schematic of model set-up and real-time operation of the preferred options**

## 7.2 Implementation of preferred options

Implementation of either of the preferred options should consider the following points.

### 7.2.1 Preferred option 1: simulation library

- The simulation library could be implemented efficiently on a national scale, benefitting from recent investment in NaFRA and the State of the Nation. They can be built on with the gradual addition of local detailed mapping.
- Implementation of this option should consider how local detailed mapping can be incorporated into the simulation library, alongside datasets that provide national coverage.
- Accurate pre-computed data of flood extents (and/or depths) at a range of AEPs are a prerequisite. Without this, improvements to the forecast accuracy of in-channel flows or levels are unlikely to increase the accuracy of outputs from this option.
- The structure of look-up libraries and routines should be reviewed to make the most efficient use of these data in real time. For example, look-up libraries can be potentially large, depending on the simulation extent. However, data sizes could be managed efficiently in an operational system by evaluating flood depths on a Flood Area by Flood Area basis.
- The hardware requirements of this option are relatively low, as it is based on a look-up of pre-computed outputs. However, there may still be significant volumes of data that require transfer across networks. Network infrastructure, rather than computer processing speed, is therefore likely to be the main limitation to this option's run times.
- Fast, predictable run times mean that the simulation library is well suited to running multiple ensemble members (that is, variations of forecast in-channel flow).
- The simulation library has the potential to allow experimentation with different scenarios. For example, the method could be readily extended to consider defence failure by the inclusion of 'what-if' scenarios in the pre-computed library. However, this will require large numbers of pre-computed scenarios to be simulated and stored.

### 7.2.2 Preferred option 2: simplified fluvial modelling

- As with the simulation library, this option can be implemented efficiently on a national scale by reusing NaFRA and State of the Nation models and data. The models are straightforward to set up, but some further quality control on the input data, such as edits to the DTM may be required.
- Breaching can be incorporated through simple adjustments in defence SoP, crest level or fragility curve models such as RASP.
- Future data or modelling improvements could improve the accuracy of this option (for example, by incorporating higher resolution DTMs). However, the level of model detail should reflect its potential use as a real-time

forecasting tool. Case studies tested by this project found that, at longer lead times, uncertainty in forecast in-channel flows or levels can have greater impact on model performance than changes to model grid resolution (of the scale tested by this study).

- Non-standard hardware (for example, GPUs or multi-CPU systems) may be required to run models based on the shallow water equations.
- Future development in hardware (for example, GPU speed) may reduce the run times for large models that are currently limited by processing speed. However, if runs of many smaller models were required, run times are more likely to be limited by other software or hardware limitations (for example, network speeds).
- Data quality used to specify asset standards of protection and crest heights should be assessed and, where possible, should incorporate accurate, up-to-date information. The performance of this option would rely heavily on the accuracy of asset data held in AIMS.

### **7.2.3 Both options**

- Implementation of either option should consider appropriate boundary condition datasets to drive the models. Interpolation of AEPs along the river network offers many possibilities to drive real-time flood mapping and link to existing forecast locations in the NFFS. G2G is also a viable means of providing flow boundary conditions to the options in real time.

## **7.3 Next steps**

This project's findings will inform a forthcoming Discovery Phase project to be undertaken by the Environment Agency. This will develop the high-level business context and help guide future prototypes for real-time flood impacts mapping.

# References

- ALFIERI, L., PAPPENBERGER, F. AND WETTERHALL, F., 2014. The extreme runoff index for flood early warning in Europe. *Natural Hazards and Earth System Sciences*, 14, 1505-1515.
- BATES, P.D., NEAL, J.C., ALSDORF, D. AND SCHUMANN, G.J.-P., 2014. Observing global surface water flood dynamics. *Surveys in Geophysics*, 35 (3), 839-852.
- BELL, V.A., KAY, A.L., JONES, R.G. AND MOORE, R.J., 2007. Development of a high resolution grid-based river flow model for use with regional climate model output. *Hydrological Earth System Sciences*, 11 (1), 532-549.
- BERTSCH, R., 2013. *Implementation of the urban environment in 2D hydrodynamic models: CITYCAT and JFLOW+ GPU*. Unpublished MSc thesis, Newcastle University.
- BGS, 2015. *Estimating the number of properties at risk from groundwater flooding* [online]. Keyworth, Nottinghamshire: British Geological Survey. Available from: <http://www.bgs.ac.uk/research/groundwater/flooding/properties.html> [Accessed 9 April 2018].
- BISHOP, C.M., 1995. *Neural Networks for Pattern Recognition*. Oxford: Clarendon Press.
- DEFRA, 2010. *Surface water management plan technical guidance*. London: Department for Environment, Food and Rural Affairs.
- EFAS, 2013. *EFAS Bulletin. June – July 2013*. Issue 2013(4). Reading: European Centre for Medium-Range Weather Forecasts. Available from: [https://www.efas.eu/download/efasBulletins/2013/bulletin\\_jun-jul\\_13.pdf](https://www.efas.eu/download/efasBulletins/2013/bulletin_jun-jul_13.pdf) [Accessed 26 April 2018].
- EFAS, 2014a. *EFAS Bulletin. April – May 2014*. Issue 2014(3). Reading: European Centre for Medium-Range Weather Forecasts. Available from: [https://www.efas.eu/download/efasBulletins/2014/bulletin\\_apr-may\\_14.pdf](https://www.efas.eu/download/efasBulletins/2014/bulletin_apr-may_14.pdf) [Accessed 26 April 2018].
- EFAS, 2014b. *EFAS Bulletin. February – March 2014*. Issue 2014(2). Reading: European Centre for Medium-Range Weather Forecasts. Available from: [https://www.efas.eu/download/efasBulletins/2014/bulletin\\_feb-mar\\_14.pdf](https://www.efas.eu/download/efasBulletins/2014/bulletin_feb-mar_14.pdf) [Accessed 26 April 2018].
- EFAS, 2014c. *EFAS Bulletin. December 2013 – January 2014*. Issue 2014(1). ). Reading: European Centre for Medium-Range Weather Forecasts. Available from: [https://www.efas.eu/download/efasBulletins/2014/bulletin\\_dec-jan\\_14.pdf](https://www.efas.eu/download/efasBulletins/2014/bulletin_dec-jan_14.pdf) [Accessed 26 April 2018].
- EFAS, 2016. *EFAS Bulletin. December 2015 – January 2016*. Issue 2016(1). Reading: European Centre for Medium-Range Weather Forecasts. Available from: [https://www.efas.eu/download/efasBulletins/2016/bulletin\\_dec-jan\\_16.pdf](https://www.efas.eu/download/efasBulletins/2016/bulletin_dec-jan_16.pdf) [Accessed 26 April 2018].
- ENVIRONMENT AGENCY, 2005. *Development of a decision support system for a risk-based approach to catchment, estuary and coastal flood management planning (MDSF2)*. Report SC050051/SR4. Bristol: Environment Agency.
- ENVIRONMENT AGENCY, 2011. *The risk of widespread flooding – capturing spatial patterns in flood risk from rivers and coasts*. SC060088/R1. Bristol: Environment Agency.



- ENVIRONMENT AGENCY, 2012. *The Tyneside Flood 28 June 2012 – hydrological report*. Yorkshire & North East Region Hydrology Team.
- ENVIRONMENT AGENCY, 2013. *What is the updated Flood Map for Surface Water?* Report version 1.0. Bristol: Environment Agency.
- ENVIRONMENT AGENCY, 2014. *Flood and coastal erosion risk management. Long-term investment scenarios (LTIS) 2014*. Bristol: Environment Agency.
- ENVIRONMENT AGENCY, 2015. *Flood incident management plan 2015 to 2020: Saving lives and livelihoods. Part A – Outcomes*. Bristol: Environment Agency.
- ENVIRONMENT AGENCY, 2016. *Investigating coastal flood forecasting: good practice framework*. Report SC140007. Bristol: Environment Agency.
- ESSEX COUNTY COUNCIL, 2014. *Flood Investigation Report: Canvey Island*. Available from: <http://www.essex.gov.uk/Environment%20Planning/Environment/local-environment/flooding/Documents/FloodInvestigationReportCanveyIsland.pdf> [Accessed 24 September 2015].
- EXERCISE WATERMARK REVIEW TEAM, 2011. *Exercise Watermark: final report*. London: Department for Environment, Food and Rural Affairs.
- FRANZ, K., HOGUE, T.S., BARIK, M. AND HE, M., 2014. Assessment of SWE data assimilation for ensemble streamflow predictions. *Journal of Hydrology*, 519 (Part D), 2737-2746.
- GARCÍA-PINTADO, J., NEAL, J.C., MASON, D.C., DANCE, S.L. AND BATES, P.D., 2013. Scheduling satellite-based SAR acquisition for sequential assimilation of water level observations into flood modelling. *Journal of Hydrology*, 495, 252-266.
- GOVERNMENT OFFICE FOR SCIENCE, 2014. *Canvey Island: Section 19 Flood Investigation Report*. London: Government Office for Science.
- HAN, D., KWONG, T. AND Li, S., 2007. Uncertainties in real-time flood forecasting with neural networks. *Hydrological Processes*, 21 (2), 223-228.
- HALCROW AND JBA CONSULTING, 2012. *Flood map for surface water improvements - pilot studies final evaluation report*. Report version 4.0.
- HUNG, N.Q., BABEL, M.S., WEESAKUL, S. AND TRIPATHI, N.K., 2009. An artificial neural network model for rainfall forecasting in Bangkok, Thailand. *Hydrology and Earth System Sciences*, 13 (8), 1413-1425.
- JEEVARAGAGAM, P. AND SIMONOVIC, S.P., 2012. Neural network approach to output updating for the physically-based model of the Upper Thames River watershed. *International Journal of Hydrology Science and Technology*, 2 (3), 306-324.
- KEEF, C., TAWN, J.A. AND LAMB, R., 2013. Estimating the probability of widespread flood events. *Environmetrics*, 24 (1), 13-21.
- KORNELSEN, K.C. AND COULIBALY, P., 2013. Advances in soil moisture retrieval from synthetic aperture radar and hydrological applications. *J Journal of Hydrology*, 476, 460-489.
- LIANG, Q. AND SMITH, L.S., 2014. A high-performance integrated hydrodynamic modelling system for urban flood inundation. *Journal of Hydroinformatics*, 17 (4), 518-533.
- MAIER, H.R. AND DANDY, G.C., 2000. Neural networks for the prediction and forecasting of water resources variables: a review of modelling issues and applications. *Environmental Modelling and Software*, 15 (1), 101-124.

MASON, D.C., SCHUMANN, G.J.-P., NEAL, J.C., GARCÍA-PINTADO, J. AND BATES, P.D., 2012. Automatic near real-time selection of flood water levels from high resolution synthetic aperture radar images for assimilation into hydraulic models: a case study. *Remote Sensing of Environment*, 124, 705-716.

MET OFFICE, 2015. *Winter storms, January to February 2014* [online]. Exeter: Met Office. Available from: <http://www.metoffice.gov.uk/climate/uk/interesting/2014-janwind> [Accessed 9 April 2018].

MET OFFICE, 2016. Cumbria floods November 2009 – a look back [online]. Exeter: Met Office. Available from: <http://www.metoffice.gov.uk/about-us/who/how/case-studies/cumbria-floods> [Accessed 9 April 2018].

NEWCASTLE CITY COUNCIL, 2013a. *The Newburn culvert collapse and citywide flooding: a review of extreme events in Newcastle 2012*. Newcastle: Newcastle City Council. Available from: [http://www.newcastle.gov.uk/sites/drupalncc.newcastle.gov.uk/files/wwwfileroot/environment-and-waste/extreme\\_events\\_scrutiny\\_review\\_2012.pdf](http://www.newcastle.gov.uk/sites/drupalncc.newcastle.gov.uk/files/wwwfileroot/environment-and-waste/extreme_events_scrutiny_review_2012.pdf) [Accessed 9 April 2018].

NEWCASTLE CITY COUNCIL, 2013b. *Summer 2012 flooding in Newcastle upon Tyne. A report on the experiences of residents and non-residential property managers*. Newcastle: Newcastle City Council. Available from: [http://www.newcastle.gov.uk/sites/drupalncc.newcastle.gov.uk/files/wwwfileroot/environment/environment/microsoft\\_word\\_-\\_summer\\_2012\\_flooding\\_report\\_-\\_final\\_-\\_july\\_2013.pdf](http://www.newcastle.gov.uk/sites/drupalncc.newcastle.gov.uk/files/wwwfileroot/environment/environment/microsoft_word_-_summer_2012_flooding_report_-_final_-_july_2013.pdf) [Accessed 9 April 2018].

NI-MEISTER, W., 2008. Recent advances on soil moisture data assimilation. *Physical Geography*, 29 (1), 19-37.

PARKIN, G. 2010. *The September 2008 Morpeth Flood: information gathering for dynamic flood reconstruction*. Unpublished summary report, Newcastle University.

PAVELSKY, T.M., ALLEN, G.H. AND MILLER, Z.F., 2014. Spatial patterns of river width in the Yukon River Basin. In *Remote Sensing of the Terrestrial Water Cycle (Geophysical Monograph Series 206)* (ed. V. Lakshmi), pp. 131-141. Hoboken, NJ: John Wiley & Sons.

PITT, M., 2008. *The Pitt Review: Learning Lessons from the 2007 Floods*. London: Cabinet Office.

PRICE, D., HUDSON, K., BOYCE, G., SCHELLEKENS, J., MOORE, R.J., CLARK, P., HARRISON, T., CONNOLLY, E. AND PILLING, C., 2012. Operational use of a grid-based model for flood forecasting. *Proceedings of the Institution of Chemical Engineers – Water Management*, 165 (2). 65-77.

PRIETO, A., PRIETO, B., ORTIGOSA, E.M., ROS, E., PELAYO, F., ORTEGA, J. AND ROJAS, I., 2016. Neural networks: an overview of early research, current frameworks and new challenges. *Neurocomputing*, 214, 242-268.

RAFIEEINASAB, A., SEO, D.-J., LEE, H. AND KIM, S., 2014. Comparative evaluation of maximum likelihood ensemble filter and ensemble Kalman filter for real-time assimilation of streamflow data into operational hydrologic models. *Journal of Hydrology*, 519 (Part D), 2663-2675.

RANDRIANASOLO, A., THIREL, G., RAMOS, M.H. AND MARTIN, E., 2014. Impact of streamflow data assimilation and length of the verification period on the quality of short-term ensemble hydrologic forecasts. *Journal of Hydrology*, 519 (Part D), 2676-2691.

RAYNAUD, D., THIELEN, J., SALAMON, P., BUREK, P., ANQUETIN, S. AND ALFIERI, L., 2015. A dynamic runoff coefficient to improve flash flood early warning in

Europe: evaluation on the 2013 central European floods in Germany. *Meteorological Applications*, 22 (3), 410-418.

SCHUMANN, G.J.-P., BATES, P.D., DI BALDASSARRE, G. AND MASON, D.C., 2012. The use of radar imagery in riverine flood inundation studies. In: *Fluvial Remote Sensing for Science and Management* (ed. P.E. Carbonneau and H. Piégay), Chapter 6, pp. 115-140. Chichester: John Wiley & Sons.

SLATER, A.G. AND CLARK, M.P., 2006. Snow data assimilation via an ensemble Kalman filter. *Journal of Hydrometeorology*, 7, 478-493.

SUN, L., NISTOR, I. AND SEIDOU, O., 2015. Streamflow data assimilation in SWAT model using extended Kalman filter. *Journal of Hydrology*, 531 (Part 3), 671-684.

THIREL, G., SALAMON, P., BUREK, P. AND KALAS, M., 2013. Assimilation of MODIS snow cover area data in a distributed hydrological model using the particle filter. *Remote Sensing*, 5 (11), 5825-5850.

WESTERHOFF, R.S., KLEUSKENS, M.P.H., WINSEMIUS, H.C., HUIZINGA, H.J., BRAKENRIDGE, G.R. AND BISHOP, C., 2013. Automated global water mapping based on wide-swath orbital synthetic-aperture radar. *Hydrology and Earth System Sciences*, 17, 651-663.

# Bibliography

- BOGNER, K. AND KALAS, M., 2008. Error-correction methods and evaluation of an ensemble based hydrological forecasting system for the Upper Danube catchment. *Atmospheric Science Letters*, 9 (2), 95-102.
- BOURGIN, F., RAMOS, M.H., THIREL, G. AND ANDRÉASSIAN, V., 2014. Investigating the interactions between data assimilation and post-processing in hydrological ensemble forecasting. *Journal of Hydrology*, 519 (Part D), 2775-2784.
- CLARK, M.P., RUPP, D.E., WOODS, R.A., ZHENG, X., IBBITT, R.P., SLATER, A.G., SCHMIDT, J. AND UDDSTROM, M.J., 2008. Hydrological data assimilation with the ensemble Kalman filter: use of streamflow observations to update states in a distributed hydrological model. *Advances in Water Resources*, 31 (10), 1309-1324.
- DEMERITT, D. AND NOBERT, S., 2014. Models of best practice in flood risk communication and management. *Environmental Hazards*, 13 (4), 313-328.
- MICHAELS, S., 2015. Probabilistic forecasting and the reshaping of flood risk management. *Journal of Natural Resource Policy Research*, 7 (1), 41-51.
- PAGANO, T.C., WOOD, A.W., RAMOS, M.-H., CLOKE, H.L., PAPPENBERGER, F., CLARK, M.P., CRANSTON, M., KAVETSKI, D., MATHEVET, T., SOROOSHIAN, S. AND VERKADE, J.S., 2014. Challenges of operational river forecasting. *Journal of Hydrometeorology*, 15, 1692-1707.
- PAPPENBERGER, F., STEPHENS, E., THIELEN, J., SALAMON, P., DEMERITT, D., VAN ANDEL, S.J., WETTERHALL, F., ALFIERI, L., 2013. Visualizing probabilistic flood forecast information: expert preferences and perceptions of best practice in uncertainty communication. *Hydrological Processes*, 27 (1), 132-146.
- SEO, D.-J., CAJINA, L., CORBY, R. AND HOWIESON, T., 2009. Automatic state updating for operational streamflow forecasting via variational data assimilation. *Journal of Hydrology*, 367 (3-4), 255-275.
- STEPHENS, E. AND CLOKE, H., 2014. Improving flood forecasts for better flood preparedness in the UK (and beyond). *The Geographical Journal*, 180 (4), 310-316.
- STEPHENS, E.M., EDWARDS, T.L. AND DEMERITT, D., 2012. Communicating probabilistic information from climate model ensembles – lessons from numerical weather prediction. *Wiley Interdisciplinary Review Climate Change*, 3 (5), 409-426.
- VAN ANDEL, S.J., WEERTS, A., SCHAAKE, J. AND BOGNER, K., 2013. Post-processing hydrological ensemble predictions intercomparison experiment. *Hydrological Processes*, 27 (1), 158-161.

# List of abbreviations

AEP	annual exceedance probability
AIMS	Asset Information Management System [Environment Agency]
API	application programming interface
CDL	continuous defence line
CEH	Centre for Ecology and Hydrology
CPU	central processing unit
DTM	Digital Terrain Model
ECMWF	European Centre for Medium-Range Weather Forecasts
EFAS	European Flood Awareness System
ERI	Extreme Run-off Index
ERIC	European Run-off Index based on Climatology
FEWS	Flood Early Warning System [flood forecasting software developed by Deltares in the Netherlands]
G2G	Grid-to-Grid [hydrological model]
GIS	geographical information system
GMT	Greenwich Mean Time
GPU	graphics processing unit
HiPIMS	High-Performance Integrated Hydrodynamic Modelling System
HSL	Health and Safety Laboratory
JRC	Joint Research Centre [European Commission]
KCL	King's College London
LIDAR	light detection and ranging
LTIS	Long-term Investment Strategy
MDSF2	Modelling and Decision Support Framework 2
MOGREPS	Met Office Global and Regional Ensemble Prediction System
NaFRA	National Flood Risk Assessment
NFCDD	National Flood and Coastal Defence Database
NFFS	National Flood Forecasting System [Environment Agency]
NHP SWF HIM	Natural Hazards Partnership Surface Water Flooding Hazard Impact Model [Programme]
NRD	National Receptor Dataset
NRFA	National River Flow Archive
NWP	numerical weather prediction

PoC	proof of concept
RASP	Risk Assessment for Strategic Planning
ReFH	Revitalised Flood Hydrograph
RoFRS	Risk of Flooding from Rivers and Sea
RFSM	Rapid Flood Spreading Model
SoP	Standard of Protection
STEPS-2	Short Term Ensemble Prediction System
UTC	Universal Time Coordinated

# Annex A: Independent peer review of the final project report

**Note to reader:** This peer review is reproduced here as delivered to the Environment Agency, with the exception of a few minor corrections agreed with the author, Professor Beven.

The review was commissioned to evaluate the scientific approach used to determine the preferred options for generating flood impact mapping for incident management in real-time. It was tasked to consider if the science and recommendations presented are reasonable interpretations of the available evidence. More specifically, around the needs of users & producers, the range of options available as well as the practical considerations on their implementation.

The results of Professor Bevens review have been considered in the application of this research, but the report has not been updated to reflect the reviews findings.

The follow review was undertaken by Professor Keith Beven of the Lancaster Environment Centre.

## Contents

- A.1 Preface: The rules of forecasting
- A.2 Key findings and observations
- A.3 Strength and weaknesses of the R&D
- A.4 Recommendations for the follow-on project
- A.5 Key issues for future R&D projects
- A.6 References

## A.1 Preface: The rules of forecasting

**Rule 1:** We are only really interested in the next event (even if we make use of past events to inform the forecasting of the next one).

**Rule 2:** The next event will be different from previous events (and can be different in many different ways).

**Rule 3:** Both underprediction and overprediction are unwelcome (particularly ‘crying wolf’ too often), so given Rule 2 it is important to allow for uncertainty (you are more likely not to be wrong).

**Rule 4:** Because of Rule 2, use adaptive forecasting (or real-time updating) whenever possible while being robust to communication failures.

And for the purposes of this report:

**Rule 5:** Rules 1–4 apply to both forecasting at a point and forecasting maps of inundation.

## A.2 Key findings and observations

### A.2.1 Sensible outcomes

I would agree that the 2 strategies chosen for future work are sensible choices. I would also suggest that both should be refined as part of any follow-on project (see Section A.4).

In the case of the pre-computed maps, it is worth noting that there is work dating back to Romanowicz and Beven (1998) which has shown that this is a viable approach for real-time flood inundation mapping, including the use of updating on the basis of adaptive forecasts during an event. That and other more recent work has not been cited in this report.

In the case of the simplified fluid modelling, it will remain computationally challenging. In the case study presented, it was possible to specify the driving discharges. In any actual real-time case, however, these would need to be made available by a forecasting system (or at least some indication of current levels). This would give continuity with the forecasting of local pluvial/surface water flooding, though it will be difficult to properly reflect the uncertainties in local rainfall observations, forecasts and predictions of run-off generation, and the routing model – at least in the short term.

### A.2.2 Not all user needs are met

The 2 chosen strategies clearly do not satisfy all the user requirements determined at the start of the report. In addition, the marking/weighting scheme adopted did not really give clear preference to these choices.

There would already appear to be certain conflict between the commitments of the Environment Agency's Flood Incident Management Plan 2015 to 2020 and the conclusions set out in the report's executive summary. The Flood Incident Management Plan seems to be much more ambitious, particularly in respect of the communication of uncertainties.

I would have expected more discussion of the user-specified needs, especially since they do not all appear to be met. In particular, different user needs require different forecasting lead times (and might be therefore subject to different degrees of uncertainty).

## A.3 Strengths and weaknesses of the R&D

### A.3.1 Strengths

The greatest strength of this report is that it has resulted in some sensible outcomes, although I would strongly recommend that of the 2 strategies chosen for future investigation, more resources should be devoted to the approach based on pre-computed maps. This recommendation is based on the possibility of being able to use pre-computed maps in both online and offline situations, including the provision of uncertain inundation mapping. When online data are available, they are also very easily incorporated into an adaptive forecasting system.



Simple routing models might become a more viable real-time strategy as computer power becomes less limiting in future, for example, the use of on-demand cloud computing. It has the advantage that it is not limited to quasi-steady state inundation maps, but the disadvantage that (initially at least) it will be run at relatively coarse resolution.

### **A.3.2 Weaknesses**

I have one major criticism of the report. This is that all the methods are essentially presented as alternative strategies when in fact they have quite different purposes and fulfil quite different needs. They are therefore not really comparable, which means that the marking system used was not very meaningful. It would have been much better to classify the methods in terms of satisfying different user decision needs (for example, different lead times and different catchment scales).

The report also pushes all consideration of visualising and communicating uncertainty into potential 'future developments', despite this being an express requirement of the flood incident room users. It would actually be quite easy to do based on pre-computed maps – again see Romanowicz and Beven (1998).

I would also suggest that there is one major omission from the report. This is any consideration of real-time updating in short-term forecasting. This is one of the most important tools for the forecaster to avoid being wrong when data are available online to allow adaptive forecasting. When online data are not available, perhaps because of communication breakdown during a major event, then the system can be made robust in continuing to work without updating. It can also be used to constrain error and uncertainty in forecasts, and consequently give improved visualisations of flooding (with uncertainties if necessary, see Section A.3.2).

#### *Comments about specific statements*

##### **Section 2.5**

'There are 2 quick win, low-cost options that provide reasonable benefits – breach risk (option 11 in Table 2.3) and long-range ensemble warning system (option 10).'

This is an interesting conclusion. I think it reflects the scoring process far more than any real or reasonable benefits. Long-range ensemble forecasting is fine for flood alerts, but of little or no use for the requirement of this project – the rainfall predictions are just not good enough (see Section A.3.1). Any breach risk system is going to involve huge uncertainties in predicting actual breaches, and to do it properly would actually require rather accurate pictures of when overtopping or critical head differences are going to occur. Thus this comment would not appear to be justified.

##### **Section 3.3**

'In-river flow or level estimates (from river gauges or forecast locations, as used in the NFFS) can be converted to return periods based on local flood frequency analysis. These can be interpolated more robustly along the river network than the flow/level measurements themselves.'

Does this make sense? We know from estimates of frequencies at Desmond, Cockermouth, Carlisle, Boscastle and so on that post-event estimates of local frequencies can vary dramatically spatially, especially where there are atmospheric river type events. In producing your maps, you are actually starting with frequency to

produce input discharges and consequent modelled levels, not the other way round. So how does this allow local variation/interpolation of frequencies?

#### **Section 4.1.4**

‘... could not be extended to assess flood impacts on other receptors such as transport networks or critical infrastructure.’

While this was not a specific remit of this report, it could have been given more prominence, especially given the Gold and Silver Command requirements outlined in the user needs (and in the reference to Canvey Island case study validation data). Consideration of a wider range of receptors should be included in the follow-on project.

#### **Section 6.2.5**

‘This allows the uncertainty in the rainfall and hydrological forecasts ...’

To be strictly correct, this allows some of the uncertainty to be transmitted [a point adopted in the text of the final report, which reads ‘some of the uncertainty’]. Rainfall forecasts are still not at the stage where the ensembles can be considered as probabilistic forecasts of future precipitation (especially for the local type of event that is most important for pluvial/surface water flooding), nor is structural and parameter uncertainty in G2G properly taken into account.

#### **Section 6.2.6**

‘During an event, individual flood defences can be categorised by probability of failure (for example, Low, Medium, High) and combined with pre-computed, per asset risk data (for example, relative/absolute contributions to NaFRA estimated annual damages) to provide indicative information on the likelihood and impact of breaching at these locations.’

This is the basis for the NaFRA approach. However, the concern in real-time forecasting is not about a prior probability of failure in an event but the posterior probability of a breach (either 0 or 1, or  $p(\text{depth of erosion}|\text{breach has occurred})$ ) in that event, as it will affect the flood levels and downstream inundation. It should be recognised that these are quite different. The possibility of defence failures is, however, an additional argument for allowing for adaptive forecasting and real-time updating on the inundation mapping.

#### **Appendix 4: Case study 2 Cocker mouth**

The results of this case study are presented uncritically, even positively, but are these deterministic results adequate to be confident for real-time forecasting and decision-making? The resolution of the NaFRA maps would also not appear to be adequate for any useful decision-making – though this should improve as NaFRA2 becomes available.

## **A.4 Recommendations for the follow-on project**

### **A.4.1 User needs and lead times**

Part of the problem of satisfying all the user needs is that different forecasting situations and decisions require quite different lead times. In particular we can distinguish situations where forecasts are required at longer lead times than the natural lag time of the catchment (small catchments where lag time is short, or long lead times

for decisions about demountable defences, evacuations and so on), and those that are within the lead time of the catchment (decisions about flood warnings).

Forecasts requiring longer lead times are more challenging in that they will be dependent on forecast rainfalls which as yet are not reliable in terms of either the position or intensities of intense precipitation. NWP rainfall forecasts in particular are not that hydrologically useful for quantitative forecasting and are better treated more qualitatively as flood alerts (as in the current Flood Forecasting Centre and EFAS systems). This means that any inundation mapping based on forecast rainfalls will be associated with significant uncertainties. The EFAS approach of expressing severity in terms of relative return period relative to a long period of re-analysis is probably the best approach to take here.

#### **A.4.2 Improvements to the selected methods**

Where forecasts can be based on observed rainfalls or upstream river flows, it will be possible to have a more direct input to inundation mapping in real time. Rule 2 of forecasting (see Section A.1) means it will often be valuable to make the forecasts adaptive – when online data are available. In doing so, it is also possible to estimate forecast uncertainties, which can be used with pre-computed maps to provide uncertain inundation patterns. The methodology (as shown by Romanowicz and Beven 1998) is simply to associate maps with a probability weight dependent on forecast flows or levels. This also allows the inundation patterns to be updated in real-time by simply changing the weights on the pre-computed maps as the forecast uncertainties change. The computer overheads in doing so are small, especially if the pre-computed maps can be stored locally.

Implicit in this report, but never stated explicitly, is the use of inundation maps based on return periods/AEPs. This might be because it is conditioned on the maps that are currently available from the NaFRA and the Environment Agency risk mapping, but it also suggests an underlying approach based on deterministic mapping based on crisp AEP discharges. This is not, I would suggest, a useful mind set for real-time inundation mapping where it is the uncertain levels (and velocities) occurring in a specific event that need to be available (see the rules of forecasting). Some users might also require velocity information to make threat-to-life assessments, which will be even more uncertain.

This suggests that, in future work, pre-computed maps should be produced to provide sufficient depth and spatial resolution to allow the uncertainties to be adequately represented (for example, Leedal et al. 2010, Neal et al. 2013). This would not be difficult to do using existing Environment Agency hydraulic models where they are available. For the simple fluvial case, the pre-calculated maps can be ranked by levels at a local gauge (or discharges but current level is what you know best!). They can then be changed according to predicted levels/discharges at that gauge (including uncertainty around that prediction if required). Forecasting methods are available for both rainfall to level prediction, and for level to level routing methods (see, for example, Leedal et al. 2013), which avoid the need to specify rating curves. But, as noted in the report for the tidal and coastal cases (where timing differences between tributaries or for potential defence failures might be important), more runs and decision trees for potential cases would then be needed.

For the simplified routing method, I would suggest that this really needs to integrate the channel flood wave routing since in the dynamic case. This will be critical to getting the water levels that induce flood plain storage more correct; it is less important for inundation mapping under steady flow conditions.

### **A.4.3 Uncertainty and its communication**

Taking account of uncertainty and its communication was a requirement of flood incident room users. As noted above, this is relatively simply done using pre-computed maps, even to the use of adaptive forecasting to improve inundation estimates and constrain uncertainties. There is, however, no mention in this report of the joint Defra and Environment Agency FD/2901 probabilistic flood forecasting project, which could provide inputs to the inundation mapping.

Communicating the meaning of uncertain inundation maps is likely to be an issue with some potential users. There is also no mention in this report of the SC120010 Public Dialogues on Flood Risk Communication project, which specifically considered the communication of uncertainty. Both reports should be taken into account in any follow-on project work.

### **A.4.4 Computational resources**

There are a number of mentions in the report about the computational requirements of implementing real-time inundation maps, particularly in respect of 'non-standard' hardware (GPUs) and the transfer of large amounts of data across the network (which might not always be available locally in extreme events).

In general, it is likely that the strategy of simplified flood routing will be much more demanding in this respect than the use of pre-computed maps. As already noted, simplified routing might become more viable in future using on-demand computing resources – although the transfer of the resulting forecasts would require network communications. For pre-computed maps, once the basic maps are loaded it is actually only colour codes for flood overlays that actually need changing in real time – see the implementations in Matlab described in Leedal et al. (2010) or overlaid on Google Earth (for example, Beven et al. 2013). Both also have zoom facilities built in. Network communications would then only be required for real-time updating or more general access using web pages.

## **A.5 Key issues for future R&D projects**

Inundation modelling depends on routing discharges (though note again the possibility of using only level information for the pre-computed map strategy above), but the critical issue in many forecasting situations, particularly those where the required lead times are longer than the natural lag time of the catchment is knowing how much run-off to route. This is a problem that is generally underestimated; it is also a primary reason for making forecasting processes adaptive when that is possible. It would be a valuable topic for future research, especially in respect of how uncertainties in rainfall forecasts feed into run-off generation and discharge forecasts.

Another important aspect of using updating in forecasting is during post-event analysis. In recent years, the Environment Agency has begun to create a database of flood levels following major events. This information is extremely valuable in testing inundation maps, particularly in terms of conditioning uncertainties in forecasting the next event, or showing where the modelled inundation maps are quite wrong. How best to use such information should also be a topic of future R&D.

Previous work has shown that, for simple downstream routing of flood waves, it is not always necessary to run a full hydraulic model. It might also be possible to emulate the outputs of a hydraulic model using a computationally fast emulator model (see, for example, Beven et al. 2008). Such emulators cannot be more accurate than the

original hydraulic model, but can be much simpler to make adaptive in real-time when online level data can be made available.

The current report chose not to address the problem of inundation maps for groundwater flooding. This is a hydrologically difficult problem, since even the best calibrated groundwater models (when they are available at all) are subject to calibration and recharge estimation uncertainties. It is also, at least sometimes, a longer time scale process so that it might be possible to relate groundwater discharges to either modelled or observed water table levels. Patterns of discharge could also then be used to define pre-computed inundation depth maps. In real time, rather than using a full groundwater model, it might also be possible to use a simple emulator, with feedback from local level sensors where this could be justified.

## A.6 References

BEVEN, K.J., YOUNG, P.C., LEEDAL, D.T. AND ROMANOWICZ, R., 2008. Computationally efficient flood water level prediction (with uncertainty). In *Flood Risk Management: Research and Practice*, Proceedings of the 1st European Conference on Flood Risk Management, FLOODrisk2008 (Oxford, 2008), edited by P. Samuels, S. Huntingdon, W. Allsop and J. Harrop. London: CRC Press/Balkema.

BEVEN, K.J., LEEDAL, D.T., HUNTER, N. AND LAMB, R., 2013. Communicating uncertainty in flood risk mapping. In *Comprehensive Flood Risk Management: Research for Policy and Practice*, Proceedings of the 2nd European Conference on Flood Risk Management, FLOODrisk2012 (Rotterdam, 2012), edited by F. Klijn and T. Schweckendiek. London: CRC Press/Balkema.

LEEDAL, D.T., NEAL, J., BEVEN, J., YOUNG, P. AND BATES, P., 2010. Visualization approaches for communicating real-time flood forecasting level and inundation information. *Journal of Flood Risk Management*, 3 (2), 140-150.

LEEDAL, D.T., WEERTS, A., SMITH, P.J. AND BEVEN, K.J., 2013. Application of data based mechanistic modelling for flood forecasting at multiple locations in the Eden catchment in the National Flood Forecasting System (England and Wales). *Hydrology and Earth System Sciences*, 17 (1), 177-185.

NEAL, J., KEEF, C., BATES, P., BEVEN, K.J. AND LEEDAL, D.T., 2013. Probabilistic flood risk mapping including spatial dependence. *Hydrological Processes*, 27 (9), 1349-1363.

ROMANOWICZ, R. AND BEVEN, K.J., 1998. Dynamic real-time prediction of flood inundation probabilities. *Hydrological Sciences Journal*, 43 (2), 181-196.

# List of appendices

The appendices are provided as separate downloadable files on the report's GOV.UK page.

- Appendix 1: User requirements summary report\*
- Appendix 2: Technical options report\*
- Appendix 3: Long-term options
- Appendix 4: Fully dynamic fluvial modelling
- Appendix 5: Simplified fluvial modelling
- Appendix 6: Simulation library
- Appendix 7: 10-day lead time NWP products
- Appendix 8: Simplified surface water modelling

## \* Important note

The User Requirements Summary Report (Appendix 1) was produced following the user consultation. It documents user needs and provides a draft framework for developing technical options.

The Technical Options Report (Appendix 2) describes the long list of options developed in response to the user needs identified during the consultation process. It also sets out the approach to scoring the options and provides an initial appraisal of each.

Both are included here for completeness. Please note that their contents have been superseded by this document. This sets out the final position which may, in some cases, differ from what is stated in the appendix version.

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