Department for Environment Food & Rural Affairs

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Environment Agency

delivering benefits through evidence

Real-time flood impacts mapping

Appendix 2a: Technical options report

SC120023/A2

Flood and Coastal Erosion Risk Management Research and Development Programme

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Email: enquiries@environment-agency.gov.uk

Author(s):
Tom Cox, Rosemary Hampson, Robert Hooper, Neil Hunter, I-Hsien Porter, Beatriz Revilla-Romero, Rebecca Stroud and Richard Wylde

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Research Contractor:
JBA Consulting
South Barn, Broughton Hall
Skipton, North Yorkshire BD23 3AE
Tel: 01756 799919

Environment Agency's Project Manager:
Mark Whitling

Theme Manager:
Sue Manson, Theme Manager, Modelling and Risk

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Professor Doug Wilson
Director, Research, Analysis and Evaluation

Note to readers

The Technical Options Report describes the long list of options developed in response to user needs identified in the consultation process. It also develops the approach to scoring the options and provides an initial appraisal of each.

However, the information contained herein has been superseded by the final project report. One example difference is that Option 14 was added later as a baseline, and so is not referenced in this document but appears as a key option in the main report.

The reader should consult the final report for the full and final details of the study.

Contents

List of tables and figures

1 Introduction

The National Flood Forecasting System (NFFS) helps the Environment Agency to deliver an effective flood forecasting and warning service. However, Category 1 responders and strategic decision-makers in Gold and Silver Command require better information from local incident rooms on the likely impact and consequences as the floods develop. The Environment Agency therefore commissioned this R&D project (SC120023) to explore the options available for transforming level, flow or threshold forecasts into real-time impact and consequence information that can be understood by emergency planners and other responders.

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 flooding of winter 2013 to 2014. Recent work, described in this report, identified a series of technical options for meeting these requirements and shortlisted 4 options for further consideration. Future work will involve proof of concept trials to investigate the practicality of each shortlisted option, how well they align with user needs, and their wider costs and benefits, thus producing a high-level business case to support their future implementation.

This report draws together work completed under Project Tasks 2, 3 and 4 (Table 1.1).

Table 1.1 Outline of work outcomes described in this report

Task	Objectives
2	• Development of a long list of technical options that meet some or all user requirements identified during the Task 1 consultation exercise • Development of acceptability criteria and an objective process for appraising each option • Initial evaluation of initial options against user requirements and acceptability criteria
3	• Further analysis of user needs, use cases and work flows to propose shortlist of options for further development • More detailed evaluation of options against user requirements and acceptability criteria
4	• A mini review of the options and their ranking to determine preferred options

Notes: Explicit reference to these tasks is not made in this report.

Section 2 introduces the concepts required to evaluate each of the proposed options, which are then described in Section 3. Section 4 presents the final set of scores for each option and recommends those suitable for proof of concept development.

Scoring matrices for each technical option are provided in Appendix 2b (Excel spreadsheet).

2 Key concepts for option development and evaluation

This section introduces a number of concepts that have been used to inform the development of specific options and their subsequent appraisal.

2.1 User requirements

User requirements are summarised here from the User Requirements Summary report (Appendix 1). These requirements had to be considered first so that relevant criteria could be developed against which to score the proposed options.

Requirements are aggregated into 2 primary user groups:

- Environment Agency Area Incident Rooms – monitoring unfolding events, running models, disseminating forecast information to Flood Warning colleagues and professional partners
- Gold and Silver Command – responding to an unfolding event and co-ordinating on the ground response. For example, police commanders might co-ordinate the Fire and Ambulance services, Coast Guard, RAF rescue, RNLI, local authority, and water, electricity and gas utilities.

A third user group, central government(for example, Defra, the Ministry of Housing, Communities and Local Government[1] or the COBR Committee), which requires a national overview during significant events, is not explicitly considered here but is likely to have similar requirements to the Gold and Silver Command.

The Project Board further identified the need to consider these user groups in the broader context of ‘producers’ and ‘users’ of real-time flood impacts information. Area Incident Rooms can be broadly considered as producers of data (running models, interrogating results, disseminating outputs to professional partners) and Gold and Silver Commands as users (Category 1 responders, emergency services, strategic decision-makers).

It is clear that the requirements of these 2 groups will be quite different. Producers, for example, might need to understand in detail the limitations of a given modelling system or data source, while users may only need to know that the degree to which a given output is suitable for their particular decision. Similarly, it is useful to think of both groups in terms of whether they require tactical or strategic level information (Table 2.1). In both cases, there are 2 primary user groups but only the groups shaded in the table are considered here.

[1] Formerly the Department for Communities and Local Government

Table 2.1 Primary user groups considered (shaded) in terms of type of user and producer

Scale/level of information	Producers	Users
Tactical	Environment Agency Flood Forecasting/Area Incident Rooms	Environment Agency Flood Warning
Strategic	Flood Forecasting Centre	Gold and Silver Command/ central government

With these distinctions in mind, the requirements for the Area Incident Room and Gold and Silver Command user groups are summarised in Table 2.2 and Table 2.3 respectively.

Table 2.2 Summary of Environment Agency Area Incident Room user requirements

Information required	Dissemination
• Hazard mapping needed to show **depth and velocities**, given that extents do not show the full picture. • More accurate forecasting of **timing** • Must be able to communicate **uncertainty**, as a range, rather than trying (and failing) to make accurate predictions to the nearest centimetre and metre. • **All sources** of flooding should be represented, if possible. • Defence representation needs to be easily manipulated/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 **breach** (of a certain size) in to a wall or coastal bank and to see a revised inundation map. • **Lead times of up to 5 days** are needed. • Must be relevant at the **property/ street scale**. • Other receptors must be considered (for example, individual roads).	• Can be easily communicated. • Highly visual, map-based • Information must be available on new technologies (for example, **mobile devices and tablets**). • Must be able to zoom in and out of an area, to see ‘most likely flood outline’ and ‘worst case scenario outline’ (for example, **web mapping**).

Table 2.3 Summary of Gold and Silver Command user requirements

Information required	Dissemination
• Professional partners typically want to know: - 'Will it reach this level?' - 'When will it reach this level?' - 'How many people will need to be evacuated?' - 'Where will they be?' • At Gold and Silver Command in Surrey there were **no queries in relation to depths, hazard and velocity maps**. Required information is more general; is there a risk to life or not? • One of the key pieces of information Silver Command wanted to know was the **time of travel** and **when the peak would pass certain locations**.	• **Prefer to limit the use of technology**; PDFs can be seen as the 'technological limit'. • **Prefer not to rely on computers** for example, Wi-Fi was recently installed at Silver Command police stations throughout Exeter but it kept dropping out. • Information must be usable '**round a table**'. • Dealing with large file sizes is a problem. • In Cornwall, a geographical information system (GIS) dataset was used to show critical infrastructure (in point format), displayed on the whiteboard in the incident room. During the incidents, they tried to overlay live GIS data but with very limited success. • Information must be **brief and simplified**.

On a general level, these requirements can be summarised as:

- **Area Incident Rooms**. Ideally require localised spatiotemporal flood depth and velocities from all relevant sources that can be applied to assess hazard at the individual receptor level. Uncertainty must be assessed at lead times of up to 5 days. Access via web mapping and mobile applications is preferred, and systems must be resilient.
- **Gold/Silver Command**. Ideally require broad-scale mapping of areas at risk of flooding. Temporal information is critical and longer lead times are preferred for strategic planning. Single/deterministic outputs are preferred. Methods must also work in an offline environment and have limited cost and training requirements.

2.2 Acceptability criteria

Acceptability criteria determine the capacity of a service or system to perform its function, both in terms of technical capacity and usability. In the context of this work, they have been used to define a list of criteria against which each of the proposed options (see Section 3.2) can be assessed, and enable objective evaluation and prioritisation of different options.

Their formal definition requires that the criteria are 'SMART':

- **S**pecific – target a specific area for improvement

- **M**easurable – quantify or at least suggest an indicator of progress
- **A**chievable – specify goals that are reachable
- **R**ealistic – state what results can realistically be achieved, given available resources
- **T**ime-related – specify when the result(s) can be achieved

To keep the criteria relatively simple, only the first 2 components of SMART are considered here.

Acceptability criteria are also typically evaluated in the context of a particular user. Given that 2 primary user groups have been identified, it is clear that some options will meet the needs of each group independently, while others will meet the needs of all groups. A flexible evaluation matrix was therefore designed to account for this (Section 2.3).

A final distinction needs to be made between functional and non-functional requirements.

- Functional requirements describe what a system does. In the context being considered here, this might include whether the model outputs can be used to consider flooding at street level, or whether information on two-dimensional (2D) velocities can be generated.
- Non-functional requirements describe how the system produces the information. For example, does the model inform its user when there is an error and how to fix it, or does it work on a mobile device?

Only functional requirements were considered in this initial scoping phase given that the emphasis of this work was on understanding the technical options available rather than developing operational software. Clearly non-functional requirements will become more important as these initial options are developed into proof-of-concepts and potentially business cases later in the project.

Table 2.4 summarises the functional acceptability criteria developed in this project. Each main category is further disaggregated into a number of relevant sub-criteria. Where relevant, a commentary is also provided on why these were chosen.

Table 2.4 Summary of functional acceptability criteria

Acceptability criteria	Sub-categories	Commentary
Flood source	• Fluvial • Coastal • Surface water • Groundwater • All sources	
Flood hazard	• 1D water levels • 2D flood extents • 2D flood depths/water levels • 2D velocities and/or hazard rating	Only hydrodynamic 2D approaches can generate flood velocities, while most approaches can generate depths/levels if a suitable digital terrain model (DTM) is available.

Acceptability criteria	Sub-categories	Commentary
Temporal information	• Onset of floodplain inundation • Time of maximum inundation • Duration of flooding • Dynamic representation of floodplain wetting and drying	Certain users may need to understand how the inundation extent will evolve – from onset to peak to recession. Only dynamic models can provide this information. Others may only require information on the onset or maximum inundation, which could be derived via an intersection of one-dimensional (1D) water levels with ground and/or embankment crest levels.
Spatial coverage	• Local scale (for example, town, river reach) • Regional scale (for example, county, catchment, river basin district) • National scale (that is, complete coverage across England and Wales)	Spatial coverage is the physical area that a given product could cover.
Suitability	• Property • Street to town • Town to county • County to national	A flood map might have spatial coverage across the entire country, but not be suitable for property level assessments. This is an important distinction – for example, the National Flood Risk Assessment (NaFRA) is a national product, but available at 25m resolution and therefore not suitable for property scale analysis.
Asset representation	• Flood defences • Culverts and bridges • Other structures (for example, gates, sluices, storage areas, pumping stations)	This is a critical consideration – some existing mapping is undefended and therefore ignores the presence of flood defences. Some real-time methods can include these defences but not represent smaller scale structures or blockage impacts.
Asset performance	• Breach inundation and/or overtopping: single asset failure • Breach inundation and overtopping: multiple asset failure • Within-event asset deterioration/failure	

Acceptability criteria	Sub-categories	Commentary
	• Worst case breach inundation	
Transparency	• Individual components can be interrogated/evaluated • Closed system, simplified 'whole model' confidence statements only	Can the various modelling components be interrogated so that weaknesses can be identified, or have the data been derived externally and therefore it is only possible to make generic confidence statements (for example, NaFRA)?

2.3 Evaluation matrix

Each of the acceptability criteria defined above are presented in an evaluation matrix (Figure 2.1). Each option is assigned an evaluation matrix.

User groups (in this case Area Incident Rooms and Gold/Silver Command) are shown as coloured bars along each row of the matrix. A shaded bar implies that the particular user requires the given functionality. For example, Area Incident Rooms ideally require information on both 2D flood depths and velocities, whereas Gold and Silver Commands are primarily only interested in the general extent of flooding. Similarly Area Incident Rooms typically require data that can be used at the individual property to town level, while Gold and Silver Commands prefer a broader or strategic overview. These requirements are fixed throughout the option appraisal process and provide a consistent basis for scoring the option's ability to meet the requirements of a given user group.

If an option meets a given acceptability criteria, it is assigned a 'Y'. For example, linking levels from the NFFS to existing NaFRA mapping would be suitable for use at street scale and above, but not for property scale assessments. A 'Y' would therefore be entered in 3 out of the 4 suitability criteria for this option. This process is preferred to a more subjective approach, in which each option is, for example, given a score between 1 and 5. Equally, it is rarely the case that an option clearly does answer a given acceptability criteria in binary terms. Some subjectivity therefore remains.

This evaluation process is completed for all options.

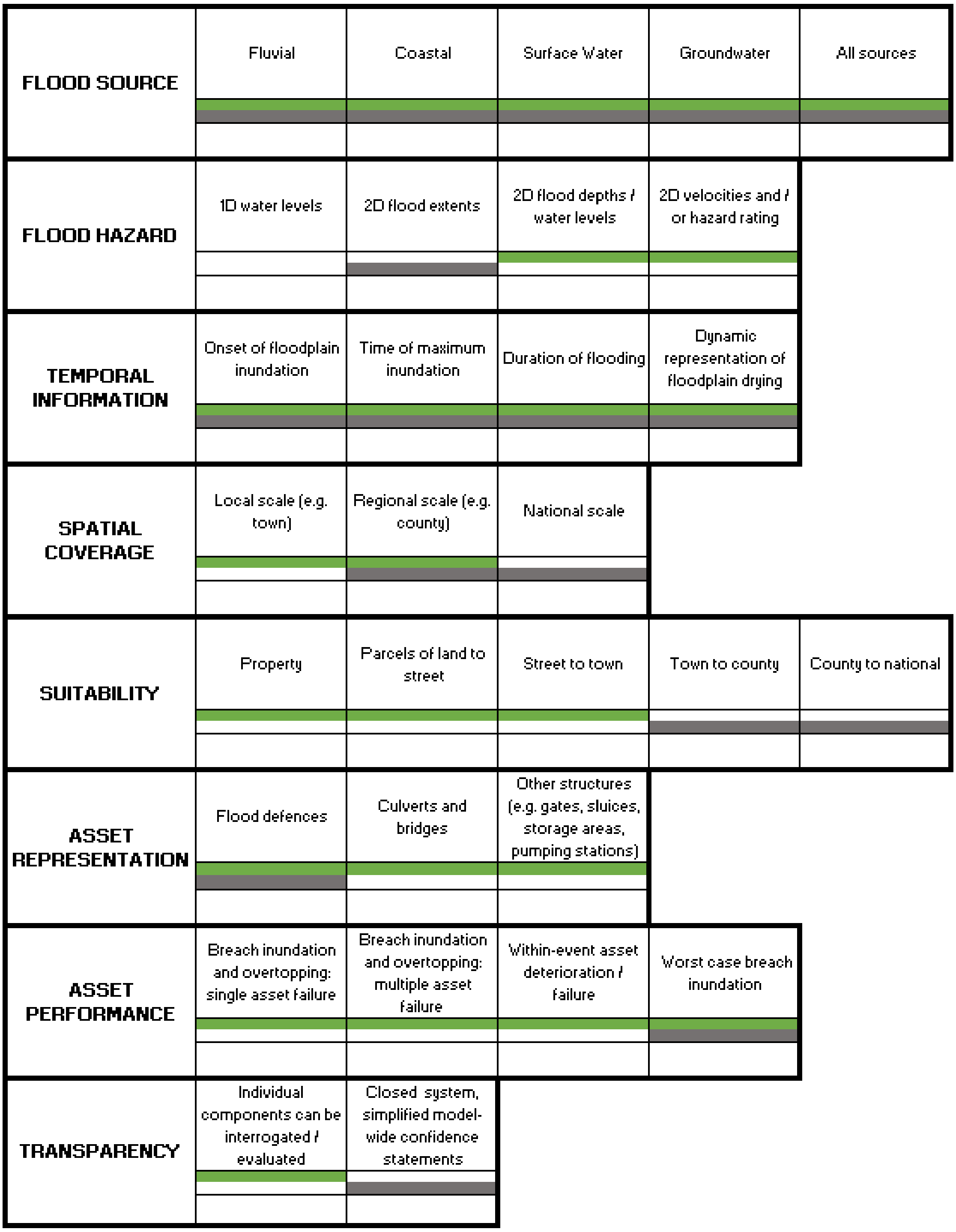


Figure 2.1 Technical option evaluation matrix

2.4 Scoring

The evaluation matrices are then used to determine an option-specific score. This allows a quantified comparison to be made between each option. Scoring is calculated as a simple average. This process is explained using the generic example shown in Figure 2.2.

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

Figure 2.2 Generic example

This option meets one out of 2 flood hazard requirements for Area Incident Rooms (green bars in Figure 2.2) and one out of one requirements for Gold/Silver Command (grey bar). The average score is therefore 0.5 × (1/2 + 1/1) = 0.75, assuming that the needs of each user group should be met equally.

This process is repeated for each acceptability criteria category and a final average score per option (across all acceptability criteria and user groups) calculated. User group specific scores are also provided.

In addition, options were assigned a final weight that altered their score according to the number of properties affected by the given flooding type. This is essential so that the options are scored on a level basis. For example, a groundwater option might score highly in all aspects and therefore receive an overall score that is comparable to a surface water option. However, the benefits of implementing a surface water forecasting system will clearly be more wide-reaching than from implementing a groundwater system; nearly 10 times the number of properties are at risk from surface water flooding than are from groundwater flooding in England according to the Long-Term Investment Strategy (LTIS) 2014 (Environment Agency 2014).

The specific ratios applied were:

- 2.4 for options that provide inundation forecasts of fluvial and coastal flooding – there are 2.4 million properties at risk from these sources in England (Environment Agency 2014)
- 3.0 for surface water options – there are 3 million properties at risk from surface water flooding in England (Environment Agency 2014)
- 0.3 for groundwater options – there are ~290,000 properties at risk of groundwater flooding in England (BGS 2015)
- 0.6 for all-sources options – 600,000 properties are at risk from both fluvial/coastal and surface water together (Environment Agency 2014) and would therefore benefit directly from a combined system rather than individual systems. This is likely to be an overestimate given that fewer still properties will be at risk from fluvial/coastal/surface water and groundwater combined.

Scores for each option are revisited in Section 4.

3 Proposed technical options

3.1 Overview

This section provides detail on each of the proposed technical options.

Options are broken down into:

- **pre-computed methods**, which use existing flood mapping in conjunction with current or forecast levels/flows to derive spatially consistent inundation information (Section 3.2.1)
- **real-time methods,** which run flood spreading models (and any other associated components) on demand during an event (Section 3.2.2)

In each case, options are split into:

- **Assets/Resources** – a product that is already available (whether Environment Agency owned or otherwise) and that can be reused for a forecasting application. This includes both input datasets and inundation products. For example, an asset might be the NFFS Grid-to-Grid (G2G) model (input), which could be coupled with NaFRA mapping (inundation product) to generate forecast extent and depth mapping.
- **Processes/Technical methods** – technical methods that must be implemented in order to generate forecast inundation maps. In the case of pre-computed options, this might simply be a mining algorithm that generates spatially realistic forecast inundation maps from a library of existing maps. For real-time options, this might instead be the actual running of a 2D hydraulic model in real time.

All options are summarised in Figure 3.1, using this framework of assets/resources and processes/technical methods.

Options that only consider flood defence breach (see Section 3.2.3) are presented separately, although it is recognised that these breach-specific options will work well only with certain other options. These are identified by the blue bordering in Figure 3.1. For example, it is difficult to envisage a breach option working well for a groundwater system, but easy for a real-time fluvial system. These have been separated out for simplicity.

Implementation costs and time to implementation are considered alongside the functionality of each option. Note that they refer to the cost/time required to get the given option to a near-operational product and not to the cost/time required to develop an initial prototype. These are indicative only at this stage and are intended to provide a relative basis upon which to assess and compare each option.

Finally, no consideration of 'impacts' is explicitly given in any of the options. Impacts mapping is governed by the availability of:

- inundation mapping
- appropriate receptor datasets

Impacts derivation is then a straightforward intersection of these data. The challenging process, and the one given attention here, is the initial process of deriving the inundation data in real time.

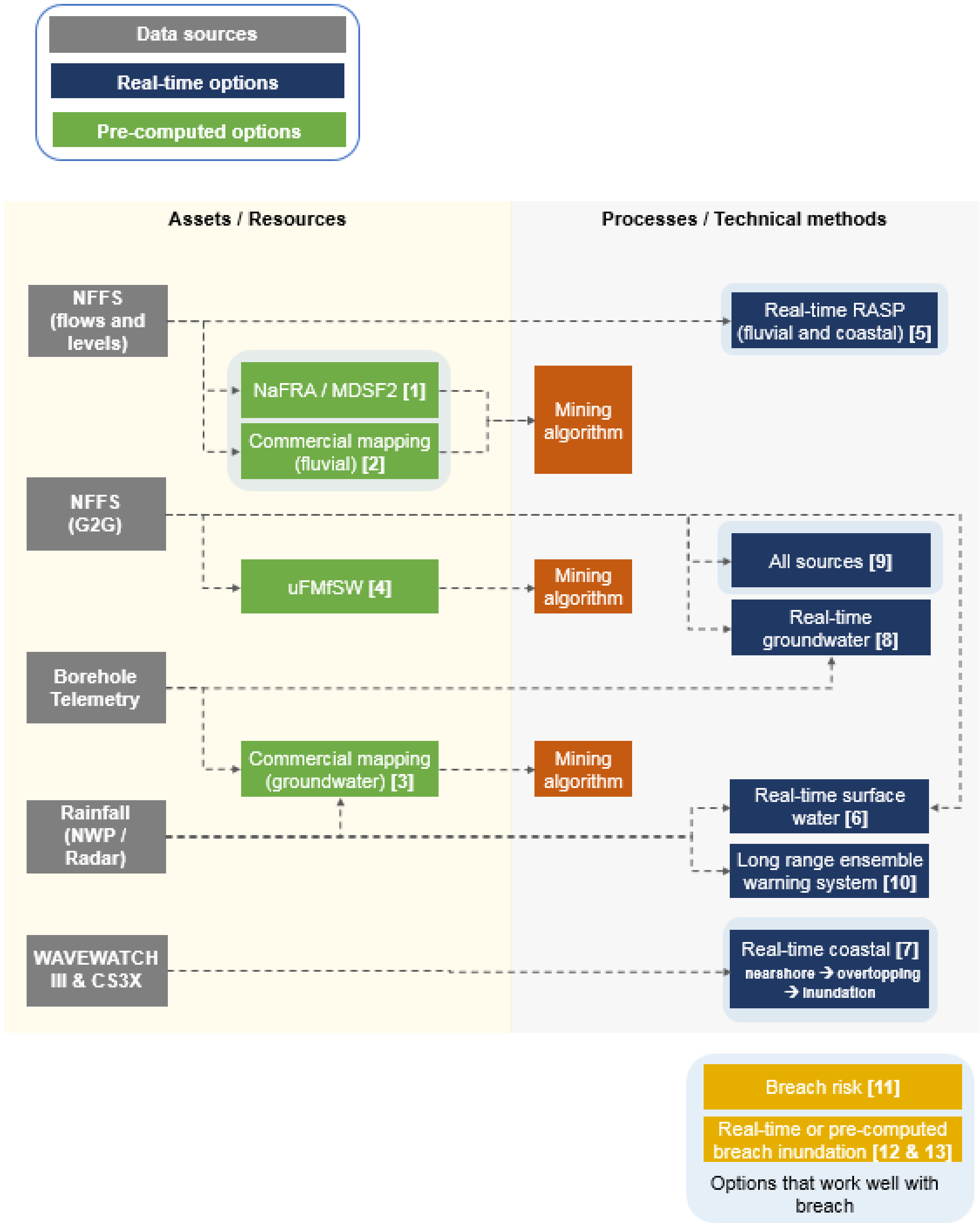


Figure 3.1 Summary of options using the asset/resources and processes/technical method framework

Notes: Option names are abbreviated, but can be linked using their option IDs. NFFS is used to describe both level/flow observations from gauges, forecast outputs from hydraulic models (for example, ISIS) or probability distributed models, and also outputs from the G2G model. Both are contained within the existing NFFS platform and are therefore an existing asset/resource. MDSF2 = Modelling and Decision Support Framework 2; NWP = numerical weather prediction; RASP = Risk Assessment for Strategic Planning

3.2 Detailed summary of each option

3.2.1 Pre-computed approaches

A common element in each of the approaches described here is the need for a linking mechanism – or mining algorithm – that allows forecast levels or flows to be linked to some form of existing 2D inundation mapping. Similarly, the process of merging together static mapping products in a way that generates spatially consistent mapping requires care. This is particularly true for a surface water look-up based approach, where rainfall may have a profile that is highly non-uniform in space. In this case, the maps being merged between 2 adjacent locations may have been originally computed using 2 very different sets of rainfall profiles. Flood depths along the boundary of these 2 maps therefore need to be interpolated in a sensible way so that sharp gradients are avoided. This is likely to be less of an issue in fluvial applications, where it is generally expected that the levels or flows being used as a look-up will change uniformly in space. These elements are common to each method and it is probably the case that a single mining algorithm could be developed and applied in any look-up approach.

<table>
<tr><td colspan="4">1. National NaFRA simulation library</td></tr>
<tr><td colspan="3">Asset/Resources</td><td rowspan="2">Process/Technical method</td></tr>
<tr><td colspan="2">Input</td><td>Inundation product</td></tr>
<tr><td colspan="2">NFFS (levels/flows)</td><td>NaFRA mapping</td><td>Mining algorithm</td></tr>
<tr><td>Technical description</td><td colspan="3">Generate a library of NaFRA (that is, MDSF2) simulations for use in real-time forecasting applications. The ongoing State of the Nation risk modelling will generate an up-to-date national product that could be mined for these purposes. However, changes to the MDSF2 software would be required so that depth maps, or extents, for each individual return period (out of 40) and breach scenario are recorded. Presently these are discarded and only aggregate risk is reported. This is a significant limitation of this approach. It is also unclear as to whether the quality of the mapping generated in MDSF2 by the Rapid Flood Spreading Model (RFSM) is of an appropriate quality for use in forecasting applications. Few previous studies have interrogated the quality of the depth mapping generated in the NaFRA, given that aggregate risk is usually the final reported metric. The RFSM is not a dynamical model and instead relies on a simplified volume-based flood spreading methodology.

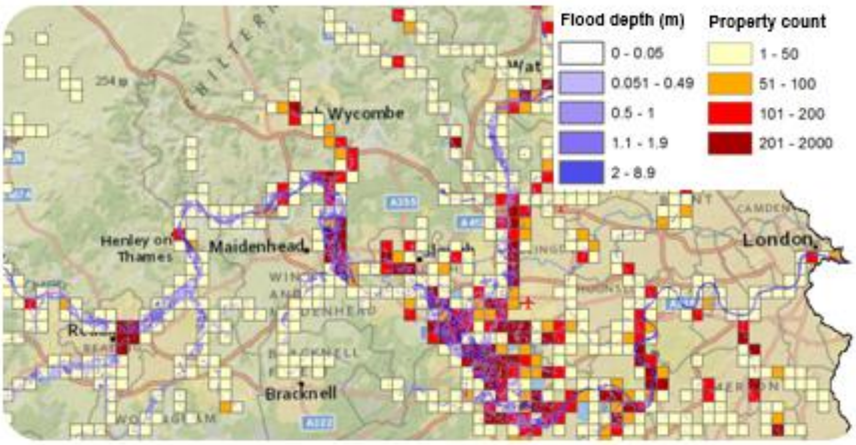
Once the appropriate library of simulations has been derived, a ‘depth map mining tool’ would be required. For fluvial reaches, this would associate forecast levels with MDSF2 run levels and select the nearest return period, or interpolate between them if necessary. For coastal reaches, the same process would be applied but forecast information would be cross-referenced against the coastal loadings database. It is recognised that loadings will vary along reaches and coastal frontages, so that the depth maps that are mined will be for a range of return period events. These would therefore need to be stitched together in such a way that generates spatially realistic footprints and avoids unrealistic step changes.

As with all approaches where 2D extents or depths are produced, GIS intersection with receptors can be used to derive relevant impacts data. Impacts could either be pre-computed, given that MDSF2 already contains a broad range of impact calculators (for example, number of properties, economic damages or social vulnerability) or calculated in real time.

This would complement option 13, if breach simulations from the NaFRA are used. However, it does presuppose that all possible breach scenarios have been sampled and recorded, which would equate to a dataset of considerable size and would take time to generate.</td></tr>
<tr><td rowspan="2">Data requirements</td><td>Available</td><td colspan="2">None</td></tr>
<tr><td>Gaps</td><td colspan="2">MDSF2 results library containing individual scenarios/system states</td></tr>
<tr><td>Route to implementation</td><td colspan="3">1. Develop NaFRA simulation library. This may require moderate to significant changes to the MDSF2 simulation engine so that individual realisations (that is, individual depth maps) are recorded for each run. The volume of data is likely to be significant.
2. Create national scenario database.</td></tr>
</table>

<table>
<tr><td></td><td colspan="3">3. Develop mining algorithm to sample from national scenario database during real-time event, linking forecast levels from the NFFS – Flood Early Warning System (FEWS) or equivalent with MDSF2 simulated flows. Interpolation may be required between return periods to obtain appropriate depth map. Trigger thresholds would be required for all reaches so that the analysis is only run when required.</td></tr>
<tr><td rowspan="2">Implementation costs</td><td>Low</td><td>Moderate</td><td>Significant</td></tr>
<tr><td colspan="3">Costs associated with modifying the MDSF2 software so that individual scenarios are stored, re-running these scenarios nationally and storing the resultant outputs are likely to be significant.</td></tr>
<tr><td>Time to implementation</td><td>Short: <1 year</td><td>Medium: 1–5 years</td><td>Long: 5+ years</td></tr>
<tr><td>Pros</td><td colspan="3">• Nationally consistent approach
• Utilises latest information in many important areas – water levels, coastal boundary condition analysis, flood defences, floodplain topography – many of which have been updated thorough to support the State of the Nation update to the NaFRA
• Uses the same system models as applied in investment planning
• Potential to consider breach scenarios</td></tr>
<tr><td>Cons</td><td colspan="3">• Robustness of mapping from the NaFRA for incident response is unclear, particularly where depths are important
• Potentially significant effort required to modify MDSF2 so that individual realisations are recorded
• Mining algorithm to determine nearest pre-computed scenario likely to require significant investment (but common to all pre-computed options)
• Requires large volume of data to be stored and accessed in real time.</td></tr>
</table>

2. National simulation library using commercial (fluvial) flood map products		
Asset/Resources		**Process/Technical method**
Input	**Inundation product**	
NFFS (levels/flows)	Commercial mapping	Mining algorithm

Technical description	This option is similar to option 1, but instead uses a national simulation library containing commercial fluvial flood map products. These datasets typically contain undefended scenarios only, but are available for a large number of return periods and are based on a nationally consistent methodology (that is, the same model has been applied everywhere) and the models applied typically solve the 2D shallow water equations, meaning that the quality of the depth information is high. There may also scope to generate defended outlines where required. These flood maps could be reused in forecasting applications by linking the design flows and/or levels that were used to derive the original mapping with either telemetered observations or forecast flows from G2G or the NFFS. As in option 1, some form of search engine tool to mine the appropriate flood map for a given event would be required. An example of an existing prototype that employs this approach is the Flood Foresight tool developed by JBA and ImageCat for the insurance industry. Here, observations from telemetry networks or outputs from numerical weather prediction (NWP) models are used to derive forecast flows, which are subsequently compared with the flows used to derive the original flood mapping. Interpolation between available maps is then applied to derive an event-specific flood map. This is intersected with receptor data to derive the number of properties at risk, and an animated graphic generated that shows how this risk will evolve over the forecast period. Relatively large spatial areas are considered, principally so that the accuracy of the approach is not over-interpreted, meaning that the outputs are most useful for strategic incident management. An example is shown below, where flood depths are overlaid by the number of properties flooded on a 1km grid.  *Example: flood depths overlaid on number of properties flooded (1km grid)*	
Data requirements	**Available**	National scale fluvial (typically undefended), subject to appropriate licensing
	Gaps	Defended mapping and breach scenarios

Route to implementation	Assuming that the necessary datasets could be obtained cost-effectively and that only undefended outlines are required, limited additional analysis would be required to implement this option. However, significant re-modelling would be required to derive defended outlines and pre-computed breach mapping would require vast resources at a national scale. For breach scenarios, use of existing NaFRA scenarios or real-time modelling (option 12) may be preferable. Algorithms to efficiently link current/forecast levels from NFFS–FEWS or equivalent with simulated flows would need to be prepared. Interpolation may be required between return periods to obtain appropriate depth and impact maps, and care will be needed to ensure spatially realistic footprints without unrealistic step changes along boundaries. Trigger thresholds would be required for all reaches so that the analysis is only run when required.		
Implementation costs	Low	**Moderate**	Significant
	The majority of cost is likely to be associated with licensing the commercial mapping products. If re-runs are required to generate defended outlines, this cost will increase.		
Time to implementation	Short: <1 year	**Medium: 1–5 years**	Long: 5+ years
Pros	• Based on nationally consistent model data. • Makes use of robust 2D modelling (rather than MDSF2 where a simplified volume-based flood spreading is applied), although this depends on the underlying flood map product sourced.		
Cons	• Defended outlines are unlikely to be available and so the method is probably best suited to larger scales and not property level. • Not suited to breach modelling (too many scenarios to consider). • Requires large volume of data to be stored and accessed in real time.		

3. Static groundwater maps linked to borehole telemetry and NWP		
Asset/Resources		**Process/Technical method**
Input	**Inundation product**	
Borehole telemetry/NWP	Groundwater mapping (commercial)	Mining algorithm
Technical description	This option relies on the generation of a library of groundwater flood extent/depth maps for use in real-time forecasting applications. The maps would need to cover a range of design events and ideally return period assessment should be tied to either groundwater levels in boreholes or winter rainfall totals/recharge (that is, at ~3 month timescales). For use in a forecasting system, live borehole levels could be used to provide a 'live view' of groundwater risk, while outputs from NWP could be used to generate forecast risk. Rainfall forecasts would have to be tied to semi-physical recharge model to derive groundwater levels; such models are available. It would also be possible to use G2G subsurface flow outputs	

	using this look-up approach (see option 8 for more details). In many cases, groundwater upwelling occurs over long time periods and can be easily identified from borehole data alone (that is, once a borehole starts spilling it is likely to do so for an extended period of time). It may therefore be relatively straightforward to link telemetered borehole levels to a set of static flood maps, much in the same way as could be done for fluvial and surface water flooding. A clear limitation of using only borehole data is the relatively sparse distribution of these gauges in England (see map below).  *Distribution of boreholes gauges in England*	
Data requirements	**Available**	A number of groundwater flood risk maps with UK-wide coverage are available (for example, BGS, ESI, JBA). The Environment Agency is currently conducting a review of these maps to determine their suitability for future use. The majority of these maps report groundwater flood susceptibility, and would not be able to differentiate between areas at risk from inundation for a particular design event. Few of the maps implicitly take into account groundwater borehole levels or winter rainfall/recharge. There are some products that do this; the JBA 5m product (2015) shows where groundwater will emerge (for design events of 20, 75, 100 and 200 years), but does not yet have national coverage or include appropriate depth information. The only groundwater flood maps that report realistic depths for different return periods are those being produced by Jacobs and JBA for Buckinghamshire and Berkshire County Councils. These are derived by estimating rates of flow emergence for different groundwater levels and routing emerging flow with JFlow. This process could be applied to generate mapping at national scales, although would clearly only be required in groundwater susceptible areas.
	Gaps	Map coverage/extent (see above) Borehole data are not always appropriately located – data length and quality issues may be problematic
Route to implementation	1. Develop library of groundwater flood event maps covering a range of flood return periods. This may involve developing new maps or using existing proprietary maps or adapting proprietary maps. 2. For agreed trigger points, create recharge–frequency relationships. For example, there could be one trigger point per groundwater Flood Alert	

	or Warning Area. 3. Prepare algorithms that can obtain forecast rainfall from NWP, convert to recharge and apply recharge–frequency relationships to derive return periods of flooding expected in each Warning Area. Combine these with available borehole data. For each Warning Area, identify appropriate design event(s) maps from library via a mining algorithm (interpolation may be required if return period falls between 2 mapped values).		
Implementation costs	Low	**Moderate**	Significant
	Implementation costs are likely to be moderate, depending on the amount of additional modelling work required. Licensing of geological mapping information would need to be factored into cost. Environment Agency owned DTMs could be used.		
Time to implementation	**Short: <1 year**	Medium: 1–5 years	Long: 5+ years
Pros	• Avoids need for real-time modelling. • Makes use of existing trigger rainfall datasets for groundwater flood forecasting.		
Cons	• No one off-the-shelf map meets the requirement. Project targeted maps may need to be developed, but these could utilise existing mapping methods.		

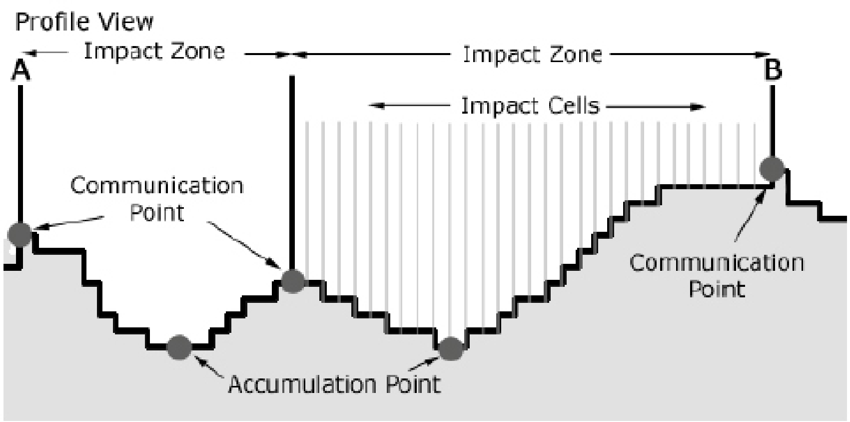
<table>
<tr><th colspan="3">4. Updated Flood Map for Surface Water simulation library linked to G2G run-off outputs</th></tr>
<tr><th colspan="2">Asset/Resources</th><th rowspan="2">Process/Technical method</th></tr>
<tr><th>Input</th><th>Inundation product</th></tr>
<tr><td>NFFS (G2G)</td><td>Updated Flood Map for Surface Water</td><td>Mining algorithm</td></tr>
<tr><td>Technical description</td><td colspan="2">A recent study by the Natural Hazards Partnership successfully demonstrated the process of coupling G2G 1km surface run-off outputs to a static archive of the updated Flood Map for Surface Water 2m maps. The basic approach assumed that G2G surface run-off was equivalent to the effective rainfall inputs (which includes losses) used to derive the updated Flood Map for Surface Water. Nine such effective rainfall totals were used to generate the updated Flood Map for Surface Water – 3 durations (1, 3 and 6 hours) and 3 rainfall probabilities (1 in 30, 1 in 100 and 1 in 1,000). The process is best described as a downscaling of the 1km G2G outputs onto a 2m grid.

An impacts library was also developed as part of this work, combining receptor datasets with the national 2m updated Flood Map for Surface Water library. The final output from the linked G2G– updated Flood Map for Surface Water was therefore an impact metric, rather than a 2m resolution flood extent/depth map. Probabilistic estimates were generated by using the G2G ensemble outputs.

This option is not described further in this work as the system is due to be developed into a near-operational prototype by the Natural Hazards Partnership during 2015.</td></tr>
</table>

3.2.2 Real-time approaches

<table>
<tr><td colspan="3">5. Real-time RASP for fluvial and coastal inundation modelling</td></tr>
<tr><td colspan="2">Asset/Resources</td><td rowspan="2">Process/Technical method</td></tr>
<tr><td>Input</td><td>Inundation product</td></tr>
<tr><td>NFFS (levels/flows)</td><td></td><td>Real-time RFSM/ISIS-FAST or JFlow/TUFLOW-GPU</td></tr>
<tr><td>Technical description</td><td colspan="2">
This option considers the use of 2 types of suitably fast flood spreading models to derive real-time inundation extents and depths from forecast in-channel levels. These levels would be derived from NFFS 1D models (for example, ISIS) rather than from the G2G model. G2G is better suited to flow forecasting and does not include the requisite channel cross-sectional data to provide accurate level information. Inflow volumes would then be calculated using the inflow volume calculation currently used in the MDSF2 implementation of RASP.
Although this option is termed real-time RASP, in reality it would use only one component (the inflow boundary condition derivation) of the RASP methodology, which refers to a broader probabilistic framework. Inflow volumes in the RASP framework or derived on a per defence basis, or along lengths of high ground in undefended areas. Inflow volumes are calculated using a simplified form of the broad crested weir equation and a number of simplifying relationships that vary with asset type, derived from either the National Flood and Coastal Defence Database (NFCDD) or the Environment Agency’s Asset Information Management System (AIMS). Inflow volumes can be calculated for both breached and non-breach cases, which is a critical advantage of reapplying this method for real-time forecasting.
The full set of equations is described in SC050051/SR4 (Environment Agency 2005) and can be easily implemented outside of the MDSF2 software.
Inflow volumes could then be combined with a suitable inundation model to derive depths and extents. Two such models are recommended below.
Option A: RFSM (or similar, for example, ISIS-FAST)
MDSF2 includes a simplified flood spreading model at its core – the RFSM. This model is used within MDSF2 given the need to run many thousands of inundation simulations in a timescale of minutes or less. The RFSM therefore presents a clear opportunity from a forecasting perspective, where fast run times are also required.
The RFSM is not a dynamical spreading model. Instead, water is allowed to spill from one ‘Impact Zone’ to another once the available volume within that Impact Zone is full. Communication points are assigned to determine the locations at which water is transferred from zone to zone (se diagram below). A projection analysis is then used to determine the depth of water on an Impact Cell basis, typically at a resolution of 25m, although higher resolutions can be specified.
</td></tr>
</table>



Schematic of RFSM concept

It would be relatively straightforward to reapply the RFSM in a real-time setting, although it would have to be decoupled from the full MDSF2 software.

There are questions over the suitability of the RFSM for such an application as limited work has been done to verify the quality of the depth predictions from the model, other than in idealised cases. The model also ignores feedback between the channel and floodplain, or lateral in/outflows, which may be a limiting factor in a forecast setting.

Option B: JFlow (or other suitably fast 2D inundation model such as TUFLOW-GPU)

JFlow has not been used in a fluvial forecasting setting previously, given difficulties associated with generating a suitable inflow boundary and an assumption that run times are still prohibitively long. However, the same simplified hydraulics used within the RASP approach could be used in conjunction with JFlow to provide a suitable boundary condition along fluvial reaches. Indicative run times for JFlow, given a range of grid resolutions and forecast times, are shown below for a 13.04km^2 model domain, demonstrating that 2D modelling is feasible for forecasting applications. Using a fully dynamical model also ensures that local flow characteristics are accurately captured, though feedback between channel and floodplain is still lacking.

Indicative run times for a 13.04km^2 model domain

Grid resolution	Number of grid cells	Model run time			
		3 hours	6 hours	12 hours	24 hours
2m	3,260,238	26min 12s	61min 0s	138min 58s	284min 35s
4m	815,060	4min 4s	9min 9s	19min 44s	40min 44s

Both these options would also enable a straightforward evaluation of breach scenarios, given that the simplified hydraulics described previously can be used to derive breach inflow volumes on a defence by defence basis.

Data requirements	**Available**	NFFS level forecasts NFCDD or AIMS to provide asset characteristics – the recently completed Continuous Defence Line could also be used

<table>
<tr><td rowspan="2"></td><td></td><td colspan="3">DTM of sufficient resolution</td></tr>
<tr><td>Gaps</td><td colspan="3">None</td></tr>
<tr><td>Route to implementation</td><td colspan="4">1. Link NFFS levels to an automated procedure that calculates inflow volumes using the simplified hydraulics described in SC050051/SR4. Where crest levels are larger than the predicted water level, end calculation and stop.
2. Assign thresholds that determine when a real-time model should be fired.
3. Modify SC050051/SR4 to allow for breach characteristics, individual assets or groups of assets to be modified (currently these are determined based on the loading condition) in real time.
4. In the case of the RFSM, it will be necessary to decouple it from the MDSF2 software so that it can be run on a standalone basis.
5. Automate RFSM or JFlow runs, including generation of model domain from analysis of DTM and post-processing. Careful consideration of how to schematise the model domain will be necessary, recognising that there will be a maximum area per simulation. It may be possible for this process to be contained within the existing NFFS platform.

It is recommended that both options (RFSM and JFlow) should be trialled if this option is shortlisted, given that for a prototype, the majority of work will involve generating the forecast inflows and not the actual model run process.</td></tr>
<tr><td rowspan="2">Implementation costs</td><td colspan="2">Low</td><td>Moderate</td><td>Significant</td></tr>
<tr><td colspan="4">To implement on a national basis will require moderate investment – particularly the automation of the model set-up and run process</td></tr>
<tr><td>Time to implementation</td><td colspan="2">Short: <1 year</td><td>Medium: 1–5 years</td><td>Long: 5+ years</td></tr>
<tr><td>Pros</td><td colspan="4">• Enables direct use of simulated levels rather than approximated look-ups. There is no need to develop complex look-up algorithms or database to store data.
• RASP hydraulics can be used to understand breach risk.
• Fast</td></tr>
<tr><td>Cons</td><td colspan="4">• Neither the RFSM or JFlow account for interactions between river and floodplain, meaning that depths may be exaggerated. Approaches could be developed to mitigate against this.
• Automated model schematisation may be difficult – for example, how should model domains be determined or inflow points defined?
• Difficulty determining when it is worthwhile firing a real-time model simulation (that is, when are inflow volumes large enough to generate flooding?)</td></tr>
</table>

<table>
<tr><th colspan="4">6. Real-time surface water linked to G2G or NWP</th></tr>
<tr><th colspan="3">Asset/Resources</th><th rowspan="2">Process/Technical method</th></tr>
<tr><th>Input</th><th colspan="2">Inundation product</th></tr>
<tr><td>NFFS (G2G) or NWP</td><td colspan="2"></td><td>Real-time JFlow</td></tr>
<tr><td>Technical description</td><td colspan="3">This is equivalent to option 4, but rather than using G2G 1km surface water outputs and coupling to a set of static (offline) updated Flood Map for Surface Water maps, a surface water inundation model would instead be run in real-time. This has the primary advantage that there is not a need to try and relate a finite set of flood outlines/depths to a variable G2G output. Similarly, G2G outputs vary in both space and time, whereas the static updated Flood Map for Surface Water outputs are based upon a spatially uniform design rainfall.

The most obvious choice of model for this application is JFlow, given that:

• it was used to generate the updated Flood Map for Surface Water and will therefore produce physically similar results
• it has sufficiently fast run times for direct rainfall applications

Thresholds will have to be set that determine when to trigger a real-time run. These thresholds could be determined via an analysis of the existing updated Flood Map for Surface Water (that is, to determine what volume of rainfall/run-off is required to generate flooding above a given critical depth). G2G outputs could then be monitored to determine when a given threshold is crossed and inundation model(s) should be launched.

Alternatively, it would be relatively straightforward to directly couple NWP or radar outputs to JFlow prior to routing these through the G2G model. The 1.5km UKV model output is the most obvious choice. A similar minimum threshold approach would be required. Both inputs could be trialled and compared as part of this option. This would further determine the value added by using the G2G as an additional modelling step.

For this option to work, it would be necessary to hold the updated Flood Map for Surface Water 2m DTM (or any other DTM with appropriate flow pathway modifications stamped in) in a central archive that can be quickly accessed for use in a real-time environment. Similarly, graphics processing units (GPUs) would have to be kept in a power-resilient location so that the system is robust and will not fail. For trialling purposes, these issues may not matter, but they will need to be considered at a later stage.</td></tr>
<tr><td rowspan="2">Data requirements</td><td>Available</td><td colspan="2">G2G run-off outputs or UKMO UKV NWP model outputs

DTM of sufficient resolution with national coverage</td></tr>
<tr><td>Gaps</td><td colspan="2">None</td></tr>
<tr><td>Route to implementation</td><td colspan="3">1. Determine trigger thresholds for each G2G model grid or similar spatial unit on the existing updated Flood Map for Surface Water.
2. Automate extraction process from either G2G for surface water run-off component, or NWP or radar forecast feed. This may be implementable using the existing NFFS–FEWS platform.
3. Run JFlow using both outputs for a number of case study locations to</td></tr>
</table>

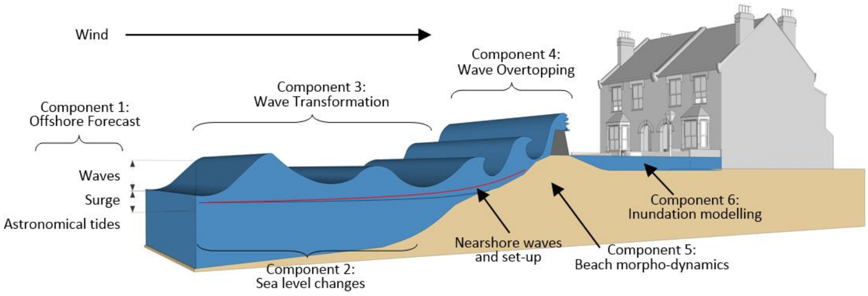
	determine relative skill.		
Implementation costs	Low	**Moderate**	Significant
	To implement on a national basis will require moderate investment, particularly the automation of the model set-up and run process.		
Time to implementation	Short: <1 year	**Medium: 1–5 years**	Long: 5+ years
Pros	• Avoids the need to pick representative outputs from the updated Flood Map for Surface Water for a given forecast rainfall or G2G surface water run-off event. • No need to store the updated Flood Map for Surface Water in an offline database. • Can apply spatially varying rainfall.		
Cons	• Run times may limit resolution, particularly for events with large spatial coverage. • There are questions over how to model long time period events where initial floodplain condition is not dry (for example, Somerset flooding in winter 2013 to 2014). • Requires stable and resilient IT infrastructure if being used in an operational setting (for prototyping this may not be a significant issue).		

7. Real-time coastal modelling system		
Asset/Resources		**Process/Technical method**
Input	**Inundation product**	
WAVEWATCH III and CS3X		Real-time nearshore transformation/wave overtopping/inundation model

Technical description	The material summarised here is based largely on the Environment Agency project, Investigating Coastal Flood Forecasting (SC140007), currently being undertaken by JBA Consulting and HR Wallingford. There is great diversity in the type and nature of coastal flood forecasting systems used operationally in the UK and internationally. However, existing Environment Agency approaches are among the most advanced in the world and there are no international systems that would provide significant improvement to the methods already in use. Coastal flooding comprises a number of linked components (see figure below): • still water level (astronomical tide and large-scale storm surge) • sea level changes • wave generation and transformation to the nearshore • wave overtopping

- beach morphodynamics
- inundation modelling

These processes combine to generate a final overtopping inflow, which can then be used to model inland flooding via an inundation model.



Linked components making up coastal flooding

Most existing coastal flood forecasting systems in the UK rely on a mix of nationally available forecasts and additional elements of regional modelling or analysis. The most important components of national forecasting are:

- tidal predictions, based on a harmonic analysis of Class A tide gauges, updated annually by the National Oceanography Centre (NOC)
- storm surge forecasts from the CS3X surge model, developed by the National Oceanography Centre (which will be superseded by Nucleus for European Modelling of the Ocean (NEMO) in 2017)
- wave forecasts from the Met Office's UK (UK4) and European (Euro8) configurations of the WAVEWATCH III) model, which is a third generation wave model developed and maintained by the US National Centres for Environmental Prediction

Additional local modelling is typically used as well as these national products, specifically to transform levels and waves to the nearshore environment. Triton, for example, is a bespoke software module, embedded within the NFFS, which ingests the forecast information from WAVEWATCH III and CS3X and translates these forecasts to more local forecasts such as local sea level, nearshore wave conditions and/or wave overtopping. This translation is done using a series of pre-defined equations and look-up tables or ‘matrices’, which themselves have been pre-computed using analysis and/or numerical modelling. In other cases, hydrodynamic models are used (for example, the Simulating WAves Nearshore model, SWAN), although there are no cases where these models are currently run in real time, principally because it has always been deemed too complicated due to the computation times of the models, the risk of model instability or failure, and the costly software development involved. The EU RISC-KIT project plans to create adaptors so that SWAN can be run within the NFFS. This work is due to be completed by summer 2015.

Once local sea levels and nearshore wave characteristics have been computed, some systems operating in the UK then compute wave overtopping, typically using one of the models contained within the European Wave Overtopping Manual (EurOtop). Most systems perform this operation based on a pre-computed matrices (managed in Triton), rather than running the wave overtopping model live. An exception to this is an ongoing project on the south bank of the Humber Estuary, where wave transformation models are being used in real time to predict coastal flood

<table>
<tr><td></td><td colspan="2">risk.

The State of the Nation flood risk analysis modelling project is generating 2 outputs that may be of use here.

• A series of 24 SWAN 2D models were constructed covering the entire coastline of England in order to transform the offshore waves into the nearshore. These models use the latest available bathymetry data to output nearshore wave data at 1km intervals along the -5m contour. Outputs are then fed into a series of SWAN 1D models to represent the beach profile in the surf zone to the toe of the individual defence structures. The modelling and results from this study are due to be provided by the summer of 2015. While none of these models are currently in use for coastal flood forecasting, clearly there may be opportunities to incorporate them in future system developments or upgrades.

• Wave overtopping profiles are being developed for approximately 2,000 of the 5,000 discrete defences, providing detailed profile data for the majority of the high risk urban areas. On completion of the project, these will be available for use within future forecasting systems.

The final stage in this modelling process – and the one of primary interest here – is the use of a coupled 2D inundation model to forecast inundation extents and depths. Most systems in the UK relate the forecasted conditions to pre-defined Flood Warning Areas, via look-ups, with existing inundation mapping generated by simple projection-based approaches or by using hydrodynamic models, such as TUFLOW. Although technically feasible, no existing coastal modelling system currently runs hydrodynamic models in real-time.

It is not clear whether a fully real-time system would add value over the existing look-up based warning approach, which is arguably far more advanced than any of the existing Environment Agency systems that are in place for other flood types. This is why a look-up based coastal modelling system has not been proposed here – it already exists, if not in a nationally consistent form. No previous work has quantified the benefit that might be gained by transitioning this system towards a real-time one. It is also not clear which components (or all) might benefit most from being run in real-time.

Should this option be shortlisted, the first and primary priority would be to answer these questions before committing to any kind of national scale system.</td></tr>
<tr><td rowspan="2">Data requirements</td><td>Available</td><td>National scale outputs – WAVEWATCH III and CS3X

To automate wave transformation/overtopping models – national repository of bathymetric datasets, cross-sectional data representing a particular beach/flood defence. Alternatively, if the State of the Nation outputs were reused, these data would have to be stored in a central repository and queried using mining algorithms to select the appropriate scenarios.

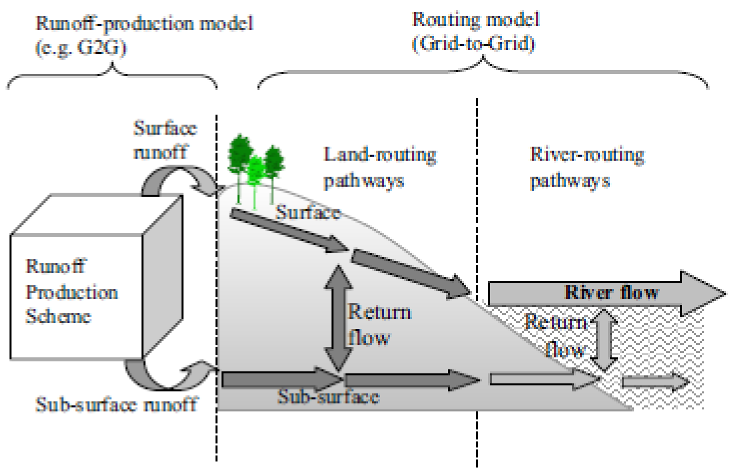
For inundation modelling – a DTM of sufficient resolution with national coastal coverage (for example, building on the Environment Agency Geomatics’ new SurfZone product).</td></tr>
<tr><td>Gaps</td><td>None</td></tr>
</table>

Route to implementation	Before implementing a real-time coastal modelling system, it would be necessary to first evaluate the improvement gained via running each modelling component in real time versus the existing look-up based approach. The route to implementation should ideally involve a benchmarking study that addresses this question by sequentially replacing the look-up based approaches with real-time approaches assessing any improvement. This is arguably beyond the scope of the present work.		
Implementation costs	Low	Moderate	**Significant**
	The infrastructure required to run wave transformation/overtopping/inundation models in real time will be significant. There are also likely to be issues relating to stability of runs, which would have to be resolved on a model-by-model basis. If only the inundation component of the modelling chain (for example, via JFlow or TUFLOW) is made real time, these cost constraints may reduce.		
Time to implementation	Short: <1 year	**Medium: 1–5 years**	Long: 5+ years
Pros	It is difficult to comment on the pros and cons of this approach without comparisons between real -time and look-up based approaches being available. See route to implementation and comment on scope.		
Cons			

8. Real-time groundwater inundation using the G2G		
Asset/Resources		**Process/Technical method**
Input	**Inundation product**	
NFFS (G2G)		Real-time JFlow

Technical description

The G2G model includes a subsurface model to simulate groundwater flow. Bell et al. (2007) summarised the key physical processes represented in the model (see figure below).



Key physical processes represented in the subsurface model

The return flow term in the model allows transfer between the subsurface and surface layers in a spatially distributed way, making it conceptually

<table>
<tr><td></td><td colspan="3"> straightforward to then apply these flows in an overland inundation model. This differs from probability distributed models, where return flow from the subsurface is typically only routed at the catchment outlet. It would be necessary to confirm exact details of how the latest iteration of the G2G model calculates these fluxes with the Centre for Ecology and Hydrology before committing to using this data. The basic approach here would be to use the land-based subsurface return flow as input to a suitably fast 2D inundation model. The obvious choice is JFlow given that it works well for direct rainfall simulations – where the rainfall in this case is replaced by the G2G subsurface return flow. It is assumed that this output is generated on a 1km grid, which is potentially problematic. Groundwater flooding is typically driven by highly localised geological features; in reality the 1km averaged return flow term in the G2G model will upwell in a number of highly localised areas within that grid, usually determined by intersection of the groundwater table with the surface layer. It will therefore be necessary to correctly assign these source locations. In reality, their exact location may not be a significant control on the final inundation extents/depths given that water will naturally flow to low spots regardless of its initial source location. Sensitivity to this should be evaluated. G2G outputs could also be supplemented with borehole telemetry data, although the same spatial distribution issues as discussed in option 3 would be encountered. As in the real-time surface water inundation mapping method, determining appropriate return flow thresholds (that is, those at which surface flooding is generated) will be necessary so that models are only triggered when necessary. Similarly, appropriate resilient IT infrastructure will be required. Both issues, while important, could be considered at a later (post-prototyping) stage. </td></tr>
<tr><td rowspan="2">Data requirements</td><td>Available</td><td colspan="2"> G2G subsurface flow outputs (land-based only) DTM of sufficient resolution with national coverage, or at least coverage in groundwater susceptible areas </td></tr>
<tr><td>Gaps</td><td colspan="2">None</td></tr>
<tr><td>Route to implementation</td><td colspan="3">Determine trigger thresholds for each G2G model grid. Unlike for the real-time surface water mapping option, there is no obvious approach via which this could be achieved.
Automate extraction process of subsurface return flow from G2G. This may be implementable using the existing NFFS–FEWS platform.
Run JFlow or equivalently fast 2D inundation model for a number of case study locations to determine relative skill.</td></tr>
<tr><td rowspan="2">Implementation costs</td><td>Low</td><td>Moderate</td><td>Significant</td></tr>
<tr><td colspan="3">To implement on a national basis will require moderate investment, – particularly the automation of the model set-up and run process</td></tr>
<tr><td>Time to implementation</td><td>Short: <1 year</td><td>Medium: 1–5 years</td><td>Long: 5+ years</td></tr>
<tr><td>Pros</td><td colspan="3">Avoids the need to pick representative outputs from existing groundwater mapping.</td></tr>
</table>

	• Spatially distributed groundwater flooding can be modelled.
Cons	• Difficult to determine when to trigger modelling chain, that is, what value of G2G return flow will generate flooding above a given threshold and therefore require a 2D run? • Sensitivity to source locations – cannot assume uniform upwelling across entire 1km grid. • Requires stable and resilient IT infrastructure if being used in an operational setting. • Run times may limit resolution.

9. All-sources inundation modelling		
Asset/Resources		**Process/Technical method**
Input	**Inundation product**	
Many		Many

Technical description	This option is essentially an amalgamation of options 5 (real-time fluvial), 6 (real-time surface water), 7 (real-time coastal) and 8 (real-time groundwater). The first 3 of these options sit together under a consistent framework and it is relatively straightforward (on a general level) to conceptualise how an all-sources system might look – primarily because each can use outputs from the NFFS (either forecast models or the G2G) and couple these to a suitable 2D inundation model. Integrating the coastal modelling system adds an additional layer of complexity. That said, a primary issue that will be encountered in an all-sources model is the way in which final combined flood extents and depths are derived. Clearly an ideal solution would be to model each flood type in a dynamically coupled way, by taking each flux at every timestep and routing it through the various model components. In reality, this would simply constitute a very high resolution G2G (that is, of the order of metres rather than kilometres) and is infeasible at present. However, there is no obvious way in which to combine each flood source without doing so, given that each component is linked. A simple addition of each source would risk double counting. The alternative would be to take the worst case output at each timestep and describe this as the ‘total flooding’. Given that it is likely that this will be dominated by a particular flood source in certain areas (for example, groundwater flooding in groundwater-dominated catchments, coastal flooding along the coastline), it may be the case that this all-sources type of modelling is not warranted. It may be more cost-effective to develop separate systems for each type rather than a fit-all approach.	
Data requirements	**Available**	See options 5, 6, 7 and 8
	Gaps	None
Route to implementation	See options 5, 6, 7 and 8	

Implementation costs	Low	Moderate	**Significant**
	Developing an integrated modelling platform on which an all-sources model could run – even if within the existing NFFS platform – would be a significant undertaking. There are likely to be numerous run time issues that have not been considered here. Whether these costs are justifiable in the context of the need for such an integrated system is not clear.		
Time to implementation	Short: <1 year	Medium: 1–5 years	**Long: 5+ years**
Pros	See options 5, 6, 7 and 8		
Cons	• No method exists at present for combining multiple flood sources in a physically consistent way. Instead it would be necessary to simply take the worst case extent/depth map for a given event or time slice, which may not be ideal. • Similarly, it may make more sense to invest in robust single-source modelling systems rather than a fit-all approach.		

10. Long-range ensemble warning system using NWP outputs		
Asset/Resources		**Process/Technical method**
Input	**Inundation product**	
Rainfall (NWP)		Hydrological processing of NWP

Technical description	Alfieri et al. (2014) proposed a statistical method (Extreme Flood Index, EFI) to derive 10 day river flow forecasts at continental scale, utilising data from the 51 member European Centre for Medium Range Weather Forecasting (ECMWF) NWP model. Forecast lead times of 10 days were achieved, using 32km resolution outputs. This is now an operational ECMWF forecast product. The approach uses surface run-off forecasts from the land surface scheme of the ECMWF model, aggregated to basin scale and compared against a long-term (20 years) hindcast dataset of basin-wide run-off to estimate the rarity of a forecast event. Processes such as evapotranspiration, soil moisture content and snowmelt are all included in the land surface component of NWPs, and run-off forecasts, at aggregated scales, are robust. However, this method performs less well where routing becomes important. This method could be used to provide a long-range ensemble-based assessment of risk across England and Wales, which could in turn be used for long-range strategic planning activities (for example, mobilisation of flood protection measures to appropriate regions, rostering of duty staff, preparation of incident rooms, public awareness). Such an approach would be a ‘long-range extension’ to existing G2G forecasts, which currently provide ensemble forecasts out to 32 hours and deterministic forecasts to 5 days. These outputs could be further combined with broad-scale libraries of likely impacts to estimate potential disruption. For example, forecast flows could be combined with a pre-computed dataset of postcode level properties at risk for given any given flow. This could be compiled from existing mapping with national coverage (for example, NaFRA, commercial flood datasets).

<table>
<tr><td></td><td colspan="3">Alternatively, real-time coupling with a simplified inundation model could be used (for example, the spreading model used within MDSF2 or coarse scale JFlow). The final output from this process would therefore be a national scale long-range hotspot map of likely flood impacts.

The Met Office also has a range of ensemble models that could be trialled as an alternative to the ECMWF outputs. These include:
60km resolution with 15 day lead time (MOGREPS medium range)
33km resolution with 7 day lead time (MOGREPS global)
2.2km and 36 hour lead time (MOGREPS UK)
This approach would complement the Flood Guidance Statement. It could therefore utilise existing procedures to guide emergency planning and resourcing decisions for Category 1 and 2 responders. Additional guidance may be required to interpret probabilistic outputs and to caveat uncertainties at long lead times.</td></tr>
<tr><td rowspan="2">Data requirements</td><td>Available</td><td colspan="2">Real-time forecasts from NWP (ECMWF or Met Office); ideally a hindcast dataset from the same NWP with the same set-up (for example, model boundaries, vertical layers, assimilation schemes, physics representation) for the rarity analysis.</td></tr>
<tr><td>Gaps</td><td colspan="2">Hindcast datasets are available from the ECMWF but may not be available from the Met Office.

Broad-scale impacts mapping from a pre-computed library may be difficult to obtain if using the NaFRA, given that individual scenarios are not stored. Commercial flood maps contain the required information but for undefended scenarios only. An alternative is therefore to couple a suitably fast 2D inundation model in real time to the forecast flows, such as JFlow. High resolution is probably not required or appropriate given the relatively coarse nature of the NWP output.</td></tr>
<tr><td>Route to implementation</td><td colspan="3">Development of a long-term (for example, 20 year) hindcast dataset if not already available. In reality and for proof of concept, it will probably be necessary to use existing ECMWF model outputs so that a working prototype can be developed.
Development and automation of appropriate processing algorithms (for ECMWF model outputs, this has already been done)
Method testing and validation against existing events; national implementation
Development of broad-scale impact mapping to provide real-time association with forecast events, either via a look-up based approach (if an appropriate dataset is available) or via coupling to a simplified spreading model.</td></tr>
<tr><td rowspan="2">Implementation costs</td><td>Low</td><td>Moderate</td><td>Significant</td></tr>
<tr><td colspan="3">Code is already available from the ECMWF and could be reused here to trial the method on UKV model outputs. Alternatively, the EFI is an operational product that is published as part of the ECMWF forecasts and could therefore be used as is. Some work, however, would be required to tie this into either a static library of impacts or simplified flood spreading model.</td></tr>
<tr><td>Time to</td><td>Short: <1 year</td><td>Medium: 1–5 years</td><td>Long: 5+ years</td></tr>
</table>

implementation			
Pros	• Provides lead times beyond anything currently possible from distributed hydrological modelling (that is, G2G); near doubling from 5 to 10 day. • Datasets are already available. • Methodology has been previously tested at European scale. • Easily adaptable should new NWP products become available (for example, higher resolution). • Can potentially be applied to both fluvial, surface water and coastal flooding. • Can be used to examine broad-scale impacts.		
Cons	• Uncertainty at 10 day lead times may result in inappropriate management decisions; conversely, some information is likely to be better than no information – and probabilistic information can be used to make better decisions (for example, if all members are diverging then decision can be delayed, if all members are converging then preventative action can be taken early). • Ensembles can be difficult to interpret, though there has been much work in this area in recent years.		

Notes: MOGREPS = Met Office Global and Regional Ensemble Prediction System

3.2.3 Breach options

A number of the options described in Section 3.2.2 include breach information by default – specifically any options that utilise the RASP inflow volume calculation methodology. However, the rest do not and it is therefore useful to consider a number of breach-specific options.

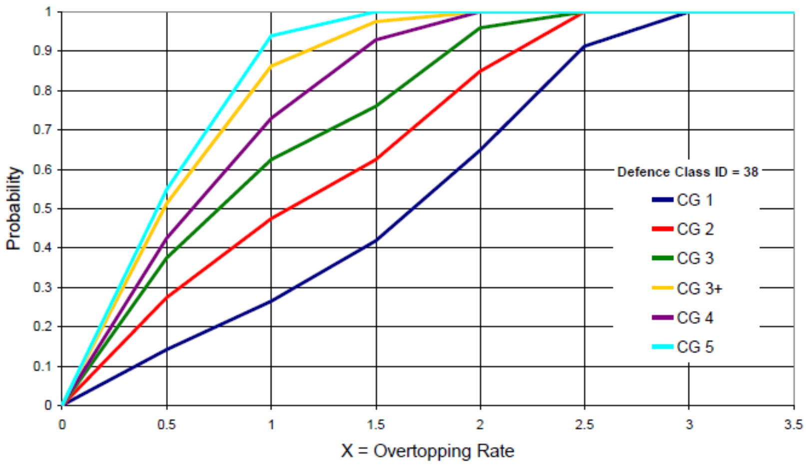
Each breach option is best considered in the context of how it could add value to the options described above, recognising that a breach option on its own will not score highly in the wider framework of real-time inundation modelling. This is because it addresses a very specific part of the problem. However, this is not a strong enough reason to exclude it from this process as, in certain areas, breach may constitute the most significant risk to property or life, for example.

<table>
<tr><td colspan="3">11. Breach risk</td></tr>
<tr><td colspan="2">Asset/Resources</td><td rowspan="2">Process/Technical method</td></tr>
<tr><td>Input</td><td>Inundation product</td></tr>
<tr><td>RASP fragility curves</td><td></td><td></td></tr>
</table>

<table>
<tr><td>Technical description</td><td colspan="3">This option involves determining the aggregate breach risk across all Flood Warning Areas (or any other relevant spatial unit) using RASP methodology. RASP fragility curves for both coastal (see example below) and fluvial assets are used in MDSF2 to determine the probability of defence failure given an asset’s condition grade and loading (that is, overtopping rate or water level). They could be applied in real time to highlight vulnerable locations, using overtopping rates or fluvial levels from telemetry networks and/or NFFS forecasts. Flood defence parameters (for example, crest level, condition grade) could also be updated during an event where suitable telemetry or local knowledge is available.

This option could be combined with pre-computed breach mapping (option 13) for the most vulnerable assets to determine impacts, or real-time breach modelling (option 12). It would work particularly well with option 5, given that it uses another component of the RASP methodology.

This is the only option that does not specifically generate new extent or depth data, and therefore does not strictly meet the objectives of this project. It does, however, complement (and is required by) other approaches that analyse breach.



Coastal example</td></tr>
<tr><td rowspan="2">Data requirements</td><td>Available</td><td colspan="2">RASP fragility curves, asset data via AIMS, telemetry observations and forecast products via NFFS</td></tr>
<tr><td>Gaps</td><td colspan="2">None</td></tr>
<tr><td>Route to implementation</td><td colspan="3">Limited work required – AIMS is already available across England and Wales and a database of fragility curves could be obtained from MDSF2 or externally. The library of fragility curves has also been recently updated.</td></tr>
<tr><td rowspan="2">Implementation costs</td><td>Low</td><td>Moderate</td><td>Significant</td></tr>
<tr><td colspan="3">See route to implementation – limited work required to trial and implement</td></tr>
</table>

	this approach.		
Time to implementation	**Short: <1 year**	Medium: 1–5 years	Long: 5+ years
Pros	• At-a-glance information on likely breach locations • Can target emergency resources at most vulnerable defences • Quick win		
Cons	• Robustness of using fragility curves for incident response is unclear and initial evidence suggests that this approach is likely to overpredict the number of failed defences during an event		

12. Real-time breach inundation

Asset/Resources		Process/Technical method
Input	**Inundation product**	

Technical description

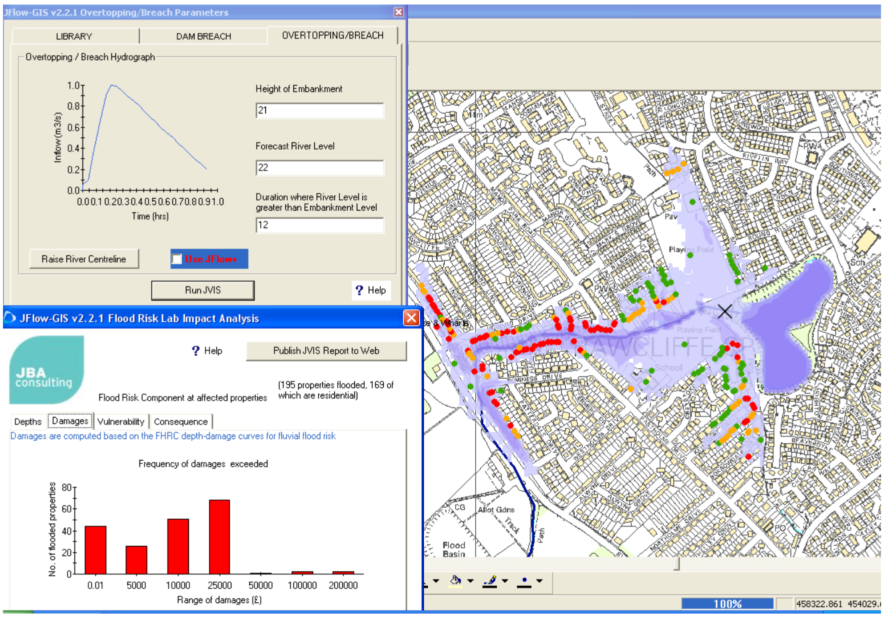
Breach scenarios could be modelled in real time for assets that are assigned a high probability of failure from option 11 (for example, >0.7). The flood spreading algorithm would have to be suitably fast, though this could be achieved using, for example, the RFSM, JFlow or ISIS-FAST.

Similar approaches have been applied before but not nationally – an example is shown below from the JVis product used by the Environment Agency's North East Region. The process applied is typically as follows.

1. DTM is obtained from database and loaded for a given location.
2. Breach hydrograph is defined by user in terms of peak level and duration of event; for forecasting applications, this information could be automatically obtained from NFFS forecast outputs.
3. Embankment height or breach characteristics are entered; this process could be automated by linking to the AIMS dataset.
4. Inflow volume is calculated for each failed asset.
5. 2D inundation model is launched automatically.
6. Flood depth map is intersected with receptor data to calculate flood impacts.
7. Results are visualised on screen and exported in a variety of formats.

Uncertainty assessments can be included by either using ensemble water level data or by perturbing some/all of the input parameters.

This option would work particularly well with option 5 (real-time RASP), given that breach inflows can be calculated using the RASP inflow volume calculation approach.



Example output

Data	**Available**	Breach information from option 11 (potentially), NFFS or

requirements		G2G forecast data; coastal overtopping rates, DTM
	Gaps	None

Route to implementation	A 2D model with fast run times for high resolution simulations (between 2m and 5m ideally) would be necessary. A FEWS adapter may also be required if this is to be implemented in real time with the existing NFFS products. FEWS adapters are available for JFlow and could be easily developed for TUFLOW-GPU or ISIS-FAST. Run times for a 4m, 6-hour JFlow simulation when coupled to FEWS were previously shown to be 10 minutes. Other packages could presumably achieve similar (or quicker) run times based on the evidence in the recent Environment Agency 2D Hydraulic Model Benchmarking Exercise, thus making this option viable. Assumptions on the characteristics of a given breach (for example, breach dimensions) would be required to convert in-channel levels to breach inflow volumes. Breach hydrographs or overtopping volumes can estimated using simple hydraulic relationships, which are then used as inputs to a hydraulic model. Simplistic methods that are applied in the MDSF2 implementation of RASP could be used initially, for example.

Implementation costs	Low	**Moderate**	Significant
	Moderate costs will be incurred to get such a system working, but these will be significantly lower than if generating a static library of inundation extents at a national scale.		
Time to implementation	Short: <1 year	**Medium: 1–5 years**	Long: 5+ years

Pros	• Immediate understanding of likely impacts of breaching and/or overtopping • Breach characteristics can be modified during the event • Can be applied on an ad hoc basis without the need for costly national modelling
Cons	• Breach probability limitations as in option 11 • Potentially significant run times for multiple breaches across large areas • Requires some modelling expertise to run the tools during an event

13. Pre-computed breach inundation		
Asset/Resources		**Process/Technical method**
Input	**Inundation product**	

Technical description	This option is similar to option 12, where real-time breach modelling is suggested, but is instead based on pre-computed look-ups that contain flood extents or depths from 2D hydrodynamic models. The option would use outputs from option 11 to indicate which areas are likely to breach. This therefore assumes that a large library, covering all possible breach locations, could be generated or is already available. Generating such a library with 2D hydrodynamic models may be cost/time

<table>
<tr><td></td><td colspan="3">prohibitive; simplified methods could be used. An obvious example is the MDSF2 RFSM. These data may be available anyway if option 1 is pursued, and indeed it may be preferred that a breach option is integrated within a more general inundation mapping option. Given that the library is pre-computed, ‘static’ assumptions may have to be made with respect to the breach characteristics (for example, width of breach, duration); such parameters that could be specified during an event using a real-time modelling option.</td></tr>
<tr><td rowspan="2">Data requirements</td><td>Available</td><td colspan="2">Breach information from option 11 (potentially)</td></tr>
<tr><td>Gaps</td><td colspan="2">Pre-computed breach inundation data are available for only a very small number of studies, typically from (non-Environment Agency) flood risk assessments. There is no central repository of such data and there is no standard specific for producing or delivering this information.

An alternative might be to use individual realisations from the State of the Nation MDSF2 model (that is, individual breach scenarios), but these are not currently stored as part of the risk calculation process.</td></tr>
<tr><td>Route to implementation</td><td colspan="3">Significant investment would be required to either compile existing breach scenario data or to generate new data from detailed modelling.

If using MDSF2, changes to the MDSF2 software would be required so that depth maps from individual breach scenarios (used to estimate aggregate risk) are recorded. Currently there is only the option to view depth maps for single system states post-run.

In each case, a regional or national breach archive would have to be developed and appropriate algorithms developed to access this in real time using live flow, level or overtopping data.</td></tr>
<tr><td rowspan="2">Implementation costs</td><td>Low</td><td>Moderate</td><td>Significant</td></tr>
<tr><td colspan="3">Generating a national archive of breach simulations will be a considerable undertaking, even if this is only done in areas with high breach potential or significant breach consequences.</td></tr>
<tr><td>Time to implementation</td><td>Short: <1 year</td><td>Medium: 1–5 years</td><td>Long: 5+ years</td></tr>
<tr><td>Pros</td><td colspan="3">• No run time limitations</td></tr>
<tr><td>Cons</td><td colspan="3">• Significant investment required at both local and national levels to develop sufficient archive of breach simulations
• Breach probability limitations as in option 11 – that is, do we trust that a breach will really occur, and how can that uncertainty be managed?
• Breach characteristics would have to be ‘static’, although this is likely to be true of any breach option given that real-time information does not typically exist.</td></tr>
</table>

4 Scoring results, shortlisted options and next steps

4.1 Scoring results

Each of the options described in Section 3 was scored according to the methodology set out in Section 2.4. A completed evaluation matrix for each option is provided in Appendix 2b.

These scores can also be combined into a cost–time diagram (Figure 4.1), which provides a snapshot of the performance of each option relative to its associated investment requirements. Outliers can be quickly identified using this analysis. The scoring applied in this diagram also takes into account the relative weights of each flood type, thus penalising options that only benefit a limited number of properties.

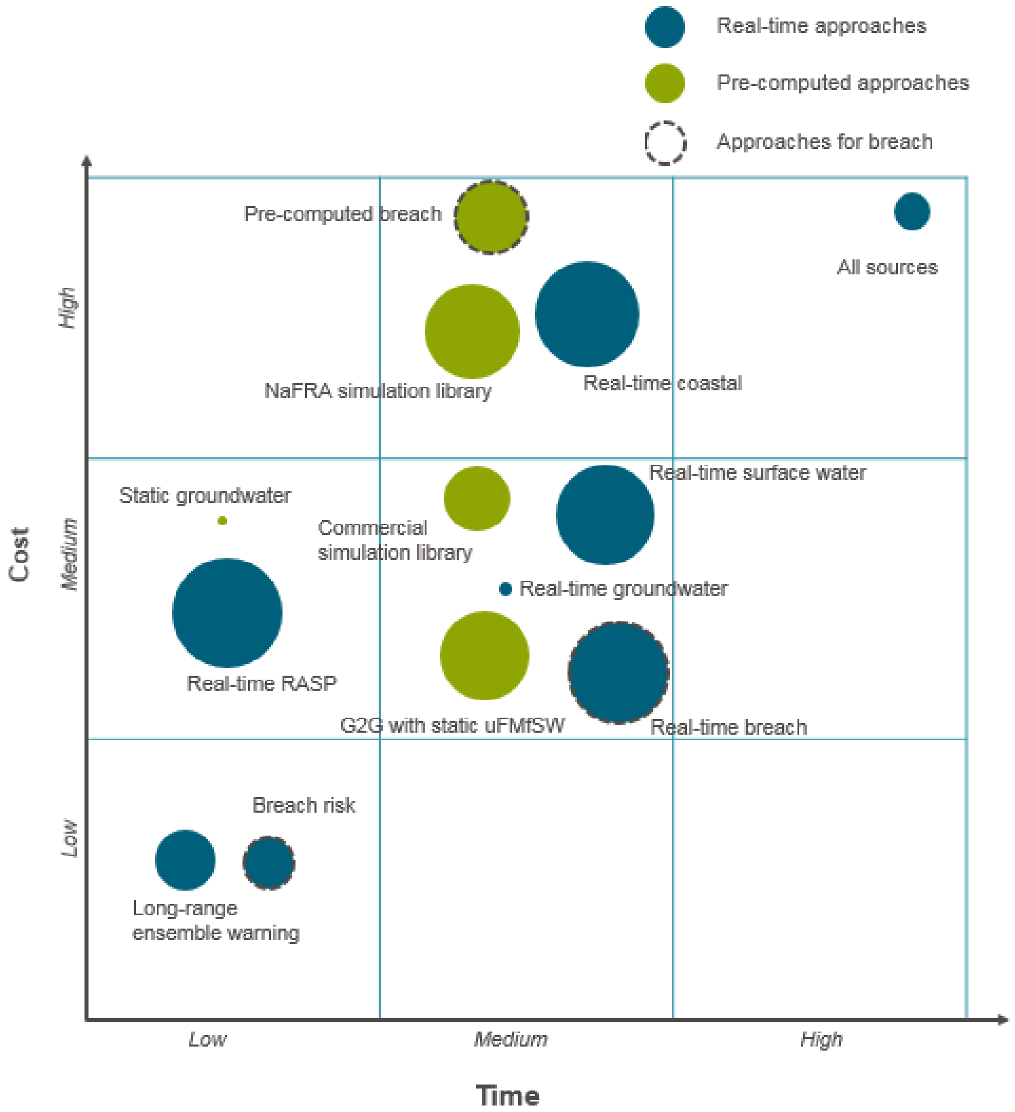


Figure 4.1 Cost–time diagram

Notes: uFmfSW = updated Flood Map for Surface Water

A number of observations can be made.

- There are obvious outliers. For example, the all-sources option has high cost and time requirements but delivers limited benefit. Conversely, real-time RASP could be a relatively quick win option and deliver considerable benefit.
- Many options score reasonably – meaning that they require medium time/cost inputs while delivering moderate to large benefits.
- Groundwater options offer particularly small benefits. This is predominantly an artefact of the scoring 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) and long-range ensemble warning system (option 10).
- The updated Flood Map for Surface Water simulation library linked to G2G run-off outputs (option 4) scores highly. However, it has already been prototyped by the Natural Hazards Partnership and there is limited value in repeating this work here.

It is useful to repeat this scoring process for each of the 2 user groups (Area Incident Rooms and Gold/Silver Command). Table 4.1 shows the ranked position of each option (from 1, highest; to 13, lowest) for their overall score (as presented in Figure 4.1) and then also for each user group. Actual scores are shown in brackets and a commentary on each option is provided.

In general, more technical options (for example, those that require the use of dynamic flood spreading models in real time) typically score most highly for Area Incident Rooms. Broader scale methods, such as the 'National NaFRA simulation library', score highly for Gold/Silver Command.

Table 4.1 Ranked scoring and commentary for each option

Option		Rank			Commentary
		Overall	AIR	GSC	
5	Real-time RASP for fluvial and coastal inundation modelling	**1** [2.02]	**1** [2.12]	**2** [1.92]	• Ranks highly across all groups
7	Real-time coastal modelling system	**2** [1.92]	**3** [1.99]	**3** [1.86]	• High cost • Benefits gained by using a real-time system over what is currently available are not clear; further scoping recommended
12	Real-time breach inundation	**3** [1.81]	**2** [2.08]	**6** [1.53]	• Ranks highly for overall and particularly for AIR • Potentially better if implemented within 'real-time RASP' option rather than on its own
6	Real-time surface water linked to G2G or NWP	**4** [1.76]	**4** [1.95]	**5** [1.58]	• Ranks highly across all groups • High benefit versus cost–time
1	National NaFRA simulation library	**5** [1.70]	**6** [1.27]	**1** [2.12]	• Ranks highly for GSC but likely to be very expensive (requires national NaFRA re-run of

Option		Rank			Commentary
		Overall	AIR	GSC	
					MDSF2 and modifications to model)
4	Updated Flood Map for Surface Water simulation library linked to G2G run-off outputs	**6** [1.61]	**5** [1.76]	**8** [1.45]	• Ranks highly across all groups • Already trialled by the Natural Hazards Partnership, so no value added by repeating here although it would provide a useful comparison to option 6
13	Pre-computed breach inundation	**7** [1.32]	**8** [1.11]	**6** [1.53]	• Potentially very high cost but with low benefits • Difficult to envisage how such a large pre-computed modelling task could be completed efficiently and how key assets would be identified
2	National simulation library using commercial (fluvial) flood map products	**8** [1.16]	**7** [1.16]	**9** [1.16]	• Lack of defended scenarios and inability to consider breach makes this option unappealing at present • Otherwise a viable look-up alternative to using the NaFRA – scores equally among both groups
10	Long-range ensemble warning system using NWP outputs	**9** [1.11]	**11** [0.46]	**4** [1.76]	• Strong option for GSC, weak option for AIR • However, very quick win with low cost–time requirements • Provides a different type of long-range output in comparison with all other options
11	Breach risk	**10** [0.92]	**9** [0.82]	**10** [1.02]	• Scoring artificially lowers score of this option (given that it does not directly generate inundation data) • Strong case if coupled with 'real-time RASP' option • Quick win
9	All-sources inundation modelling	**11** [0.55]	**10** [0.58]	**11** [0.53]	• Benefits not clear given expense
8	Real-time groundwater inundation using G2G	**12** [0.15]	**12** [0.17]	**12** [0.14]	• Limited benefit of implementing groundwater forecasting system at a national scale
3	Static groundwater maps linked to borehole telemetry and NWP	**13** [0.13]	**13** [0.15]	**13** [0.11]	

Notes: Shaded options represent the primary set recommended for prototyping. Ordered by overall rank for Area Incident Rooms (AIR) and Gold/Silver Command (GSC)

4.2 Shortlisted options and next steps

Based on the scoring and commentary presented above, it is recommended that the following options (shaded in Table 4.1) are prototyped in the next phase of this work.

- **Real-time RASP for fluvial and coastal inundation modelling (option 5)** – this option ranks highly across all user groups (rank 1, Area Incident Room; rank 2, Gold/Silver Command) and can potentially be applied in both fluvial and coastal forecasting. It is also recommended that this prototype also incorporates the following complementary breach options:
  - breach risk (option 11)
  - real-time breach inundation (option 12)
- **Real-time surface water linked to G2G or NWP (option 6)** – this option ranks highly across all user groups and provides high benefit versus cost–time requirements.
- **Long-range ensemble warning system using NWP outputs (option 10)** – this option ranks highly for Gold/Silver Command, has low cost–time requirements and will provide an alternative output type (in terms of forecast time period) to all other options.

In addition, it is recommended that the following options are included as a contingency, noting that options outside of the main set offer similarly limited benefit to cost–time ratios based on the scoring approach applied.

- National NaFRA simulation library (option 1)
- Real-time coastal modelling system (option 7)
- Two out of three of: National simulation library using commercial (fluvial) flood map products (option 2) OR All-sources inundation modelling (option 9) OR Real-time groundwater inundation using the G2G (option 8)

Following agreement on the options to be progressed to proof of concept development, a short technical specification will be developed for each option which will describe in more detail the inputs, intermediate analysis steps and outputs. Areas where new methods and/or data may be required will also be highlighted.

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