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Real-time flood impacts mapping

Appendix 6a: Simulation library

SC120023/A6

Flood and Coastal Erosion Risk Management Research and Development Programme

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Professor Doug Wilson
Director, Research, Analysis and Evaluation

Contents

List of tables and figures

1 Pro-forma summary

This proof of concept (PoC) is based on pre-computed look-up tables, generated in the first instance from Modelling and Decision Support Framework 2 (MDSF2) models produced as part of an ongoing nationwide risk modelling programme, State of the Nation. These look-ups relate return period to flood depth within a hydraulically discrete Flood Area unit for a ‘defences in place’ scenario. During a flood event, an average return period for each Flood Area can be determine by interpolation along the river network from locations where the flow/level return period relationship is well understood and observations are available in real time (that is, telemetered gauging stations). The Flood Area averaged return period is then used to ‘look up’ flood depths across the floodplain at an instant in time.

Results from this PoC are encouraging when compared with observations from the case study events and results from more sophisticated modelling alternatives. Moreover, run times for a single execution are already extremely fast using only a desktop PC (approximately 2 minutes) and there is considerable scope for further optimisation within any future operational implementation. For nationwide use, potentially very large look-up table datasets would need to be stored and accessed efficiently by the software.

At present, the PoC only considers fluvial settings. Further work is required to extend the approach to tidal and coastal areas.

2 Proof of concept overview

2.1 About this option

Name in Technical Options Report (Appendix 2): National NaFRA simulation library

Number in Technical Options Report: Option 1

MDSF2 is the principal flood risk modelling software used by the Environment Agency. It is used to deliver the National Flood Risk Assessment (NaFRA), the Long-term Investment Strategy (LTIS) and for scheme appraisals. The software is available on the Central Modelling Platform and many Environment Agency staff and consultants have been trained in its use. The State of the Nation project is undertaking a comprehensive update to the NaFRA and to the MDSF2 modelling software. When this is delivered, there will be a new validated set of baseline NaFRA models that cover the entirety of the fluvial, tidal and coastal floodplain of England.

This option – and the subsequent refinements proposed in Section 6 – are based on the reuse of the updated State of the Nation MDSF2 baseline models. The models have been subject to an intensive programme of data and method improvements, and a great deal of care and attention has been put into their preparation. The input data have been reviewed and updated where necessary by local, knowledgeable Environment Agency staff and the results of the risk models screened and validated. This therefore provides a robust national set of baseline models upon which to build a complete set of operational forecasting models. Other advantages of using the State of the Nation baseline models include the consistency of approach between the risk and forecasting models and extremely fast run times for real-time use.

The simulation library PoC option involves the use of the State of the Nation baseline models to pre-compute a set of look-up tables that can be used as surrogates for running the Rapid Flood Spreading Model (RFSM) within MDSF2 for each in-river water level combination. In other words, the RFSM model is run offline for all Flood Areas for all return periods to obtain a 'defences in place and none fail' set of floodplain depth grids that can be used to rapidly estimate the depth and extent of flooding which might be expected given a set of in-river water levels.

A look-up table of depths (and therefore extents) by return period for a scenario where defences are in place but none can fail has been generated using the RFSM visualisation engine within MDSF2. This consists of 40 depth grids for each Flood Area; one for each NaFRA return period (ranging from 1 in 1 year to 1 in 1,000 year). In-river water flow/level gauge readings from across the catchment can be converted to return periods (based on local flood frequency analysis), which can then be interpolated more robustly along the river network[1] (than the flow/level measurements themselves) and be allocated to the individual NaFRA assets. Once the return period has been allocated to each asset, the depths can be read – and interpolated where necessary – from the look-up tables to give the depths and extent for the event being simulated. As such, the option provides only a 'snapshot' of flood inundation for a particular set of flow/level observations – although it can be run at multiple instances throughout an observed/forecast time series.

[1] A method for interpolating return periods along river networks was first developed and applied in the joint Defra/Environment Agency R&D project, Spatial Coherence – Risk of Widespread Flooding (SC060088). More recently it has underpinned the inland flood hazard modelling component of the H21 Evidence Update for National Risk Assessment 2016 project carried out by JBA Consulting on behalf on the Environment Agency and Defra.

2.2 Functional requirements

The Technical Options Report summarised the user requirements identified during the consultation exercise at the outset of this project. These were then presented as an evaluation matrix for each option.

- Each row of the table presents the detail required by different user groups for a particular functional aspect. For example, spatial coverage may be local, regional or national scale.
- The user groups are shown as coloured bars along each row of the table. In this case, the user groups are Area Incident Rooms (green bars) and Gold/Silver Command (silver bars). A shaded bar implies that the particular user group requires the given functionality.
- If the PoC option meets a given acceptability criteria, it is assigned a 'Y'.

Figure 2.1 shows the evaluation matrix for this PoC.

FUNCTIONAL REQUIREMENTS

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

Figure 2.1 Evaluation matrix: simulation library

2.3 Workflow

The flow chart presented in Figure 2.2 shows, in generalised terms, how this option works. Subsequent sections of this appendix refer to the reference numbers in the flow chart to give:

- specific information about how the option was tested, and the data and software used in this project (Section 3)
- considerations for operational implementation (Section 5)

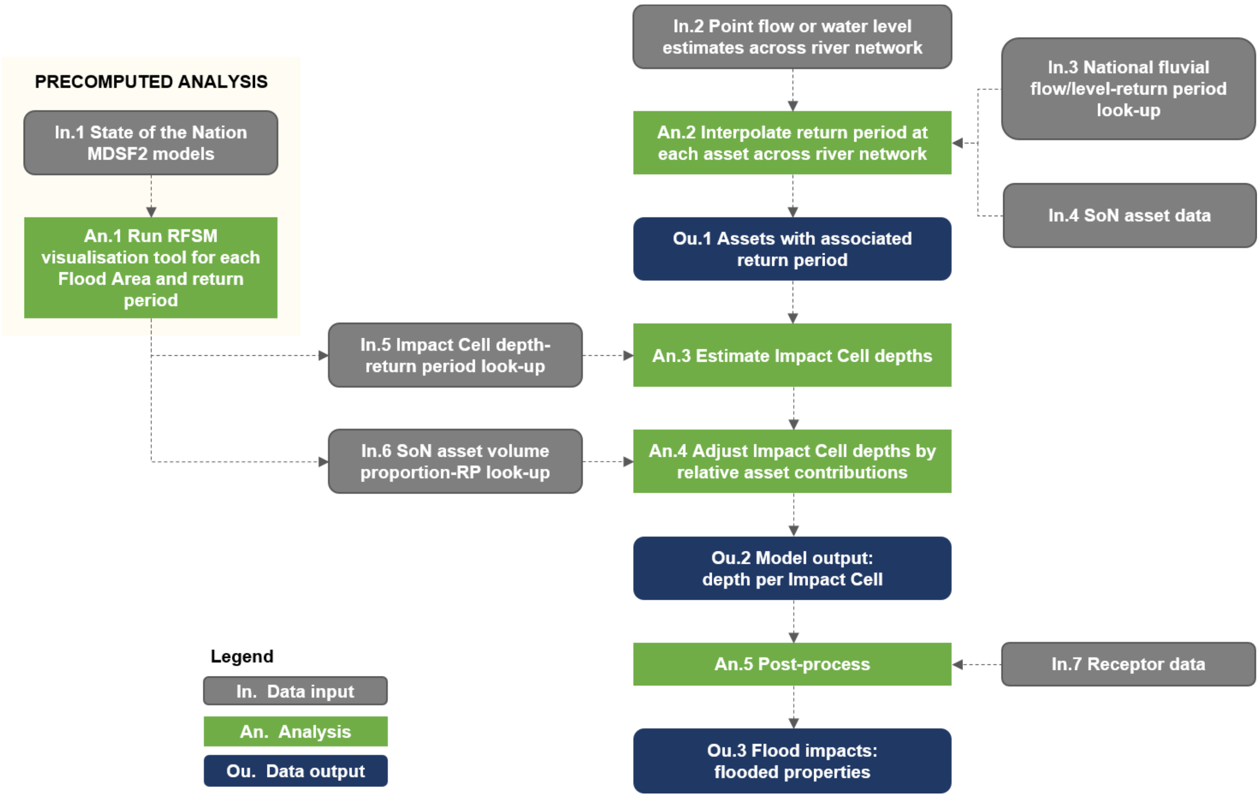


Figure 2.2 Flow chart showing PoC workflow for the simulation library option

3 Proof of concept testing

3.1 Case studies

This section describes the case studies and data (boundary conditions, evaluation data and model outputs; Table 3.1) available to this PoC test. Full descriptions of each case study and dataset are given in Section 5 of the main report.

Table 3.1 Summary of available case study data

	Morpeth	**Cockermouth**	**Thames**
Event	5–7 September 2008	12–30 November 2009	6–17 February 2014
Inputs	Observed Sensitivity test (+10%, -20%) G2G simulated and sample of ensemble	Observed Sensitivity test (±20%) G2G simulated and sample of ensemble	Observed Sensitivity test (±20%) G2G simulated and sample of ensemble
Evaluation data	Maps of flood depth at hourly intervals Morpeth flood summary report (Parkin 2010) Flood Warnings issued	Aerial photograph Flood Warnings issued	Satellite radar Flood Warnings issued
Evaluation tests*	A1, A2, B1, B2, C1	A1, A2, B1, B2, C1	A1, A2, B1, B2, C1
Outputs	Flood extents Depth, water level Velocity, hazard		
Comments	Sensitivity test of observed flows +10% undertaken for model stability.	Aerial photographs were only available at the maximum of the event, so test B2 (property counts over time) was not performed.	Satellite radar was only available at a single time which coincided with modelled results, so test B2 (property counts over time) was not performed. The Thames model was not run with G2G data due to time constraints.

Notes: [1] See Section 4.1.5 of the main report for a description of each evaluation test.
Tests shown in light grey were not available or were not considered by this option.
G2G = Grid-to-Grid

3.2 Testing the PoC option

Details of how the PoC option was implemented, including filenames and versions, are given here for reference. The flow chart for this option is shown in Figure 2.2.

3.2.1 Input data

Table 3.2 Flow chart: In.1 State of the Nation MDSF2 models

Files and source	MDSF2 models are stored as ArcGIS personal geodatabases that contain all the spatial, tabular and look-up table information required to perform the flood risk calculation. A State of the Nation MDSF2 model has been created for each of the 44 'supercatchment' across England. Supercatchments range considerably in size from 400km^2 to 14,000km^2. An MDSF2 model consists of 2 databases, ModelDatabase.mdb and PostProcessing.mdb, which contain the input data and risk calculation results respectively. Only ModelDatabase.mdb is required to create the look-ups described below via the RFSM visualisation engine within MDSF2. **Morpeth** Supercatchment 7500, ModelDatabase.mdb Supercatchment area = 4,274km^2 **Cockermouth** Supercatchment 2200, ModelDatabase.mdb Supercatchment area = 2,371km^2 **Thames** Supercatchment 3701, ModelDatabase.mdb Supercatchment area = 8,533km^2
Description/required inputs	Inputs to State of the Nation MDSF2 baseline models fully described in the MDSF2 Software User Manual
File formats	ArcGIS personal geodatabase
Data overheads	Morpeth: Supercatchment Group 7100 to 7400, file size 712MB Cockermouth: Supercatchment Group 2200 to 2500, file size 827MB Thames: Supercatchment 3701, file size 1,128MB

Table 3.3 Flow chart: In.2 Point flow or water level estimates across river network

Files and source	For expediency in testing this PoC, flow and water level 'measurements' were extracted from the detailed models that underpin the fully dynamic fluvial modelling PoC (see Appendix 4)
Description/required inputs	Flow and/or level measurements, either from the gauging station network or alternative modelling (for example, G2G) at an instant in time
File formats	Custom text file containing gauging station ID and observed flow/level value
Data overheads	Negligible (<10KB)

Table 3.4 Flow chart: In.3 National fluvial flow/level–return period look-up

Files and source	**Flow return period look-ups** Morpeth: peakFlows2200.csv, hydrograph shapes and values in 2200_RP2.csv to 2200_RP1000.csv Data were developed as part of the recent 'H21 Evidence Update for National Risk Assessment 2016' project and are described below. Cockermouth: peakFlows7500.csv, hydrograph shapes and values in 7500_RP2.csv to 7500_RP1000.csv Thames: peakFlows3701.csv **Level return period look-ups** Morpeth: tblFluvialLevel_Catchment2200, data extracted from the State of the Nation MDSF2 baseline models and links level and return period on a per asset basis (supplied by HR Wallingford) Cockermouth: tblFluvialLevel_Catchment7500 Thames: tblFluvialLevel_Catchment3701
Description/required inputs	Pre-computed look-up tables that convert flow/level to return period (or vice versa) At gauging stations, these look-up tables may be based on more rigorous flood frequency analysis. Elsewhere, highly automated methods are required to generate these data and provide complete coverage across the national river network. A National Fluvial Levels Database has been compiled and is maintained (that is, updated where better local estimates are available through detailed modelling) to support MDSF2 modelling for NaFRA across England. The database comprises regularly spaced points along Main Rivers and Critical Ordinary Watercourses and a corresponding water level return period 'loading' table at each location. Each loading table contains 40 water level return period data points. To support recent fluvial modelling undertaken as part of the

	'H21 Evidence Update for National Risk Assessment 2016' project, JBA developed an alternative national loading database based on river flow. At approximately 1km intervals along the Environment Agency's Detailed River Network dataset (and at all confluences and bifurcations), catchment descriptors were extracted automatically from version 3 of the Flood Estimation Handbook CD-ROM and used in conjunction with Revitalised Flood Hydrograph (ReFH) rainfall run-off methods to derive peak flow estimates and hydrograph shapes for the 2, 5, 10, 25, 50, 75, 100, 200 and 1,000 year return periods. This dataset is hereafter referred to as the National Fluvial Flows Database.
File formats	National Fluvial Levels Database: ArcGIS personal geodatabase National Fluvial Flows Database: comma separated value text files
Data overheads	**Flow return period look-ups and hydrograph shapes** Morpeth: Total 7.7MB, PeakFlows 800KB Cockermouth: Total 15.1MB, PeakFlows 1.5MB Thames: Total 30.1MB, PeakFlows 2.9MB **Level–return period look-ups** Morpeth: 490KB Cockermouth: 1.03MB Thames: 27.75MB

Table 3.5 Flow chart: In.4 State of the Nation asset data

Files and source	Morpeth: tblAsset_Catchment2200 Data were extracted from the State of the Nation MDSF2 baseline models (supplied by HR Wallingford). Cockermouth: tblAsset_Catchment7500 Thames: tblAsset_Catchment3701
Description/required inputs	MDSF2 models require a continuous defence line (CDL) dataset that represents the most appropriate location for the interface between the river and the floodplain. It should follow the line of raised flood defence assets and the natural bank or high ground between the river and the floodplain. Each asset is also attributed with the key parameters required to run the risk calculation within MDSF2 (that is, crest level, ground level, asset type, condition grade and standard of protection). Where possible, the CDL is built from the latest asset information held within the Environment Agency's Asset Information Management System (AIMS). Morpeth: 261 assets, total length = 41.533km Cockermouth: 526 assets, total length = 99.838km

	Thames: 15,989 assets, total length = 2,452.850km
File formats	ArcGIS personal geodatabase
Data overheads	Morpeth: 134KB Cockermouth: 300KB Thames: 6.75MB

Table 3.6 Flow chart: An.1 Run RFSM visualisation tool for each Flood Area and return period; In.5 Impact Cell depth-return period look-up

Files and source	.csv and .shp files added into ArcGIS geodatabase tables **Impact Cell depth-return period look-ups** Morpeth: mor_cell_depth Cockermouth: coc_cell_depth Thames: tha_cell_depth **Impact Cell locations in GIS** Morpeth: mor_cell_ground_height Cockermouth: coc_cell_ground_height Thames: tha_cell_ground_height
Description/required inputs	Impacts Cells are used to describe the floodplain topography at 50m × 50m horizontal resolution within the MDSF2 RFSM. For each case study location, HR Wallingford ran the RFSM visualisation engine within MDSF2 to produce look-ups that consist of 40 depth grids for each Flood Area; one for each NaFRA return period (ranging from 1 in 1 year to 1 in 1,000 years), for a scenario where defences are in place and none are permitted to fail. Morpeth: 2,940 Impact Cells, 5 Flood Areas, total area 5.1km^2 Cockermouth: 7,941 Impact Cells, 6 Flood Areas, total area 15km^2 Thames: 231,129 Impact Cells, 88 Flood Areas, total area 621km^2
File formats	Look-ups supplied as delimited text files (.csv) Impact Cell locations supplied as ArcGIS shapefiles
Data overheads	**Impact Cell depth-return period look-ups** Morpeth: 800KB Cockermouth: 2.04MB Thames: 75.5MB **Impact Cell locations in GIS** Morpeth: 800KB

	Cockermouth: 1.73MB Thames: 45.5MB (reduced to area of interest 16.59MB)

Table 3.7 Flow chart: An.1 Run RFSM visualisation tool for each Flood Area and return period; In.6 State of the Nation asset volume proportion-return period look-up

Files and source	**Asset volume proportion-return period look-ups** Morpeth: Morpeth_assetproportions.csv Cockermouth: Cockermouth_assetproportions.csv Thames: Thames_assetproportions.csv **Impact Zone locations in GIS** Morpeth: ImpactZone.shp Cockermouth: ImpactZone.shp Thames: ImpactZone.shp
Description/required inputs	Impacts Zones are used to calculate water levels across the floodplain within the MDSF2 RFSM. For each case study location, HR Wallingford extracted information from the RFSM visualisation engine within MDSF2 to produce look-ups that give the proportion of the Impact Zone depth contributed from an asset at NaFRA return periods (ranging from 1 in 1 year to 1 in 1,000 years). Morpeth: 193 Impact Zones, 5 Flood Areas, total area 5.1km^2 Cockermouth: 387 Impact Zones, 5 Flood Areas, total area 14.2km^2 Thames: 8,012 Impact Zones, 57 Flood Areas, total area 496.4km^2
File formats	Look-ups supplied as delimited text files (.csv) Impact Zone locations supplied as ArcGIS shapefiles
Data overheads	**Asset volume proportion-return period look-ups** Morpeth: 1.15MB Cockermouth: 1.83MB Thames: 1.02GB **Impact Zone locations in GIS** Morpeth: 800KB Cockermouth: 1.73MB Thames: 45.5MB (reduced to area of interest 16.59MB)

3.2.2 Intermediate processing

Table 3.8 Flow chart: An.2 Interpolate return period at each asset across river network; Ou.1 Assets with associated return period

Software	
Scripts were written in Python using ArcPy modules. The procedure takes all CDL assets and associates each asset with the nearest flow interpolation point and nearest flow return period look-up point (from the National Fluvial Flows Database) on the river network. The association is achieved using the smallest distance along river network between asset midpoints, snapped to the nearest point on the river and associated points. Using observed flow values from gauges (or other inputs at a small set of points), the script interpolates where necessary across a larger set of flow interpolation points, which are evenly distributed along the river network. This process provides a flow at an asset that can be converted to a return period using the associated look-up. For each Flood Area, an average return period is calculated for all assets that have an associated inflow (at that instant). This Flood Area average return period is then applied to every asset bounding that Flood Area.	
Hardware	
Description	Network interpolations were made on a PC with a 2.50GHz central processing unit (CPU) and 16GB of RAM.
Size of files	Asset dataset attributed with associated return period Morpeth: 206KB Cockermouth: 361KB Thames: 9.4MB
Network logistics	Input/output files were stored on the local PC hard drive.
Run times	Morpeth: ~2 minutes for a river network interpolation associated with a single execution/inundation snapshot Cockermouth: ~2 minutes for a river network interpolation associated with a single execution/inundation snapshot Thames: ~2 minutes for a river network interpolation associated with a single execution/inundation snapshot
Size of model domain	Morpeth: 261 assets, 2,940 Impact Cells, 193 Impact Zones, 5 Flood Areas, total area 5.1km^2 Cockermouth: 526 assets, 7,941 Impact Cells, 387 Impact Zones, 6 Flood Areas, total area 15km^2 Thames: 15,989 assets, 231,129 Impact Cells, 8,012 Impact Zones, 88 Flood Areas, total area 621km^2

Table 3.9 Flow chart: An.3 Estimate Impact Cell depths; An.4 Adjust Impact Cell depths by relative asset contributions

Software	
Scripts were written in Python using ArcPy modules. Each Impact Zone has an associated list of possible contributing assets. The asset's associated return period is used to look up the proportion that the asset should add to all Impact Cells within the Impact Zone. For each Impact Cell, the assets that contribute to the cell are found. Each asset has a return period associated with it; the Impact Cell depth at these return periods is calculated, using interpolation if necessary. Each asset proportion is multiplied by the Impact Cell depth for the asset return period and a sum of all depth contributions calculated to give a depth at that cell. The total proportion may not add up to 1; it may be higher or lower. The depth value obtained is therefore normalised such that the proportion is 1.	
Hardware	
Description	Flood depth look-ups were made on a PC with a 2.50GHz CPU and 16GB of RAM.
Size of files	**Impact Cell depth-return period look-ups** Morpeth: 715KB Cockermouth: 2.1MB Thames: 76MB **Asset volume proportion-return period look-ups** Morpeth: 1.15MB Cockermouth: 1.83MB Thames: 1.02GB **Asset dataset attributed with associated return period** Morpeth: 206KB Cockermouth: 361KB Thames: 9.4MB
Network logistics	Input/output files were stored on the local PC hard drive.
Run times	Morpeth: ~5 minutes for a single execution/inundation snapshot Cockermouth: ~5 minutes for a single execution/inundation snapshot Thames: ~1 hour for a single execution/inundation snapshot (30 minutes is time spent on data set-up than does not have to be repeated if multiple snapshots run at once;30 minutes is approximately how long an individual snapshot would take if many are run at the same time) Note all run times are for a single core running serially over the whole model domain. It would be simple to multi-process, running each Flood Area separately which would decrease the run time. There are also many additional data pre-processing methods that would reduce run time, in particular the set-

	up/pre-process time.
Size of model domain	Morpeth: 261 assets, 2,940 Impact Cells, 193 Impact Zones, 5 Flood Areas, total area 5.1km^2 Cockermouth: 526 assets, 7,941 Impact Cells, 387 Impact Zones, 6 Flood Areas, total area 15km^2 Thames: 15,989 assets, 231,129 Impact Cells, 8,012 Impact Zones, 88 Flood Areas, total area 621km^2

3.2.3 Output data

Table 3.10 Flow chart: Ou.2 Model output: depth per Impact Cell

Outputs provided	2D grids of flood depth at 50m × 50m resolution
File sizes	Single inundation snapshot in ArcGIS geodatabase format
Morpeth	800KB
Cockermouth	1.86MB
Thames	48MB

3.2.4 Post-processing

Flow chart: In.7, An.5, Ou.3

Flood impacts were assessed in a generic way for each PoC option as described in Section 4 of the main report. The outcomes of these evaluation tests are presented in Section 4 of this appendix.

4 Proof of concept evaluation

This section provides detailed information on the outputs of the PoC. Its purpose is to provide supporting information for each case study event to demonstrate:

- the outputs available from the option
- the technical feasibility of the option
- the simulation performance of the option against observed data

The cases for flow and level inputs are presented separately for the 3 case study events. The findings are summarised in Table 4.1.

Table 4.1 Summary of PoC findings

Case study	Findings
Morpeth	Flood extent is predicted accurately at Morpeth in both the ‘flow inputs’ and ‘level inputs’ cases. The flood extents for both types of boundary condition are similar. Results are included along the banks of several minor tributaries. The coarse resolution of the output grids (50m × 50m resolution) makes these additional areas of flooding significant for the overall accuracy metrics calculated. Modelled depths are assessed by comparison to observed data. The results of the level driven simulation are more accurate than for the flow-driven run. Inaccuracies in the distribution of flood depths are likely to result from limitations in the topographic representation within MDSF2. This PoC is sensitive to inflow at Morpeth. Changes in modelled extent occur at the upstream (western) end of the town centre in both the flow and level driven simulations. When coupled to G2G ensemble inflows, the forecast flood outline is underpredicted in most cases and there is considerable variation in the area in which flooding is forecast.
Cockermouth	Results at Cockermouth are accurate for both the flow and level driven model results. Overall, the maximum flood extent is accurately predicted, although there are areas within that extent where the model underpredicts. Flood depth distribution was assessed, although in the absence of observed data this is limited to a sensibility check. The results of the level driven model run are skewed towards depths >0.90m, whereas there is less skew in the results of the flow-driven model run, in which the depth categories have a more even distribution. An assessment to sensitivity to inflows found only minor changes to the total flood outline. Results from both flow and level driven simulations contain variations in the extent and location of dry islands within the flood extent, but the overall flooded extent changes very little. A high degree of consistency in the flood outline was also found when

Case study	Findings
	using G2G ensemble members to produce inflows for the simulations.
Thames	PoC outputs for this case overpredict flood extents by a large margin compared with the available observed data. The large degree of overprediction is reflected in the model skill assessment and is the main feature of the flood depth assessment (for which the observed depth distribution is not available). Discussion of these results includes: • assessment of the available observed data • sensibility of the model results – they lie within the maximum extent of the Flood Warning Areas • factors in the set-up of the fully dynamic fluvial modelling PoC that could affect the inflow estimation used here The relative difference, between the results of the modelling with both flows and levels inputs is small. In common with other PoCs, testing of model sensitivity to inflow was not carried out for the Thames case study due to a lack of boundary condition information.

4.1 Case study 1: Morpeth, September 2008 – flow inputs

4.1.1 Location

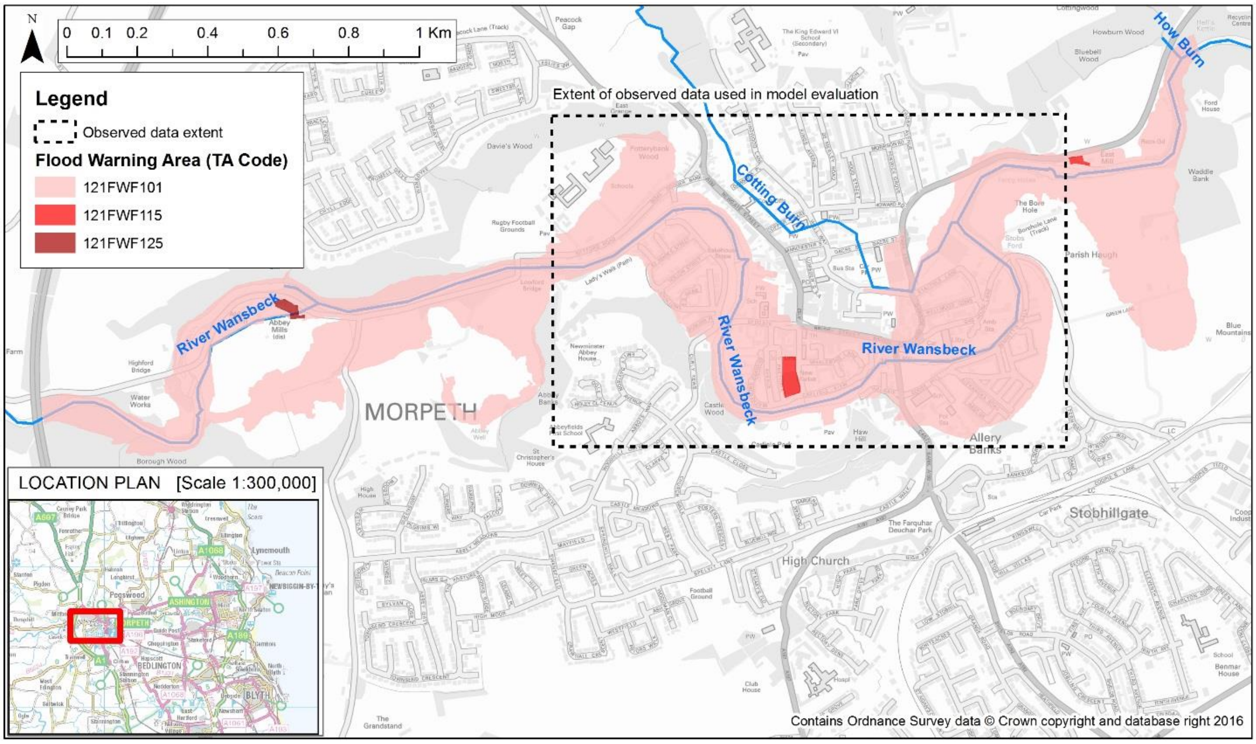


Figure 4.1 Location map for Morpeth case study

Table 4.2 Description of Flood Warning Areas featured in the Morpeth case study

Flood Warning Target Area Code	Name
121FWF101	River Wansbeck at Morpeth
121FWF115	River Wansbeck at East Mill and Morpeth Riverside Leisure Centre
121FWF125[1]	River Wansbeck at Abbey Mills

Notes: [1] This is outside the extent of the observed flood outline data.

4.1.2 Model outputs

Figure 4.2 **Model outputs for Morpeth event: flow inputs**

4.1.3 Extent flooded (Test A1)

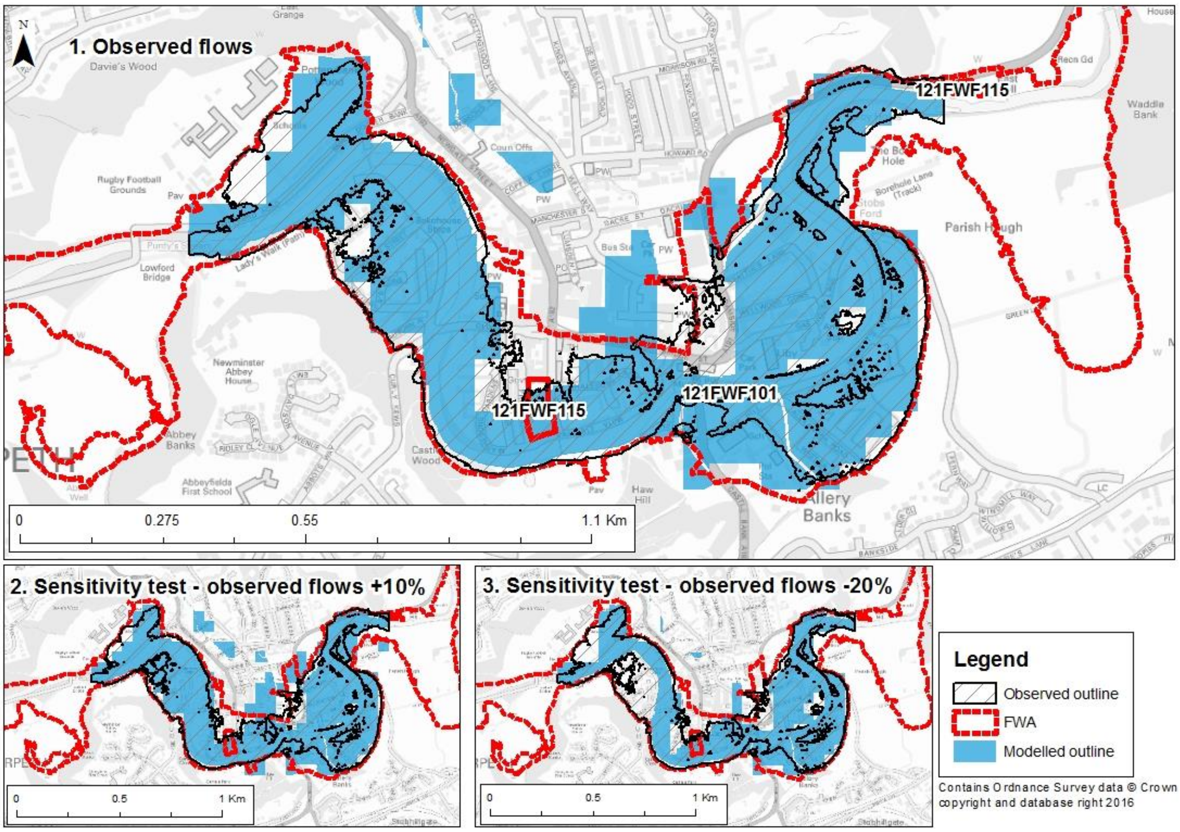


Figure 4.3 Maximum modelled and observed extent flooded: flow inputs

Table 4.3 Comparison of modelled and observed area flooded for each Flood Warning Area for Morpeth event: flow inputs

Flood Warning Area (FWA)	Area (m^2)	Area flooded			
		Modelled		Observed	
		m^2	% of FWA	m^2	% of FWA
All	586,998	441,450	75.2	439,788	74.9
121FWF101	582,260	437,527	75.1	435,947	74.9
121FWF115	4,738	3,923	82.8	3,841	81.1
121FWF125	–	–	–	–	–

Notes: For the purposes of comparison, the areas of the Flood Warning Areas have been trimmed to the extent of the available observed data.

Interpretation

The simulation library output consists of 50m resolution grid cells. There are some cells of irregular size and shape at the boundaries of the channel, where they have been trimmed using the asset lines. Another feature of the results is the inclusion of tributaries; at Morpeth, the forecast outline includes some tributaries, which produce area of forecast flooding to the north of the main channel.

Model prediction is generally accurate, especially considering the coarse resolution of the results. The 50m grid size means that a single cell constitutes a large margin of error, in terms of flood extent.

The flooded area is within 1% of the observed flood extent within the area covered by the Flood Warning Areas, although this is made up of some overprediction and some underprediction.

In line with other PoC options, sensitivity testing assessed model inflows in the range +10% to -20% using the same inflow data as the fully dynamic fluvial modelling PoC (see Appendix 4). These tests produced notable changes in forecast flood outlines, especially in the upstream (western) part of the town centre. This PoC is therefore sensitive to inflow, although overall accuracy was not severely affected in these tests.

4.1.4 Model performance (Test A2)

Model performance scores were derived by comparison of modelled and observed flood outlines. Percentages were calculated as follows.

- Correct wet: proportion of flood extent that is correctly predicted by the model. Modelled extent = observed extent (blue)
- Overprediction: proportion of flood extent that is overpredicted by the model. Modelled extent > observed extent (green)
- Underprediction: proportion of flood extent that is underpredicted by the model. Modelled extent < observed extent (purple)

Skill and bias scores were calculated using the equations given below. ‘Correct dry’ areas are never included in the scores, as this is heavily dependent on the extent of the model domain.

$$SKILL = \frac{Correct\ Wet}{Correct\ Wet + Overprediction + Underprediction}$$

$$BIAS = \frac{Correct\ Wet + Overprediction}{Correct\ Wet + Underprediction}$$

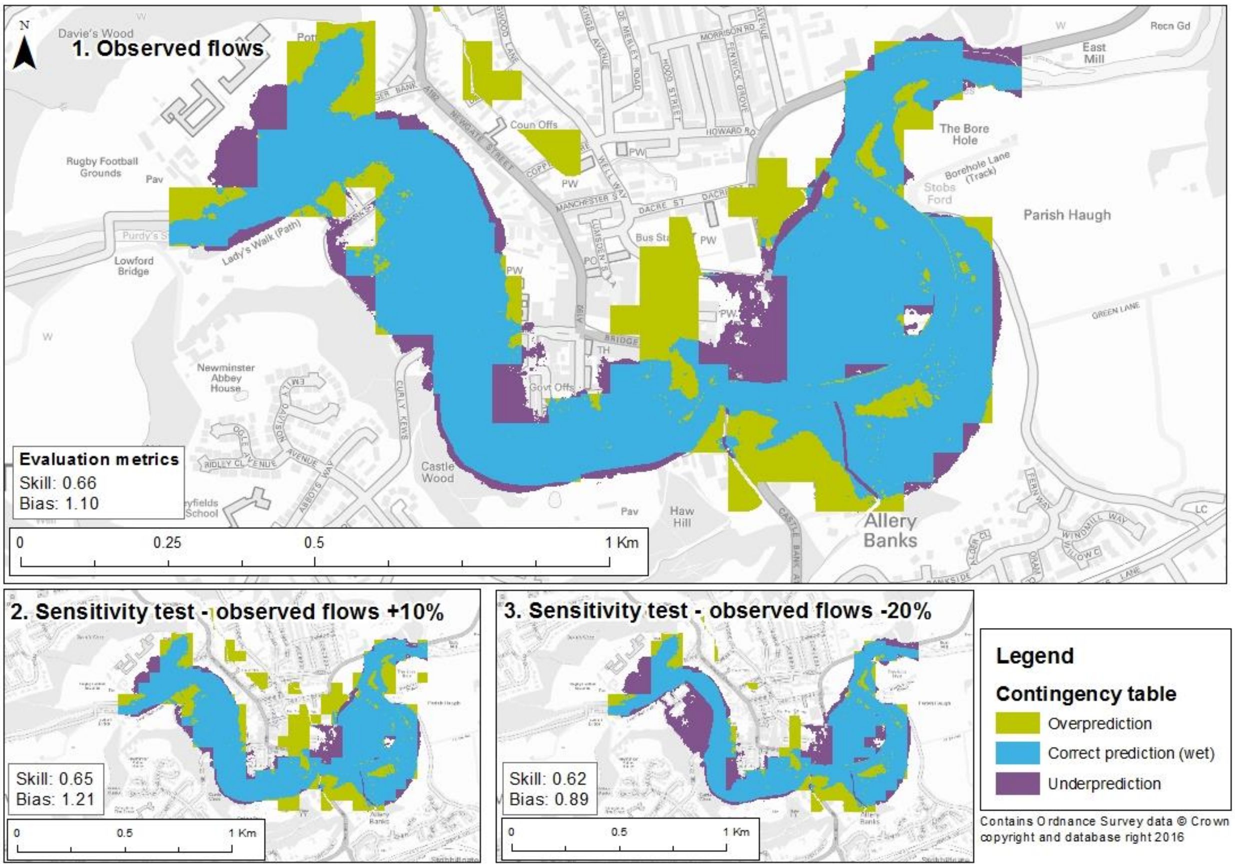


Figure 4.4 Model performance in predicting flooded extent at Morpeth: flow inputs

Table 4.4 Model performance metrics for Morpeth event: flow inputs

Flood Warning Area	**Correct wet (%)**	**Over-prediction (%)**	**Under-prediction (%)**	**Skill**	**Bias**
Modelled outline (all)	**66.0**	**21.0**	**13.0**	**0.66**	**1.10**
Modelled outline (within area covered by Flood Warning Areas only)					
121FWF101	72.6	13.9	13.6	0.73	1.00
121FWF115	95.9	3.0	1.1	0.96	1.02
121FWF125	–	–	–	–	–

Notes: Metrics are reported for the full modelled flood outline first. Subsequent rows of the table report the metrics for the model flood outline within given Flood Warning Areas. This distinguishes between performance across the full model domain and performance in locations where there is known to be flood risk to property.

Interpretation

This test displays the areas of underprediction and overprediction in the model results. The majority of the flood outline consists of correct prediction (shown by a skill score of 0.66), although there are areas of both overprediction and underprediction. Although these areas are of similar magnitude, there is slightly more overprediction – resulting in a positive value for model bias. Lack of flood extent observations on some of the tributaries may contribute to this.

4.1.5 Property counts (Test B)

Properties within flood extent

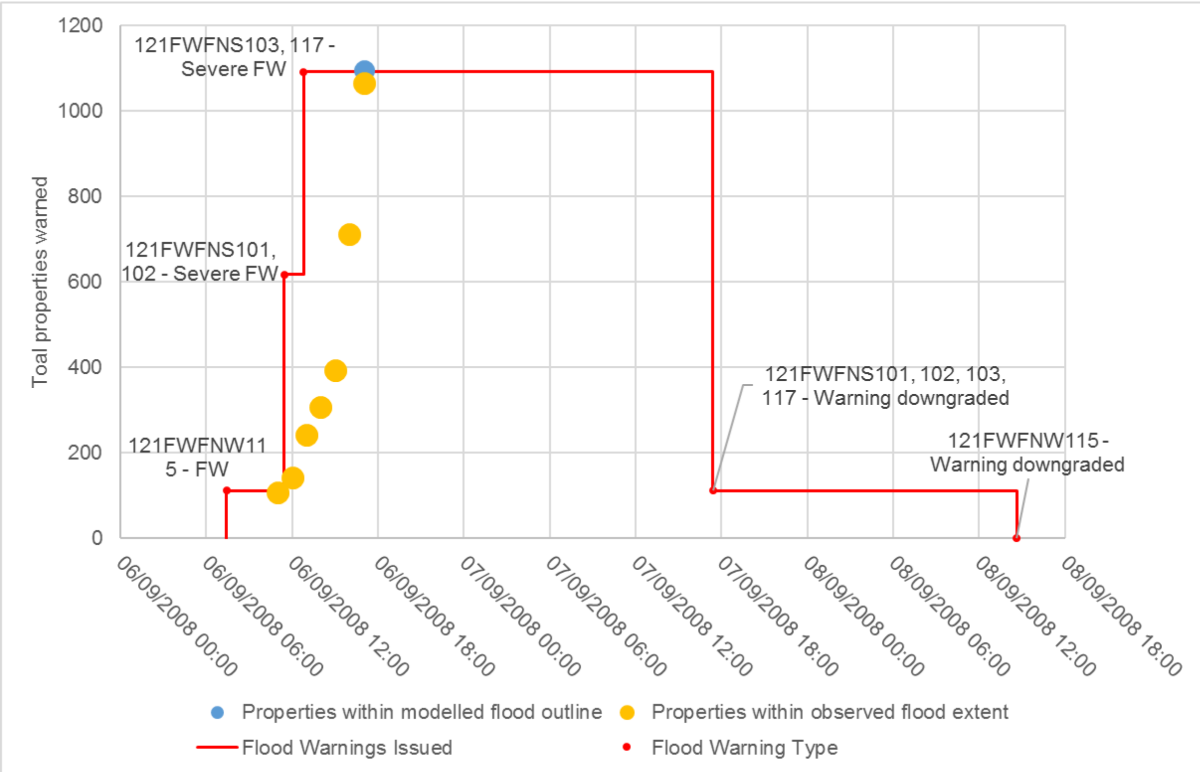


Figure 4.5 Properties within flood extent for Morpeth event: flow inputs

Notes: Properties are mapped below.

Table 4.5 Maximum number of flooded properties for Morpeth event: flow inputs

Flood Warning Area	Properties warned[1]	Observed[2]	Predicted[3]
All	–	1,065	1,095
121FWF101	–	1,060	1,090
121FWF115	–	5	5
121FWF125	–	–	–

Notes: [1] Properties warned: counts of properties within each Flood Warning Area that received a flood warning during the event. Morpeth's Flood Warning Areas have been revised since the 2008 event, so it is not possible to provide numbers of properties.
[2] Observed is based on the intersection of National Receptor Dataset (NRD) property points and observed flood outline.
[3] Predicted is based on the intersection of NRD property points with maximum modelled flood outline.

Interpretation

The number of properties within the modelled flood outline is accurate; results are within 5% of the number of properties within the observed extent. The final property count (1,095 properties within Flood Warning Areas) is the result of some areas of overprediction and some areas of underprediction. The location of these properties is shown in Figure 4.6.

This PoC was tested for the maximum flood outline only and therefore time-stepped results are not available for comparison against the observed property counts.

Properties mapped by model prediction

Figure 4.6 shows property points (from the NRD), colour-coded according to whether the model overpredicts, underpredicts or correctly predicts the observed flood outline.

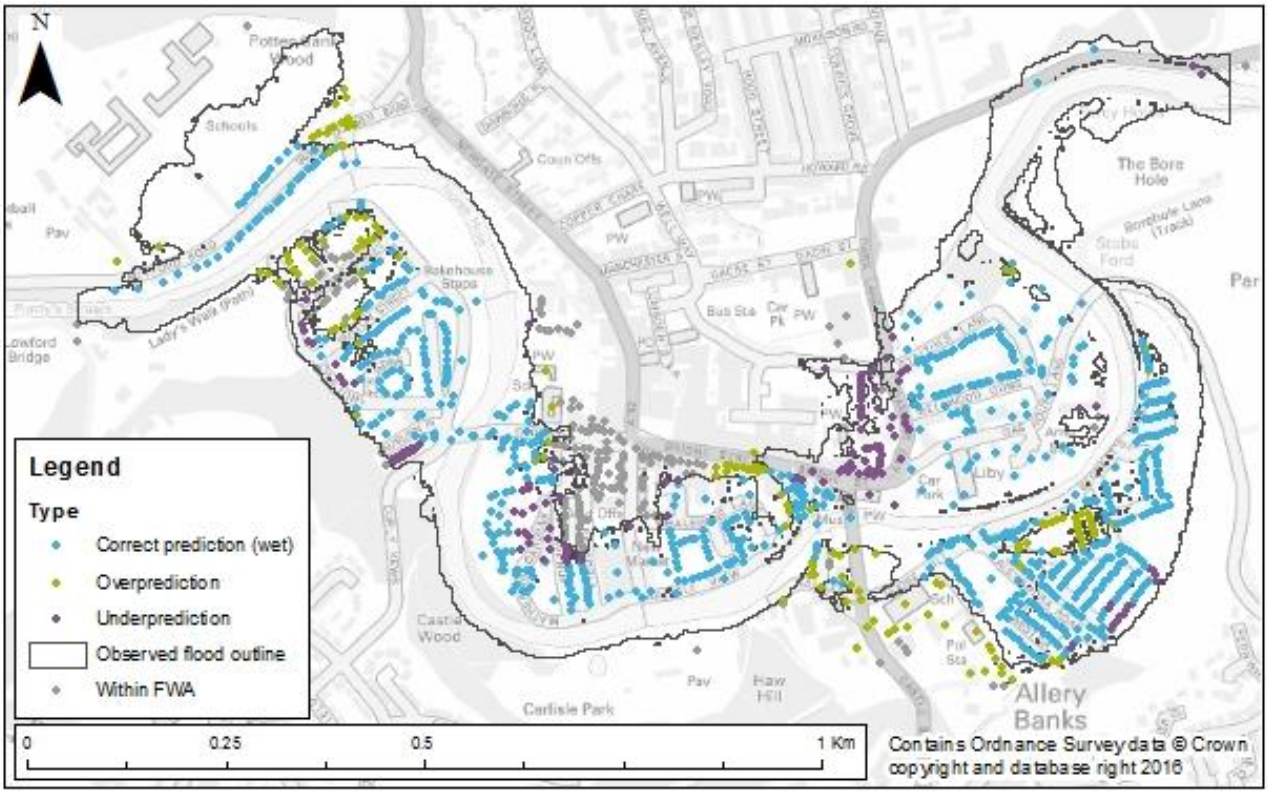


Figure 4.6 Model performance in predicting extent of flooding at Morpeth: flow inputs

4.1.6 Depth analysis (Test C)

Flooded depths

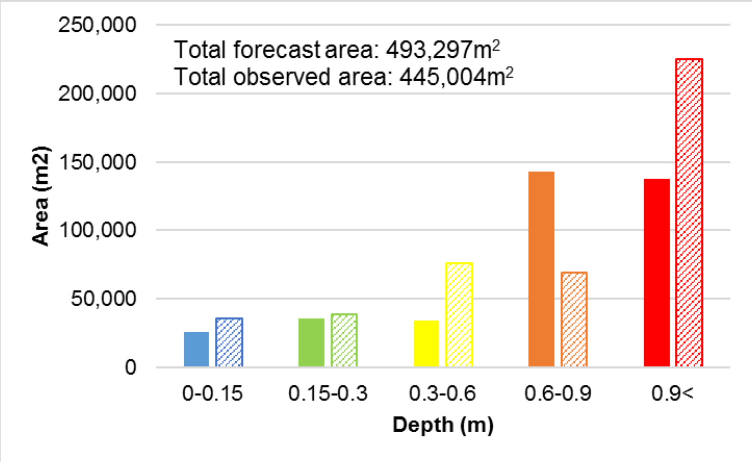


Figure 4.7 Distribution of flooded depths at Morpeth at 17:00 (peak) on 6 September 2008: flow inputs

Notes: Solid bars show modelled depths (from the PoC option).
Dashed bars show observed depths (based on data supplied by Newcastle University).
Channel depths are not included in the modelled results and the observed area would be expected to be greater. Channel area = 117,304m^2
Total areas quoted on each plot include the channel area for both forecast and observed results.

Modelled	Observed	Depth (m)
		0.00–0.15
		0.15–0.30
		0.30–0.60
		0.60–0.90
		>0.90

Interpretation

The forecast depth distribution shows that there is a smaller area flooded at depths >0.90m, although it should be noted that the channel is excluded from the forecast in this PoC.

The largest errors in forecast depths are in the categories between 0.30m and 0.90m, in which the distribution of forecast depth is skewed towards the deeper category.

Forecast depths in this PoC are derived from a pre-computed look-up; they do not use hydraulic modelling methods. This approach therefore does not explicitly model flood spreading on the floodplain during the event, which may contribute to the differences in observed and modelled depths.

4.1.7 G2G

Table 4.6 Details of available G2G data for Morpeth event

Simulation data	Start: 5 September 2008 00:00GMT	End: 7 September 2008 23:45GMT
Forecast data	UKV ensemble rainfall forecast 2km resolution, 24 ensemble members, 15-minute rainfall totals Lead times: 30 hours	
Forecast origins available	5 September 2008 12:00GMT	
Forecast origins tested	5 September 2008 12:00GMT	
Ensembles tested	All 24 ensemble members were tested. Inflows were extracted from G2G at the grid square corresponding to the main river model inflow on the River Wansbeck (G2G grid ID 150094).	

Comparison of G2G simulated and observed inflows on River Wansbeck

Inflows on the River Wansbeck at the upstream extent of the model are plotted in Figure 4.8. The start time of the G2G data provided is midnight on 5 September 2008. The start time of the observed data is midnight on 6 September 2008.

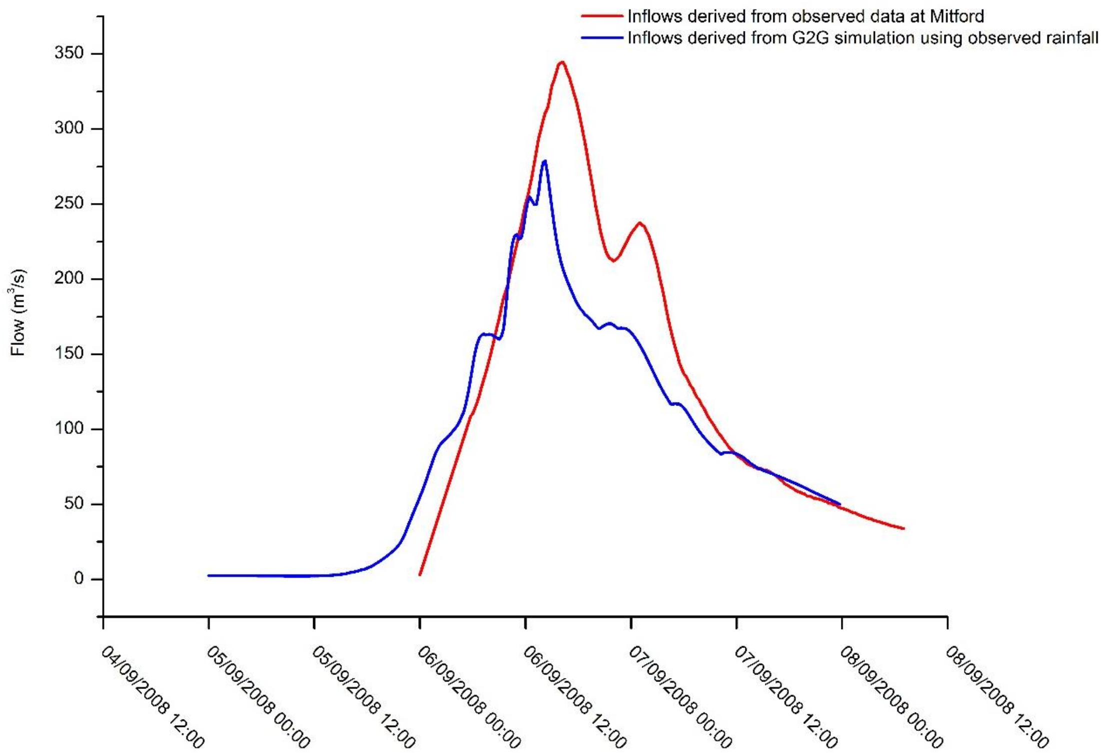


Figure 4.8 Hydrograph for the River Wansbeck: flow inputs

Flood extent – maximum

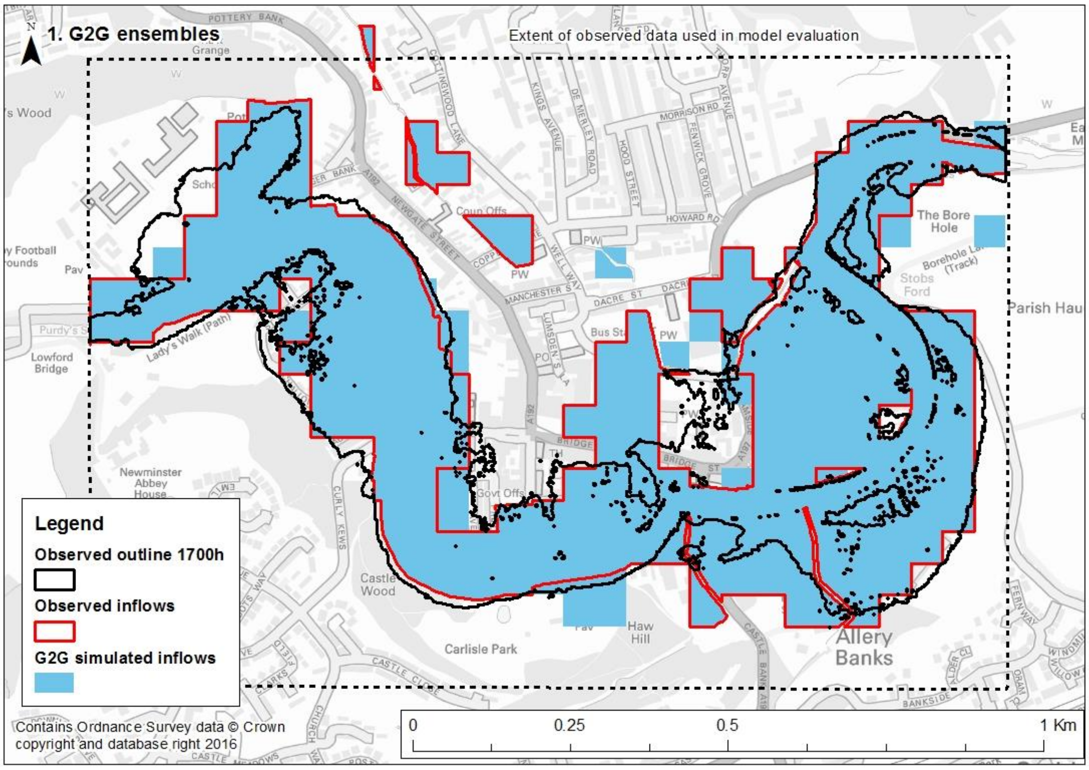


Figure 4.9 Observed and G2G simulated maximum flood extent for Morpeth event: flow inputs

The hydrograph (Figure 4.8) shows that simulated flows from G2G (fed with observed rainfall) are notably smaller than observed flows at the upstream model boundary during the event peak and recession. Volume under the G2G simulated hydrograph is also substantially lower.

Nonetheless, the results of the run using G2G simulated inflows predict the flood outline to a reasonable degree of accuracy. There are some areas of underprediction such as the left bank in the town centre.

The forecast outline in the G2G simulated run is very similar to the result of the run using observed inflows, suggesting that variations in the inflow in the G2G run are not large enough to affect model outputs – the inflow hydrographs themselves, shown above, are not especially dissimilar in terms of peak magnitude.

G2G ensemble members

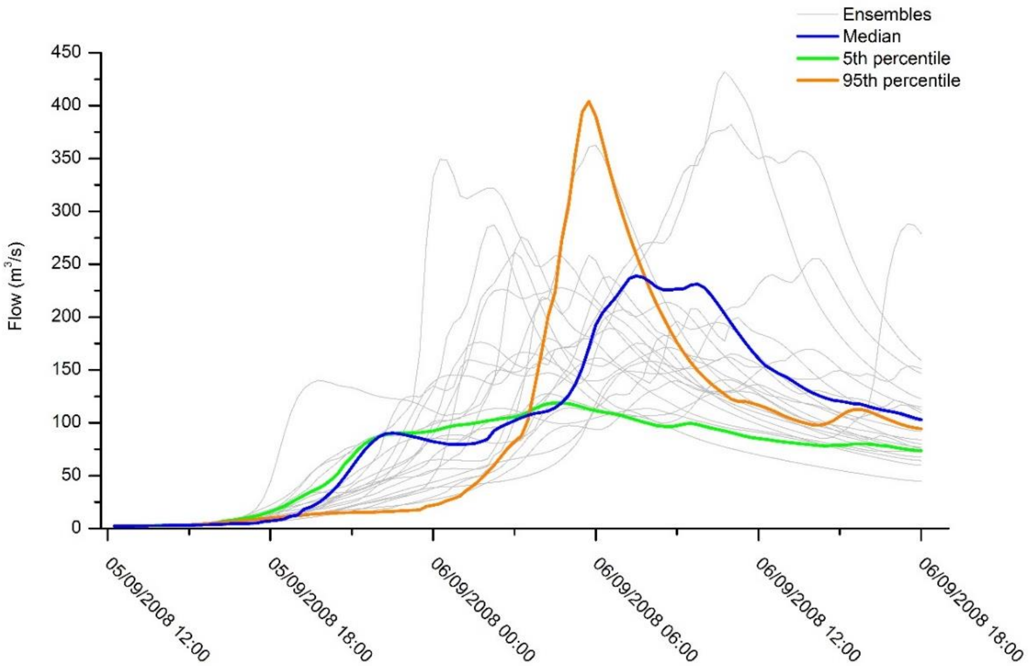


Figure 4.10 G2G ensemble members: inflows to hydraulic model for Morpeth event

Flood extent – maximum observed and maximum G2G

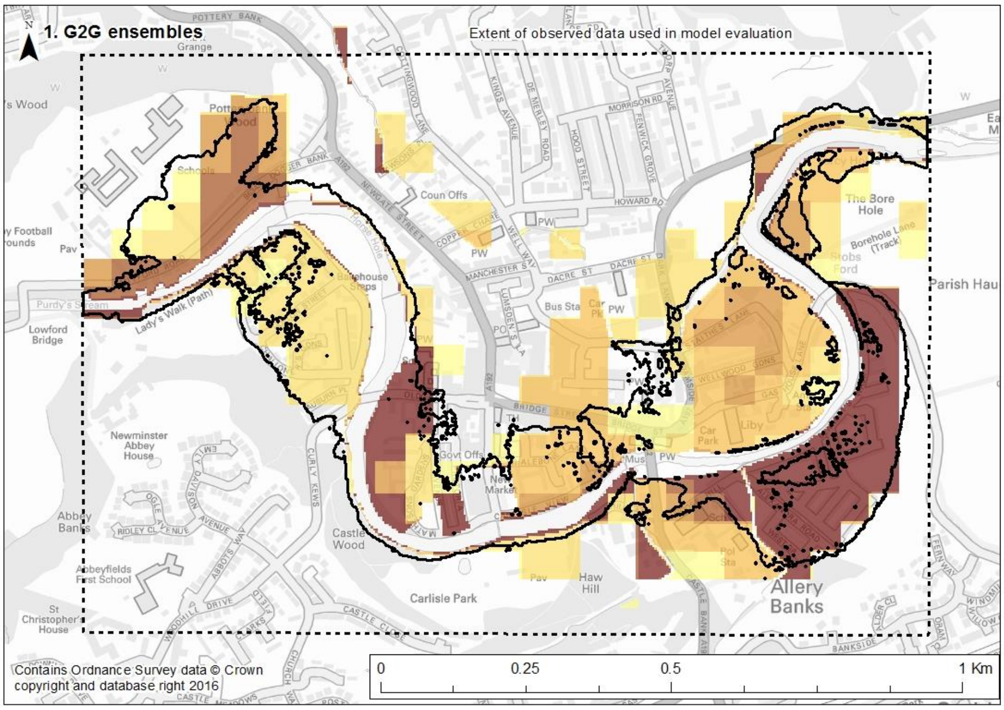


Figure 4.11 Maximum observed and maximum G2G simulation of flood extent for Morpeth event: flow inputs

Notes: The map shows the maximum observed outline (black outline) against the maximum extent of the 3 ensemble G2G runs (yellow-brown shading). G2G results are trimmed to the extent of observed data.

Darker colours on the map show where flood outlines from all 3 runs predict the same location as flooded, while the lightest colour shows areas predicted to flood by only one ensemble member.

Property counts – maximum

The number of properties in the observed flood extent is 1,065.

Note that, in this case, the model underpredicts flood extent in some areas. The final row of Table 4.7 shows the number of properties within the observed outline that appear in none of the ensemble members.

Table 4.7 Number of NRD property points within the flood outlines for Morpeth event: flow inputs

Flood outlines	Number of properties[1]	Cumulative property count[2]	Notes
21–24 × ensemble overlap	473	473	Area shown as flooded in all tested ensemble members
17–20 × ensemble overlap	59	532	–
13–16 × ensemble overlap	117	649	–
9–12 × ensemble overlap	246	895	
5–8 × ensemble overlap	255	1,150	
1–4 × ensemble overlap	112	1,262	
Within observed outline but not forecast	76	–	Area not shown as flooded in any tested ensemble member

Notes: [1] This column shows the number of properties within each separate zone of the modelled outlines, ordered from the area where all ensembles coincide, to properties that appear in one ensemble member only.
[2] This column lists the cumulative number of properties within the modelled outlines, ordered by areas predicted to flood in the most ensemble members to the least ensemble members. For example, at this lead time, 5 properties are within the outlines of the largest number of ensembles, 963 properties are within the outline given by the least number of ensemble members.

4.2 Case study 1: Morpeth, September 2008 – flow inputs

4.2.1 Location

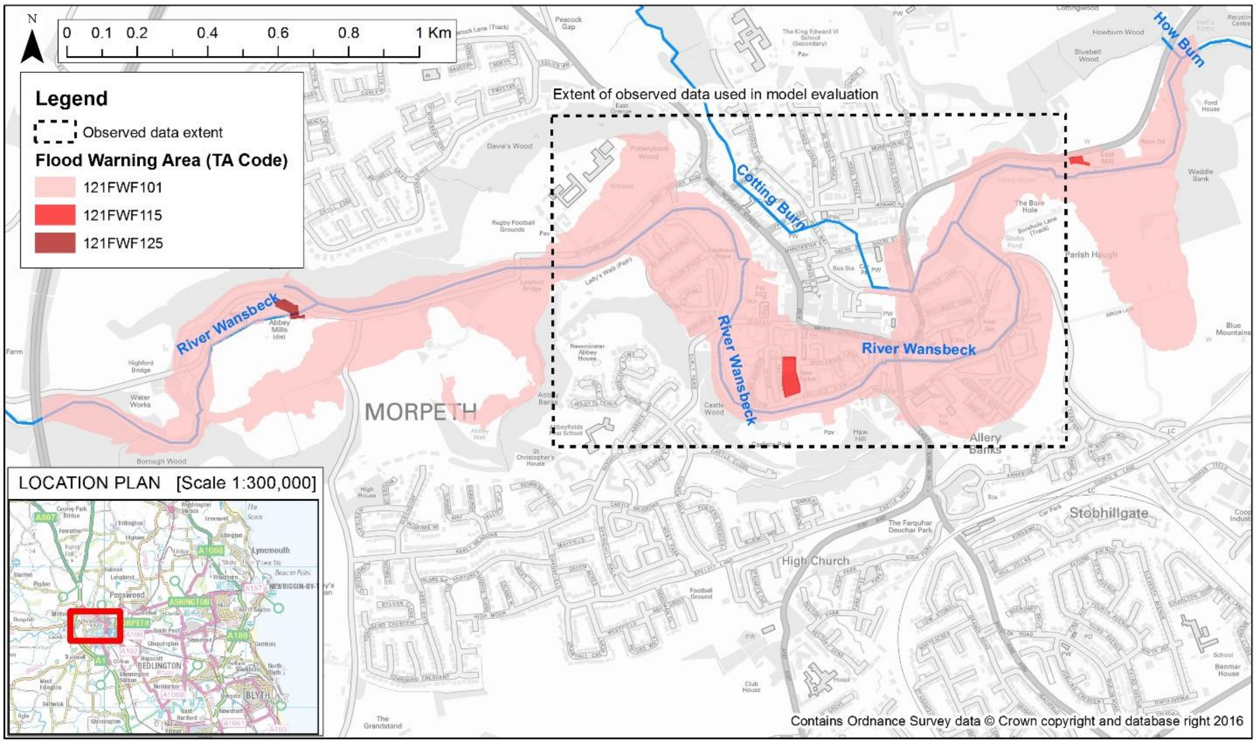


Figure 4.12 Location map for Morpeth case study

Table 4.8 Description of Flood Warning Areas featured in the Morpeth case study

Flood Warning Target Area Code	Name
121FWF101	River Wansbeck at Morpeth
121FWF115	River Wansbeck at East Mill and Morpeth Riverside Leisure Centre
121FWF125 [1]	River Wansbeck at Abbey Mills

Notes: [1] This is outside the extent of the observed flood outline data.

4.2.2 Model outputs

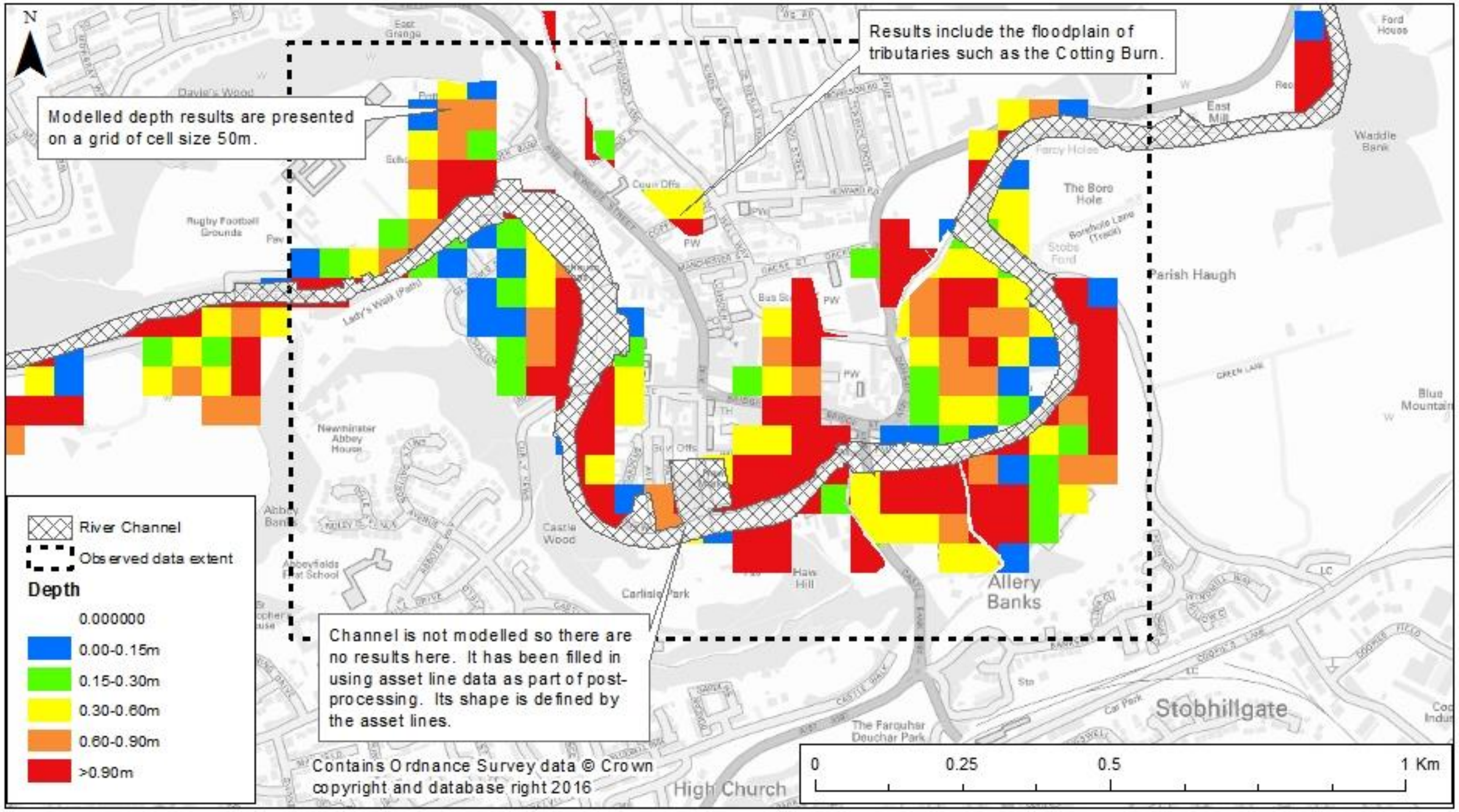


Figure 4.13 Model outputs for Morpeth event: level inputs

4.2.3 Extent flooded (Test A1)

Extent flooded

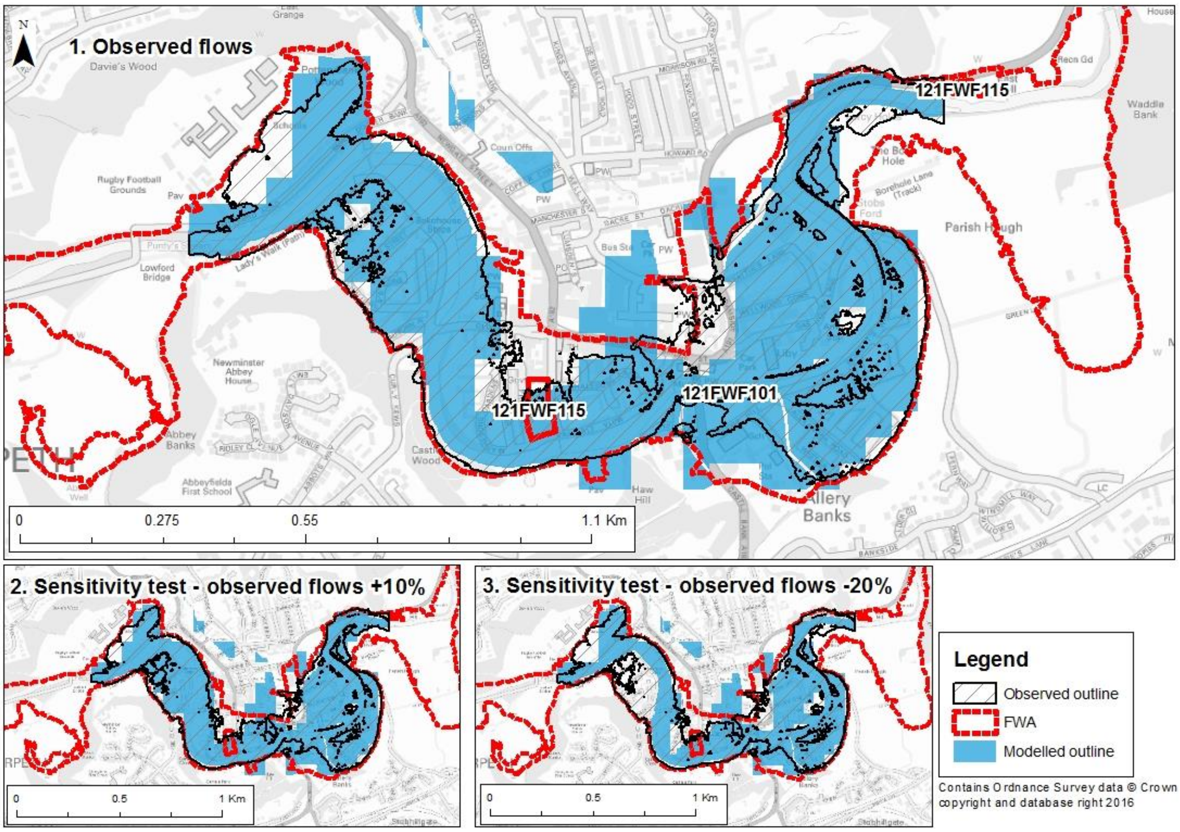


Figure 4.14 Maximum modelled and observed extent flooded: level inputs

Table 4.9 Comparison of modelled and observed area flooded for each Flood Warning Area for Morpeth event: level inputs

Flood Warning Area (FWA)	**Area (m²)**	**Area flooded**			
		Modelled		**Observed**	
		m²	**% of FWA**	**m²**	**% of FWA**
All	586,998	442,315	75.4	439,788	74.9
121FWF101	582,260	438,391	75.3	435,947	74.9
121FWF115	4,738	3,924	82.8	3,841	81.1
121FWF125	–	–	–	–	–

Notes: For the purposes of comparison, the areas of the Flood Warning Areas have been trimmed to the extent of the available observed data.

Interpretation

The simulation library output consists of 50m resolution grid cells. There are some cells of irregular size and shape at the boundaries of the channel, where they have been cropped to the asset lines. Another feature of the results is the inclusion of tributaries; at Morpeth, the forecast outline includes some tributaries, which produce areas of forecast flooding to the north of the main channel.

The outline of the modelled results is very similar to the results using flow inputs. The accuracy of the model is similar, with an error against the observed data within 1.0% (in terms of flooded area). As with the flow inputs results, there are areas of underprediction in the main floodplain and areas of overprediction on tributaries. The latter may relate to limitations in the available observations of flood extent and depth.

This PoC is sensitive to boundary condition specification, and when sensitivity testing was carried out, the change in forecast flood outline was more noticeable in the upstream (western) part of the town centre.

4.2.4 Model performance (Test A2)

Model performance scores were derived by comparison of modelled and observed flood outlines. Percentages were calculated as follows.

- Correct wet: proportion of flood extent that is correctly predicted by the model. Modelled extent = observed extent (blue)
- Overprediction: proportion of flood extent that is overpredicted by the model. Modelled extent > observed extent (green)
- Underprediction: proportion of flood extent that is underpredicted by the model. Modelled extent < observed extent (purple)

Skill and bias scores were calculated using the equations given below. ‘Correct dry’ areas are never included in the scores, as this is heavily dependent on the extent of the model domain.

$$SKILL = \frac{Correct\ Wet}{Correct\ Wet + Overprediction + Underprediction}$$

$$BIAS = \frac{Correct\ Wet + Overprediction}{Correct\ Wet + Underprediction}$$

Maximum modelled extent compared to maximum available observed extent

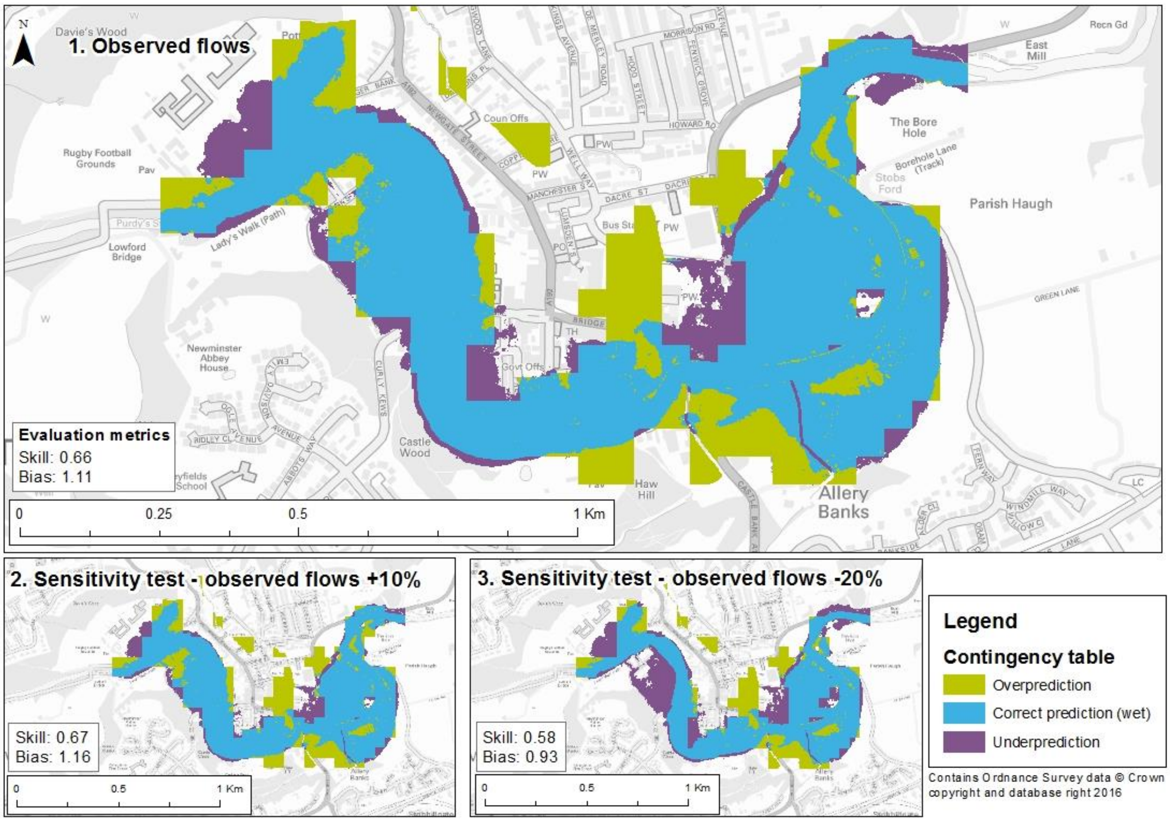


Figure 4.15 Model performance in predicting flooded extent at Morpeth: level inputs

Table 4.10 Model performance metrics for Morpeth event: level inputs

Flood Warning Area	Correct wet (%)	Over-prediction (%)	Under-prediction (%)	Skill	Bias
Modelled outline (all)	**65.5**	**21.4**	**13.1**	**0.66**	**1.11**
Modelled outline (within area covered by Flood Warning Areas only)					
121FWF101	72.0	14.2	13.8	0.72	1.00
121FWF115	95.9	3.0	1.1	0.96	1.02
121FWF125	–	–	–	–	–

Notes: Metrics are reported for the full modelled flood outline first. Subsequent rows of the table report the metrics for the model flood outline within given Flood Warning Areas. This distinguishes between performance across the full model domain and performance in locations where there is known to be flood risk to property.

Interpretation

In general, the model results are accurate, with a large proportion of correct prediction (skill score of 0.66, which is comparable to the flow-driven run). There are areas of both overprediction and underprediction, although there is more overprediction overall which results in a positive value for model bias.

An important part of the overprediction seen in these results is the inclusion of tributaries, where flooding is overpredicted. As discussed above, limitations in the available observed data may contribute to this.

4.2.5 Property counts (Test B)

Properties within flood extent

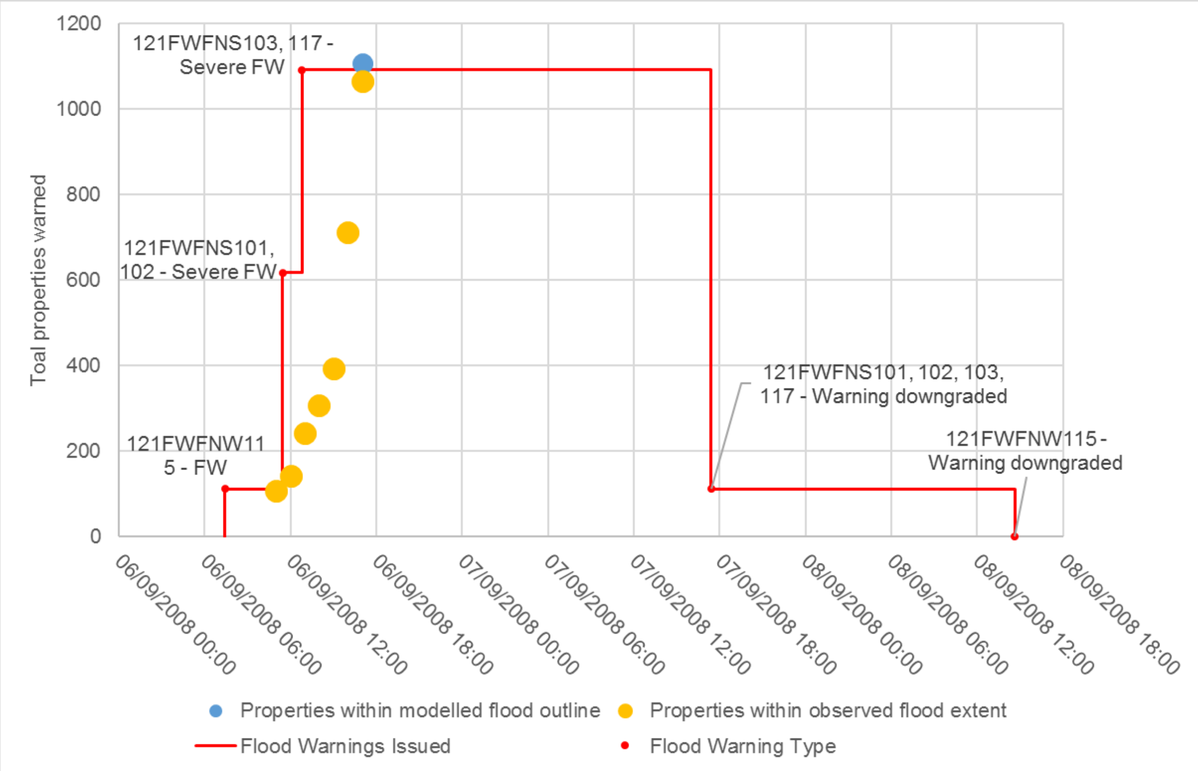


Figure 4.16 Properties within flood extent for Morpeth event: level inputs

Notes: Properties are mapped below.

Table 4.11 Maximum number of flooded properties for Morpeth event: level inputs

Flood Warning Area	Properties warned[1]	Observed[2]	Predicted[3]
All	–	1,065	1,107
121FWF101	–	1,060	1,102
121FWF115	–	5	5
121FWF125	–	–	–

Notes: [1] Properties warned: counts of properties within each Flood Warning Area that received a flood warning during the event. Morpeth's Flood Warning Areas have been revised since the 2008 event, so it is not possible to provide numbers of properties.
[2] Observed is based on the intersection of NRD property points and observed flood outline.
[3] Predicted is based on the intersection of NRD property points with maximum modelled flood outline.

Interpretation

The number of properties within the modelled flood outline is accurate – results are within 5.0% of the number of properties within the observed extent.

The final property count (1,107 properties within Flood Warning Area) is the result of some areas of overprediction and some areas of underprediction. These are shown in Figure 4.17.

This PoC has been tested for the maximum flood outline only and therefore time-stepped results are not available for comparison against the observed property counts.

Properties mapped by model prediction

Figure 4.17 shows property points (from the NRD), colour-coded according to whether the model overpredicts, underpredicts or correctly predicts the observed flood outline.

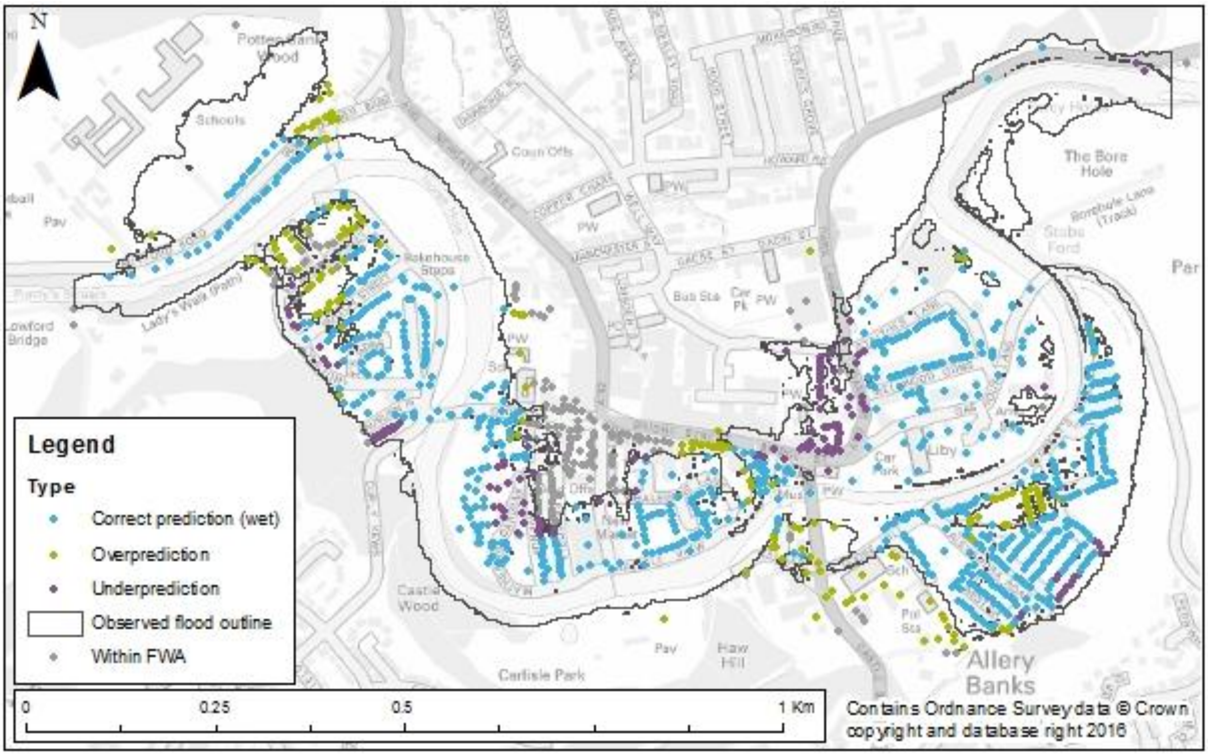


Figure 4.17 Model performance in predicting extent of flooding at Morpeth: level inputs

4.2.6 Depth analysis (Test C)

Flooded depths

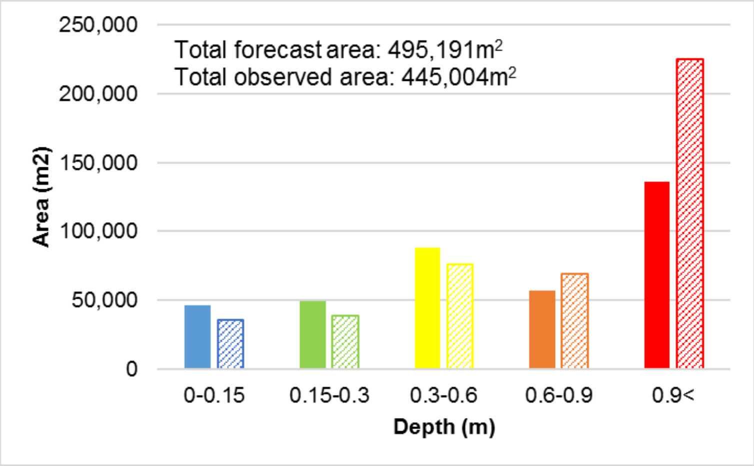


Figure 4.18 Distribution of flooded depths at Morpeth at 17:00 (peak) on 6 September 2008: level inputs

Notes: Solid bars show modelled depths (from the PoC option).
Dashed bars show observed depths (based on data supplied by Newcastle University).
Channel depths are not included in the modelled results and the observed area would be expected to be greater. Channel area = 117,304m^2
Total areas quoted on each plot include the channel area for both forecast and observed results.

Modelled	Observed	Depth (m)
		0.00–0.15
		0.15–0.30
		0.30–0.60
		0.60–0.90
		>0.90

Interpretation

The forecast depth distribution shows that there is a smaller area flooded at depths >0.90m than in the observed distribution, although it should be noted that the channel is excluded from the forecast in this PoC.

In contrast to the flow inputs assessment, the modelled depth distribution accurately replicates the observed for the depths below 0.90m.

Earlier metrics have shown that the forecast area is accurate in this PoC at Morpeth. These results for the predicted depth further build confidence in the quality of outputs from this PoC.

4.3 Case study 2: Cockermouth, November 2009 – flow inputs

4.3.1 Location

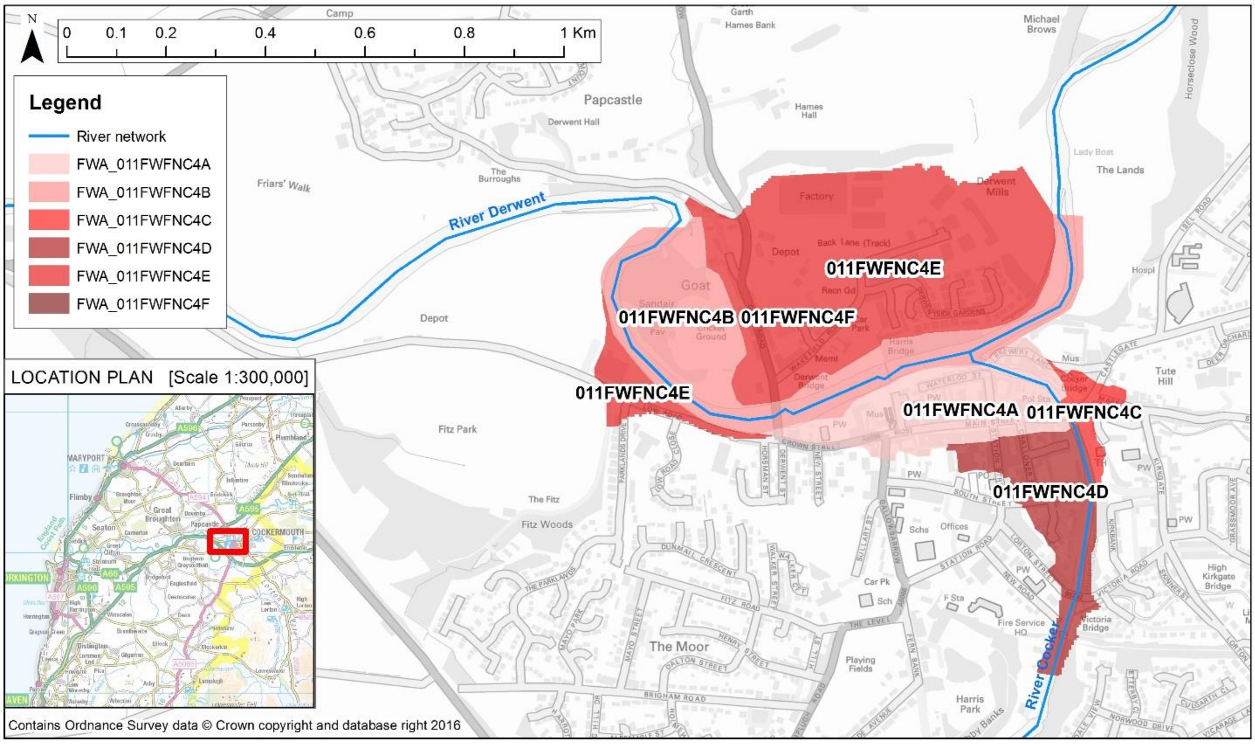


Figure 4.19 Location map for Cockermouth case study

Table 4.12 Description of Flood Warning Areas featured in the Cockermouth case study

Flood Warning Target Area Code	Name
011FWFNC4A	Rivers Cocker and Derwent at Cockermouth, Bridge Street, Crown Street, High Sand Lane and Main Street
011FWFNC4B	Rivers Cocker and Derwent at Cockermouth, Cricket Ground and Trout Hotel Car Park
011FWFNC4C	River Cocker at Cockermouth, The Old Courthouse and Market Place Area
011FWFNC4D	River Cocker at Cockermouth, Challoner Street, Croft Terrace, Jubilee Court and Rubbybanks Road
011FWFNC4E	River Derwent at Cockermouth, Gote Road to Derwent Mills Area and Low Road
011FWFNC4F	Cockermouth Gote Road and St Leonards

4.3.2 Model outputs

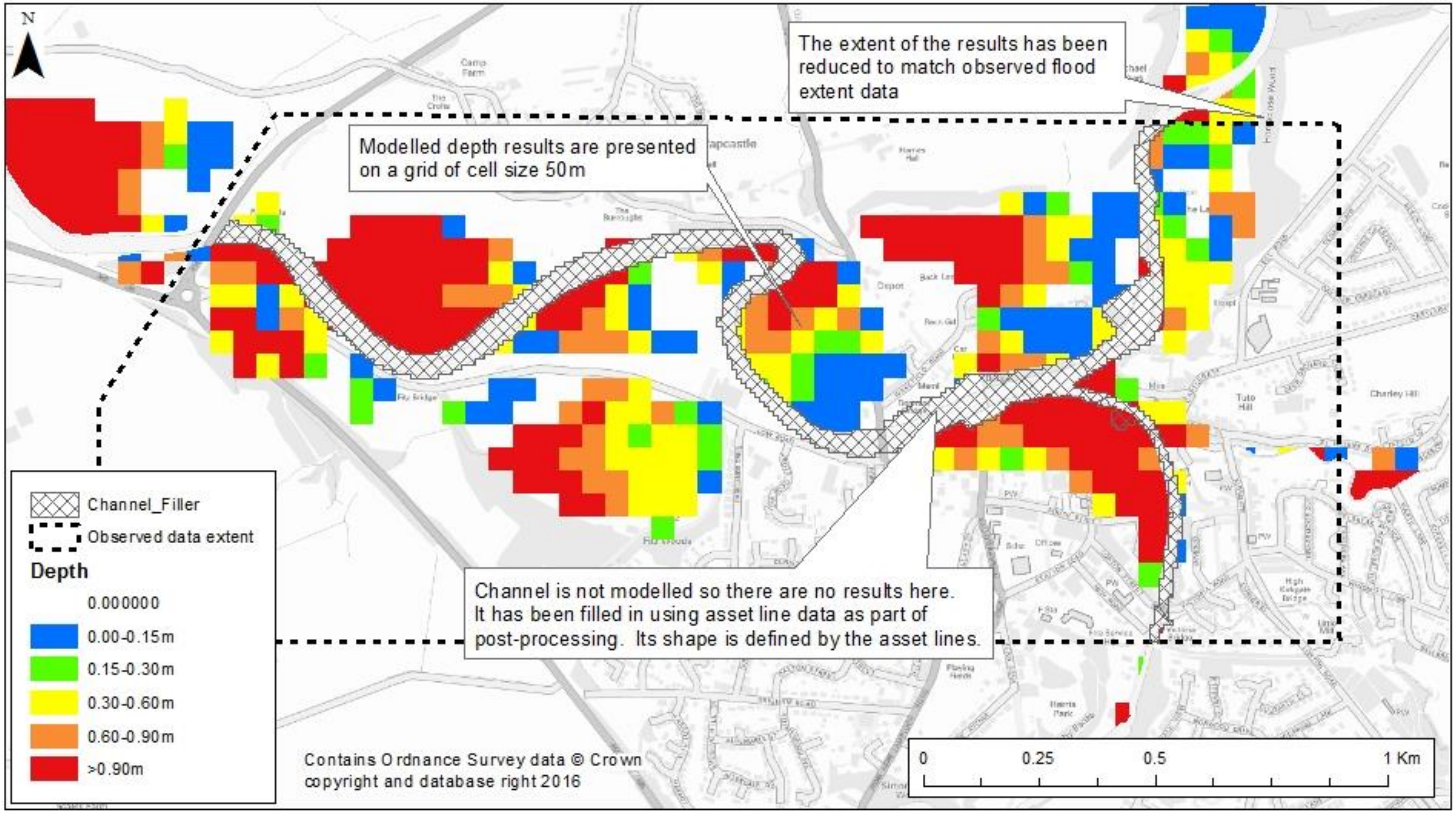


Figure 4.20 Model outputs for Cockermouth event: flow inputs

4.3.3 Extent flooded (Test A1)

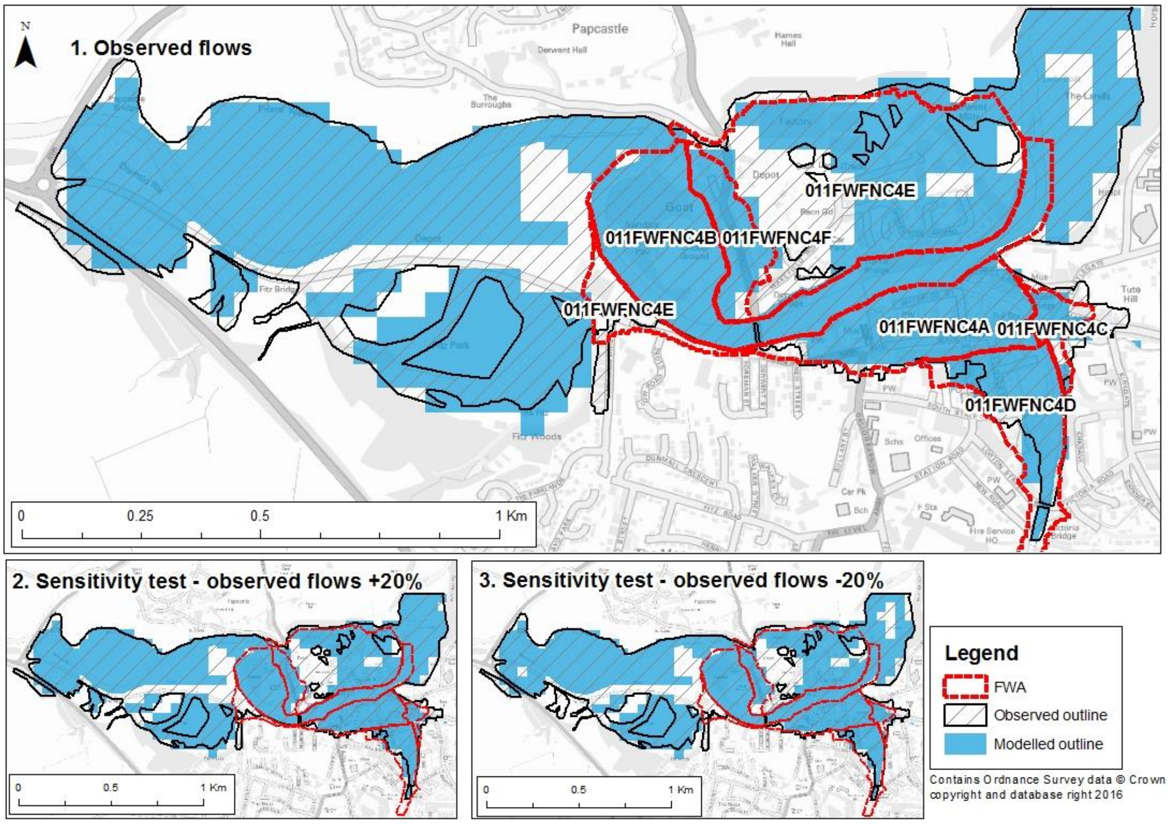


Figure 4.21 Maximum modelled and observed extent flooded: flow inputs

Table 4.13 Comparison of modelled and observed area flooded for each Flood Warning Area for Cockermouth event: flow inputs

Flood Warning Area (FWA)	Area (m^2)	Area flooded			
		Modelled		Observed	
		m^2	% of FWA	m^2	% of FWA
All	**560,039**	**436,908**	**78.0**	**508,774**	**90.9**
011FWFNC4A	73,728	67,874	92.1	70,731	95.9
011FWFNC4B	134,289	132,060	98.3	133,541	99.4
011FWFNC4C	13,362	9,860	73.8	12,788	95.7
011FWFNC4D	57,177	42,159	73.7	37,810	66.1
011FWFNC4E	252,013	158,462	62.9	224,436	89.1
011FWFNC4F	29,469	26,492	89.9	29,469	100.0

Notes: For the purposes of comparison, the areas of the Flood Warning Areas have been trimmed to the extent of the available observed data.

Interpretation

The simulation library output consists of 50m resolution grid cells. There are some cells of irregular size and shape at the boundaries of the channel, where they have been trimmed by the asset lines. Another feature of the results is the tributaries; at Cockermouth, the forecast outline includes a tributary at the eastern end of the tested area, but the flooding here is not significant to the results.

This option is accurate in terms of the overall flood outline, although there are areas of underprediction within this area. The accuracy of the overall extent of flooding (not considering areas of underprediction within that area) is high, especially given the coarse nature of the results. Total error in the forecast flood outline is within 15% of the observed outline.

Sensitivity testing considered the change in flood outlines after a ±20% change in inflow. The overall flood extent is not especially sensitive to inflow and there were only minor changes to the flood outline in the areas that were previously underpredicted.

4.3.4 Model performance (Test A2)

Model performance scores were derived by comparison of modelled and observed flood outlines. Percentages were calculated as follows.

- Correct wet: proportion of flood extent that is correctly predicted by the model. Modelled extent = observed extent (blue)
- Overprediction: proportion of flood extent that is overpredicted by the model. Modelled extent > observed extent (green)
- Underprediction: proportion of flood extent that is underpredicted by the model. Modelled extent < observed extent (purple)

Skill and bias scores were calculated using the equations given below. 'Correct dry' areas are never included in the scores, as this is heavily dependent on the extent of the model domain.

$$SKILL = \frac{Correct\ Wet}{Correct\ Wet + Overprediction + Underprediction}$$

$$BIAS = \frac{Correct\ Wet + Overprediction}{Correct\ Wet + Underprediction}$$

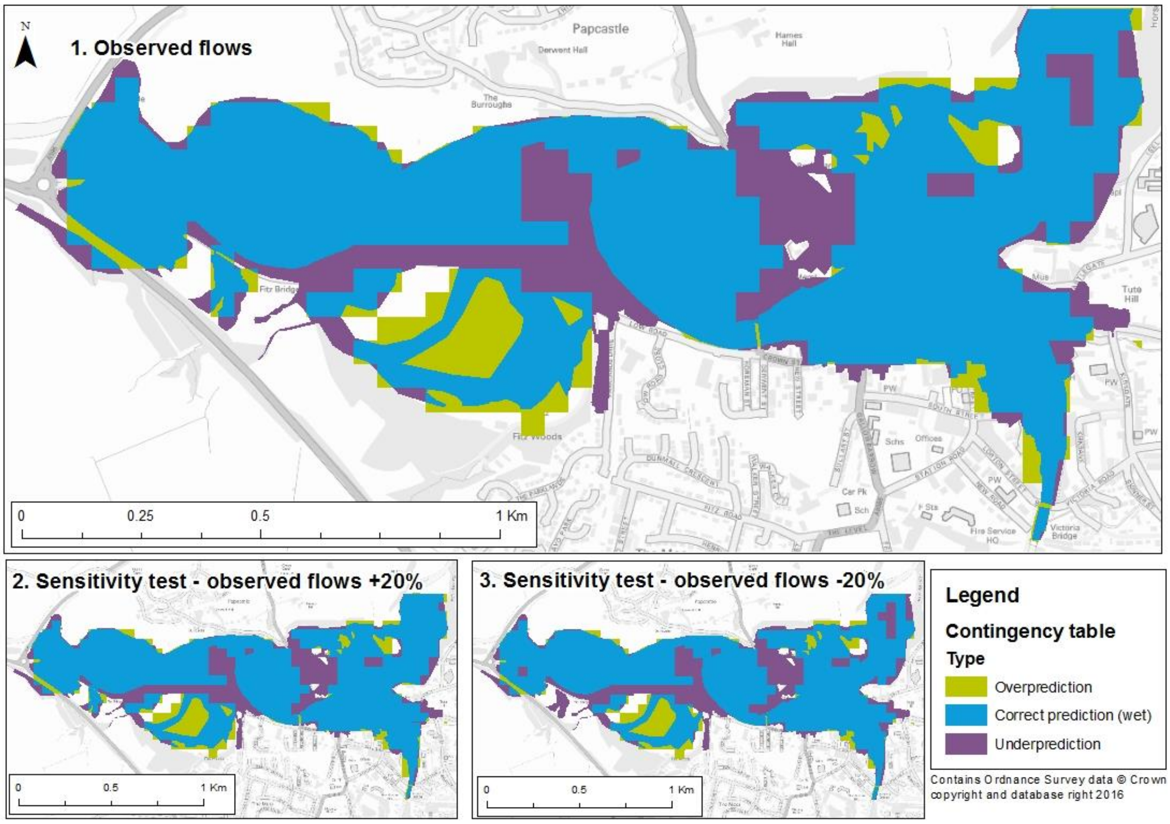


Figure 4.22 Model performance in predicting flooded extent at Cockermouth: flow inputs

Table 4.14 Model performance metrics for Cockermouth event: flow inputs

Flood Warning Area	Correct wet (%)	Over-prediction (%)	Under-prediction (%)	Skill	Bias
Modelled outline (all)	**72.4**	**8.3**	**19.4**	**0.72**	**0.88**
Modelled outline (within area covered by Flood Warning Areas only)					
011FWFNC4A	95.5	0.2	4.3	0.96	0.96
011FWFNC4B	98.8	0.5	1.6	0.98	0.99
011FWFNC4C	71.3	3.3	24.4	0.72	0.78
011FWFNC4D	78.4	15.6	5.9	0.78	1.12
011FWFNC4E	62.0	5.1	33.0	0.62	0.71
011FWFNC4F	89.9	0.0	10.1	0.90	0.90

Notes: Metrics are reported for the full modelled flood outline first. Subsequent rows of the table report the metrics for the model flood outline within given Flood Warning Areas. This distinguishes between performance across the full model domain and performance in locations where there is known to be flood risk to property.

Interpretation

There is a large proportion of correct prediction in the model results at Cockermouth (72% of total modelled outline). This results in a high score for model skill, which increases above 0.90 in some Flood Warning Areas.

However, the coarse results grid and the lack of explicit modelling of overland flow in the modelling method are demonstrated in the model results at the following locations.

- The observed outline at Cockermouth includes areas such as the braided floodplain flow to the south of the main floodplain. The 50m model output is not able to predict this, resulting in an area of overprediction
- At the western end of the flood extent, a road cuts off the floodplain, but some flood spreading is observed due to a culvert in the embankment. This floodplain flow is not explicitly modelled in this option, resulting in underprediction here.

4.3.5 Property counts (Test B)

Properties within flood extent

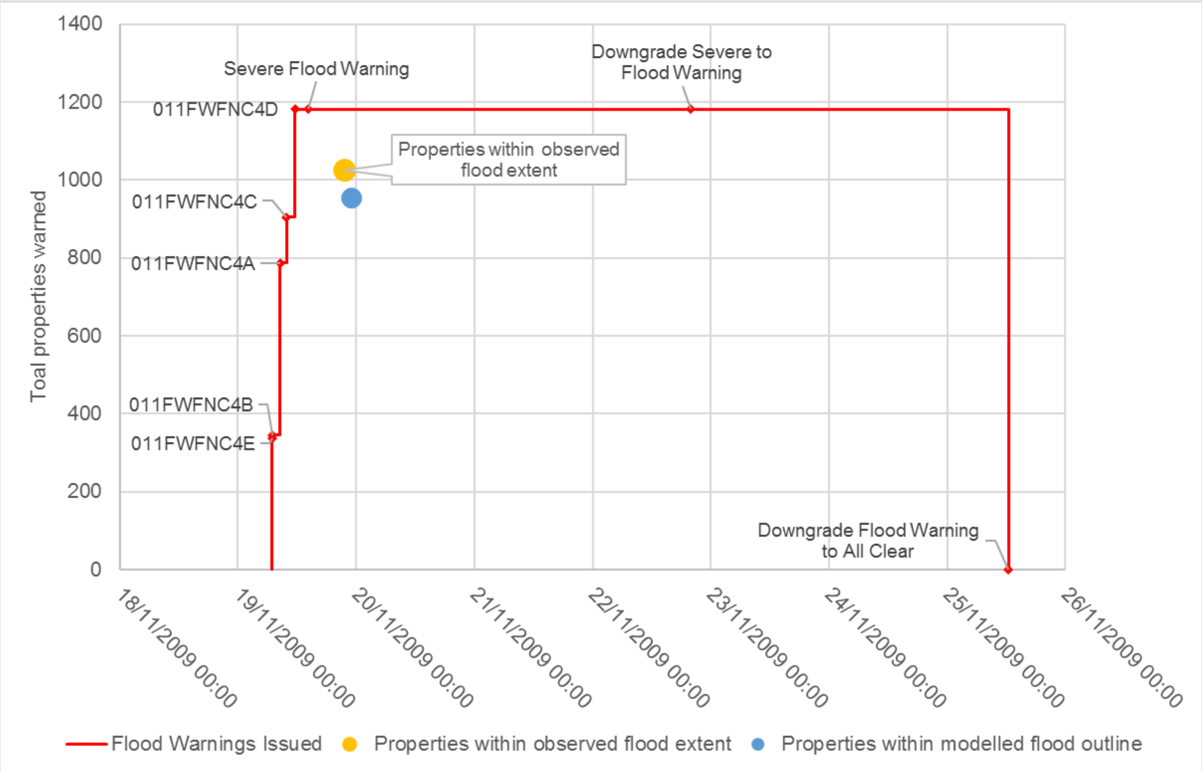


Figure 4.23 Properties within flood extent for Cockermouth event: flow inputs

Notes: Properties are mapped below.

Table 4.15 Maximum number of flooded properties for Cockermouth event: flow inputs

Flood Warning Area	Properties warned[1]	Observed[2]	Predicted[3]
All	**1,180**	**1,036**	**956**
011FWFNC4A	442	415	392
011FWFNC4B	9	7	9
011FWFNC4C	117	116	98
011FWFNC4D	278	189	236
011FWFNC4E	336	309	221
011FWFNC4F	119	119	72

Notes: [1] Properties warned: counts of properties within each Flood Warning Area that received a flood warning during the event.
[2] Observed is based on the intersection of NRD property points and observed flood outline.
[3] Predicted is based on the intersection of NRD property points with maximum modelled flood outline.
Flood Warning Area F is nested within Flood Warning Area E.

Interpretation

With 956 properties in the modelled flood outline (Table 4.15), the simulation library is broadly consistent with numbers of properties within the observed flood extents (1,036 properties within the observed outline). The results are consistent with the level driven version of the PoC (see Section 4.4.5). There are some areas of overprediction and underprediction, which are shown in Figure 4.24.

This PoC produces a maximum flood outline only and therefore time-stepped results are not available for comparison against the observed property counts.

Properties mapped by model prediction

Figure 4.24 shows NRD property points, colour-coded according to whether the model overpredicts, underpredicts or correctly predicts the observed flood outline. Only properties within the existing Flood Warning Area are considered.

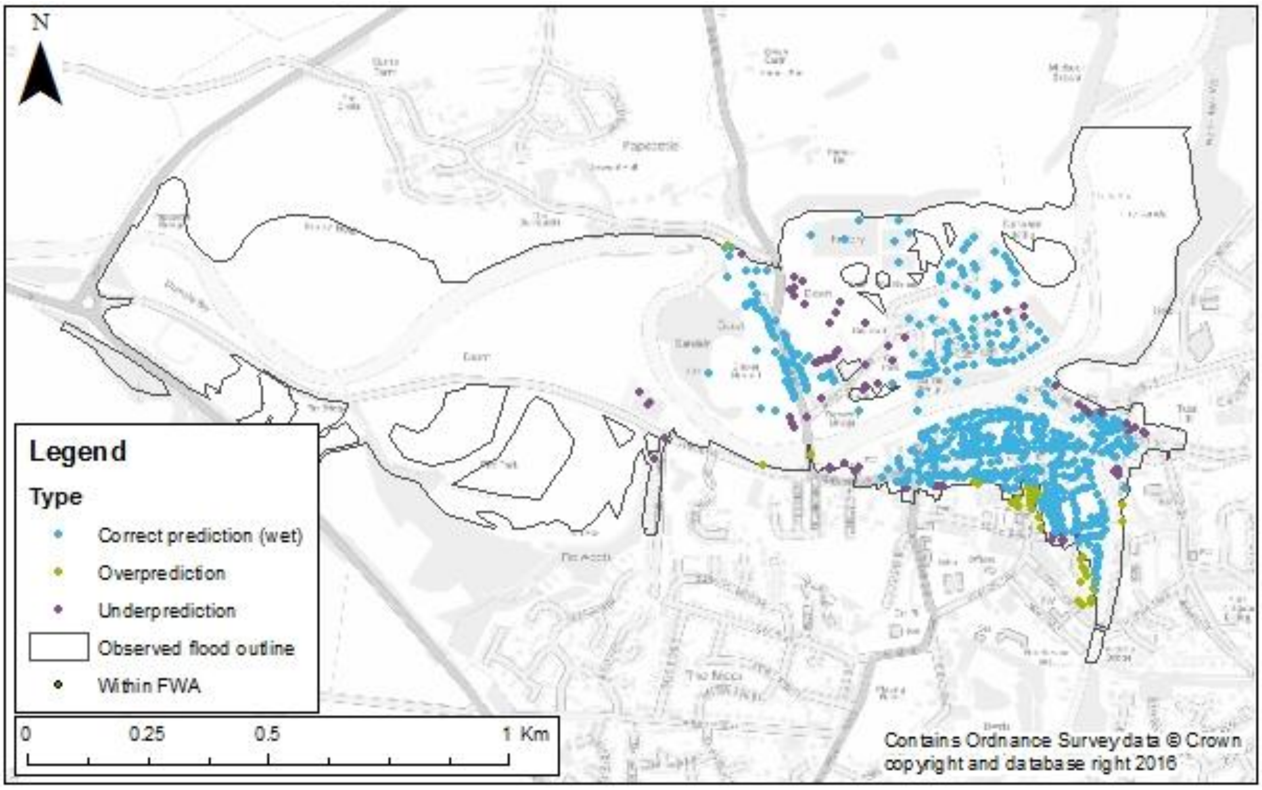


Figure 4.24 Model performance in predicting extent of flooding at Cockermouth: flow inputs

4.3.6 Depth analysis (Test C)

Flooded depths

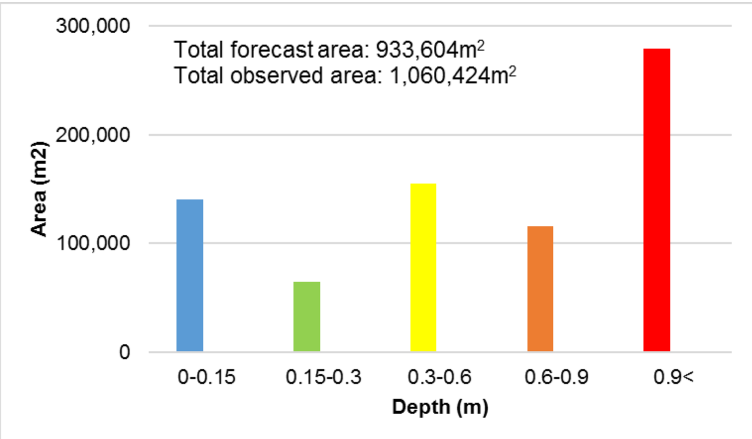


Figure 4.25 Distribution of flooded depth at the peak of the flood at 02:15 on 20 September 2009: flow inputs

Notes: Solid bars show modelled depths (from the PoC option); no observed depths are available.
Channel depths are not included in the modelled results and so the observed area would be expected to be greater. Channel area = 178,608m^2
Total areas quoted on each plot include the channel area for both forecast and observed results.

Modelled	Observed	Depth (m)
		0.00–0.15
		0.15–0.30
		0.30–0.60
		0.60–0.90
		>0.90

Interpretation

Observed depth data are not available at Cockermouth and so the depth forecast can only be assessed in terms of model sensibility.

The results for this PoC at Cockermouth are skewed towards the deepest category (>0.90m). This skewed distribution is likely to be more severe if channel depths are taken into account; the channel is not included in the forecast results for this PoC.

The distribution of flood depths does not follow a smooth progression from shallow to deep categories, which at first glance seems counterintuitive. However, the lack of observed data prevents further assessment of this aspect of the results.

It is likely that the lack of real-time hydraulic modelling in this PoC (there is no explicit modelling of flood spreading on the floodplain) contributes to this effect.

4.3.7 G2G simulation

Table 4.16 Details of available G2G data

Simulation data	Start: 18 November 2009 00:00GMT	End: 28 November 2009 23:45GMT
Forecast data	Met Office Global and Regional Ensemble Prediction System (MOGREPS) ensmble rainfall forecast 24km resolution, 24 ensemble members, 3 hour rainfall totals Lead times: 54 hours Note that this is the MOGREPS product that was available at the time of the event. The MOGREPS data available now are a significant improvement (see Section 6).	
Forecast origins available	18 November 2009 11:00 to 25 November 2009 23:00, at 12 hourly intervals A total of 16 sets of ensemble forecasts were produced.	
Forecast origins tested	19 November 2009 11:00 (results displayed) 19 November 2009 23:00	
Ensembles tested	Ensemble members were ranked by peak flow at the grid square corresponding to the main river model inflow on the River Derwent (G2G 1km cell centroid 313500, 532500). The ensemble members that gave the 5th percentile, median and 95th percentile were tested.	

Comparison of G2G simulated and observed flows on the River Derwent

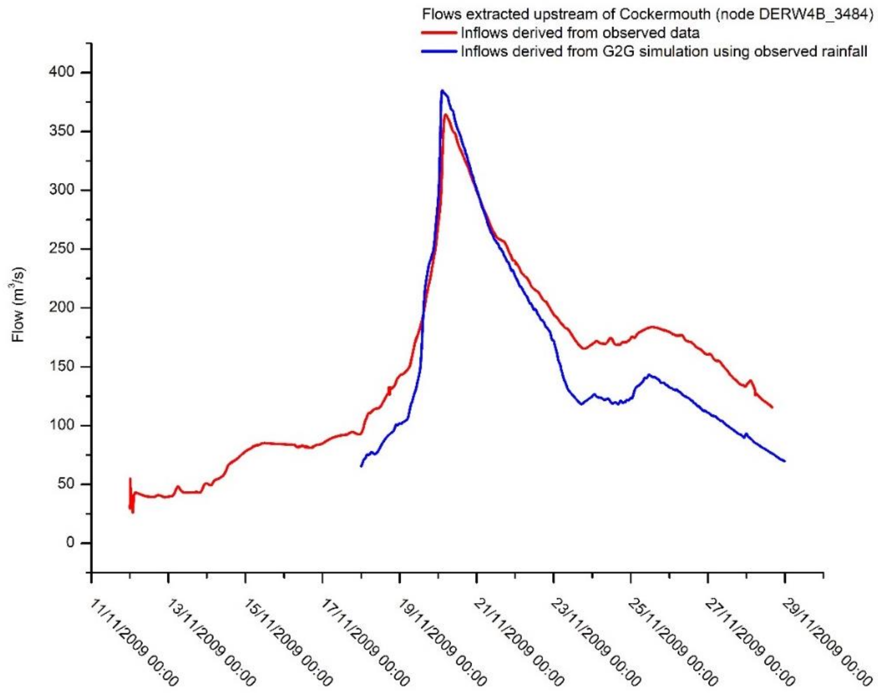


Figure 4.26 River Derwent hydrograph

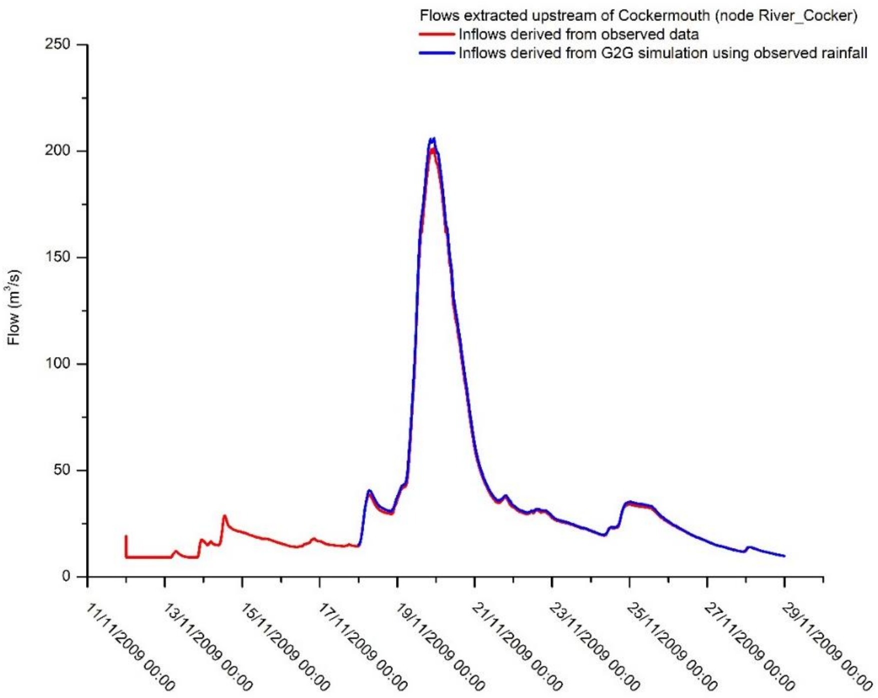


Figure 4.27 River Cocker hydrograph

The hydrographs show flows on the Derwent at a model node approximately 2.75km upstream of the extent of the observed outline (model node: DERW4B_3484).

The start date of the G2G simulated data provided is midnight on 18 November 2009. However, this is well before the peak of the event and there is no flooding at this time. Starting the model run later in the event therefore has minimal impact on predicted flood extents. The start date of the observed time series data is midnight on 12 November 2009.

Flood extent – maximum observed and maximum G2G

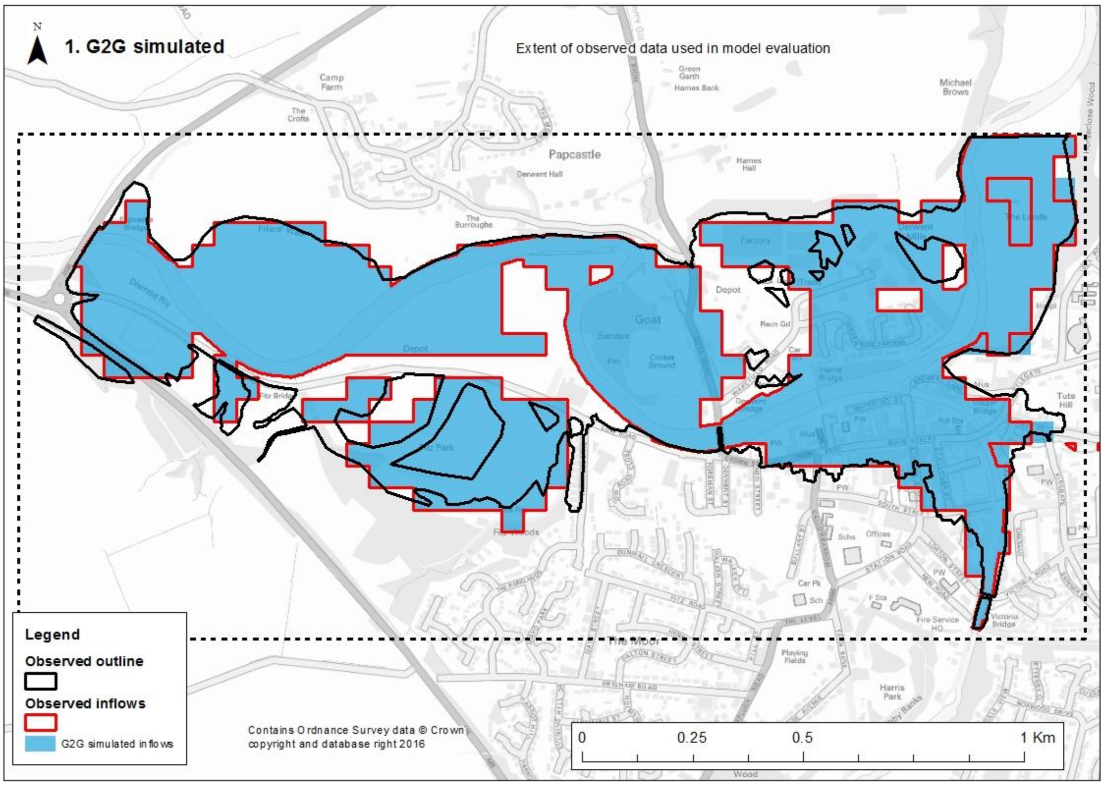


Figure 4.28 Observed and G2G simulated maximum flood extent for Cockermouth event: flow inputs

The hydrographs show that simulated flows from G2G (fed with observed rainfall) are very similar to observed flows at the upstream model boundary. Volume under the G2G simulated hydrograph is also comparable. Consquently, the modelled flood extent is similar.

Extents modelled from both G2G simulated and observed flows match well with the maximum observed outline in most areas, although there are dry islands within the maximum flood extent. There is very little change betwen the observed inflows model extent,and the G2G simulated model extent.

G2G ensemble members

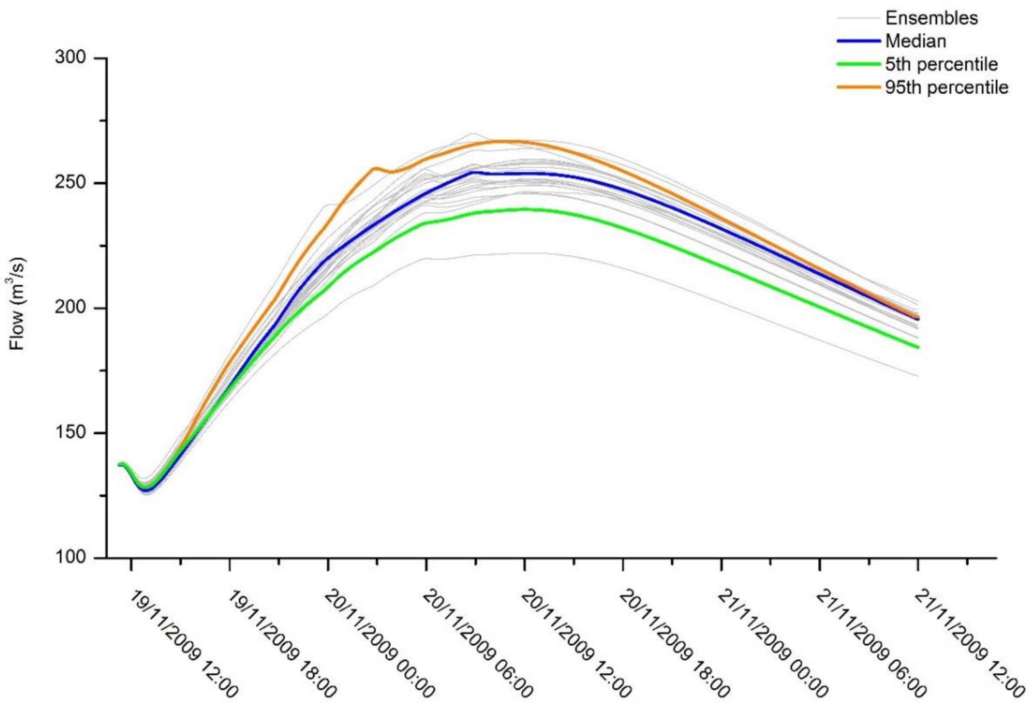


Figure 4.29 River Derwent inflows to PoC

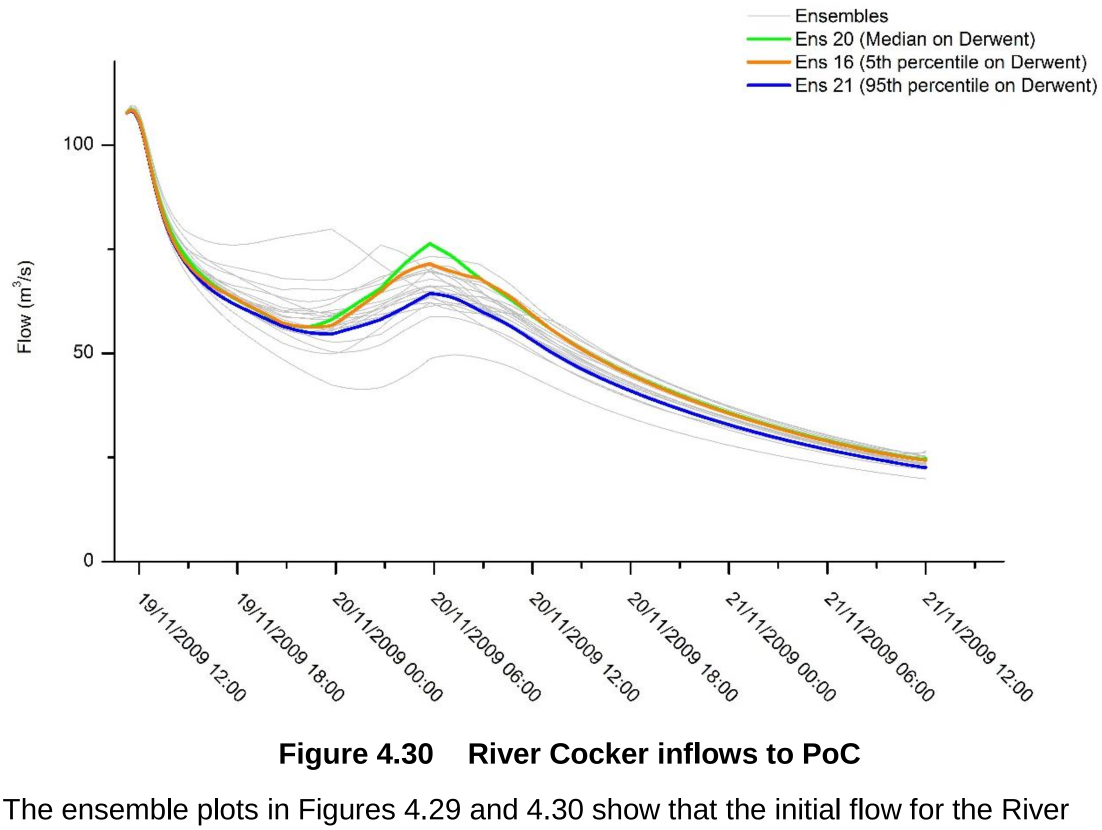


Figure 4.30 River Cocker inflows to PoC

The ensemble plots in Figures 4.29 and 4.30 show that the initial flow for the River Cocker is greater than the peak later in the run. Although initial flows on the River Cocker are high, flows on the River Derwent are consistently greater and it is still the River Derwent that drives flood risk through Cockermouth in this event.

Flood extent – maximum

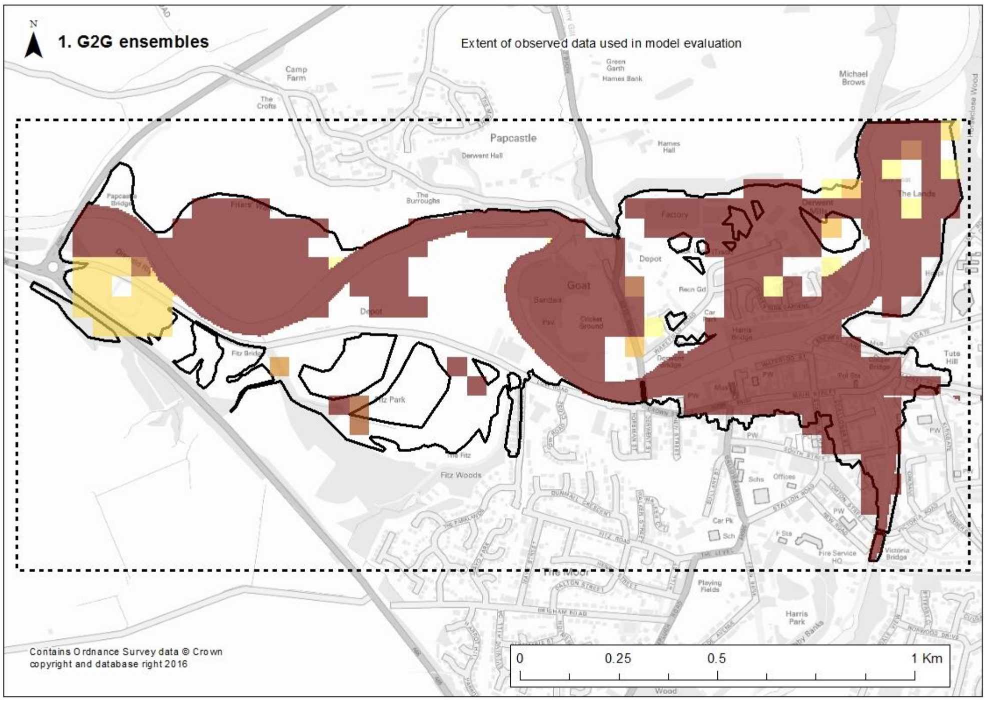


Figure 4.31 Maximum observed and maximum G2G simulation of flood extent for Cockermouth event: flow inputs

Notes: The map shows the maximum observed outline (black outline) against the maximum extent of all ensemble G2G runs (yellow-brown shading). G2G results are trimmed to the extent of observed data.
Darker colours on the map show where flood outlines from a greater number of runs coincide, while the lighter colours show areas predicted to flood by fewer ensemble members.

Property counts – maximum

The number of properties in the observed flood extent is 1,036.

In this case, the model underpredicts flood extent in some areas. The final row of Table 4.17 shows the number of properties within the observed outline that appear in none of the ensemble members.

Table 4.17 Number of NRD property points within the flood outlines for Cockermouth event: flow inputs

Flood outlines	Number of properties[1]	Cumulative property count[2]	Notes
21–24 × ensemble overlap	1,024	1,024	Area shown as flooded in all tested ensemble members
17–20 × ensemble overlap	1	1,025	–
13–16 × ensemble overlap	0	1,025	–
9–12 × ensemble overlap	4	1,029	–
5–8 × ensemble overlap	3	1,032	–

Flood outlines	Number of properties[1]	Cumulative property count[2]	Notes
1–4 × ensemble overlap	11	1,043	–
Within observed outline but not forecast	205	–	Area not shown as flooded in any tested ensemble member

Notes: [1] This column shows the number of properties within each separate zone of the modelled outlines, ordered from the area where all ensembles coincide, to properties that appear in one ensemble member only.
[2] This column lists the cumulative number of properties within the modelled outlines, ordered by areas predicted to flood in the most ensemble members to the least ensemble members. For example, at this lead time, 5 properties are within the outlines of the largest number of ensembles, 963 properties are within the outline given by the least number of ensemble members.

4.4 Case study 2: Cockermouth, November 2009 – level inputs

4.4.1 Location

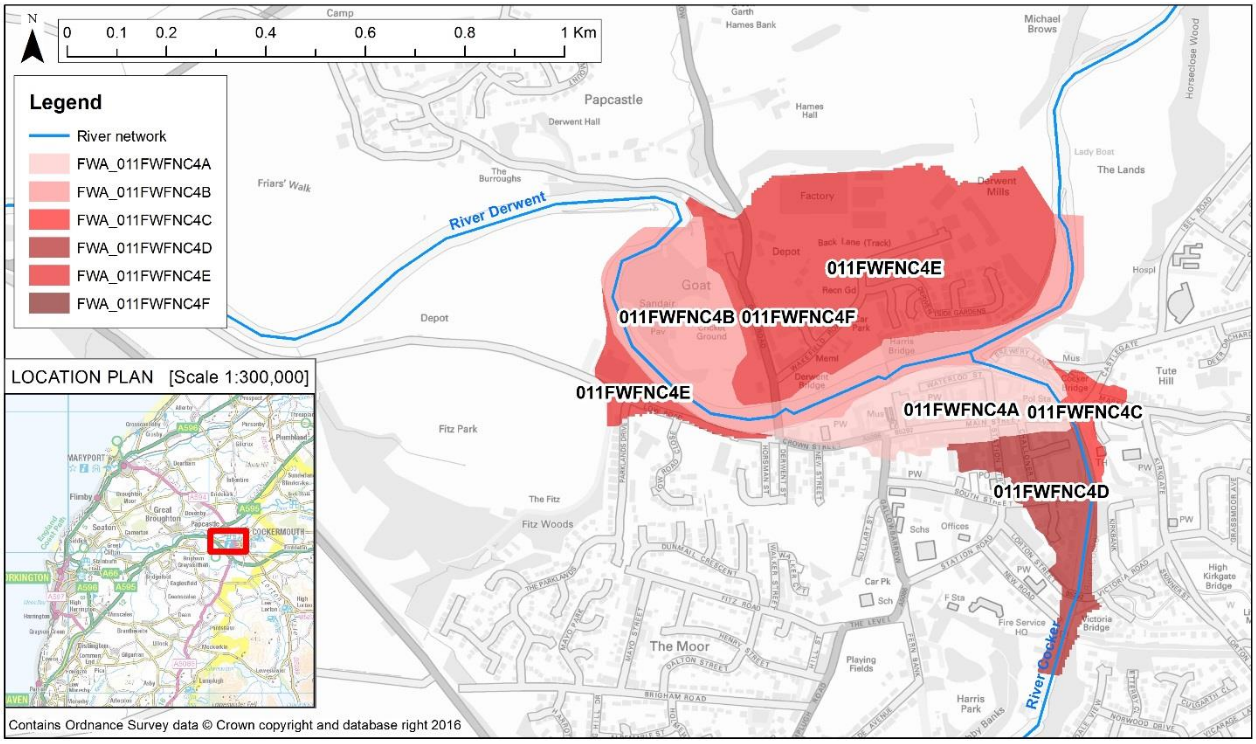


Figure 4.32 Location map for Cockermouth case study

Table 4.18 Description of Flood Warning Areas featured in the Cockermouth case study

Flood Warning Target Area Code	Name
011FWFNC4A	Rivers Cocker and Derwent at Cockermouth, Bridge Street, Crown Street, High Sand Lane and Main Street
011FWFNC4B	Rivers Cocker and Derwent at Cockermouth, Cricket Ground and Trout Hotel Car Park
011FWFNC4C	River Cocker at Cockermouth, The Old Courthouse and Market Place Area
011FWFNC4D	River Cocker at Cockermouth, Challoner Street, Croft Terrace, Jubilee Court and Rubbybanks Road
011FWFNC4E	River Derwent at Cockermouth, Gote Road to Derwent Mills Area and Low Road
011FWFNC4F	Cockermouth Gote Road and St Leonards

4.4.2 Model outputs

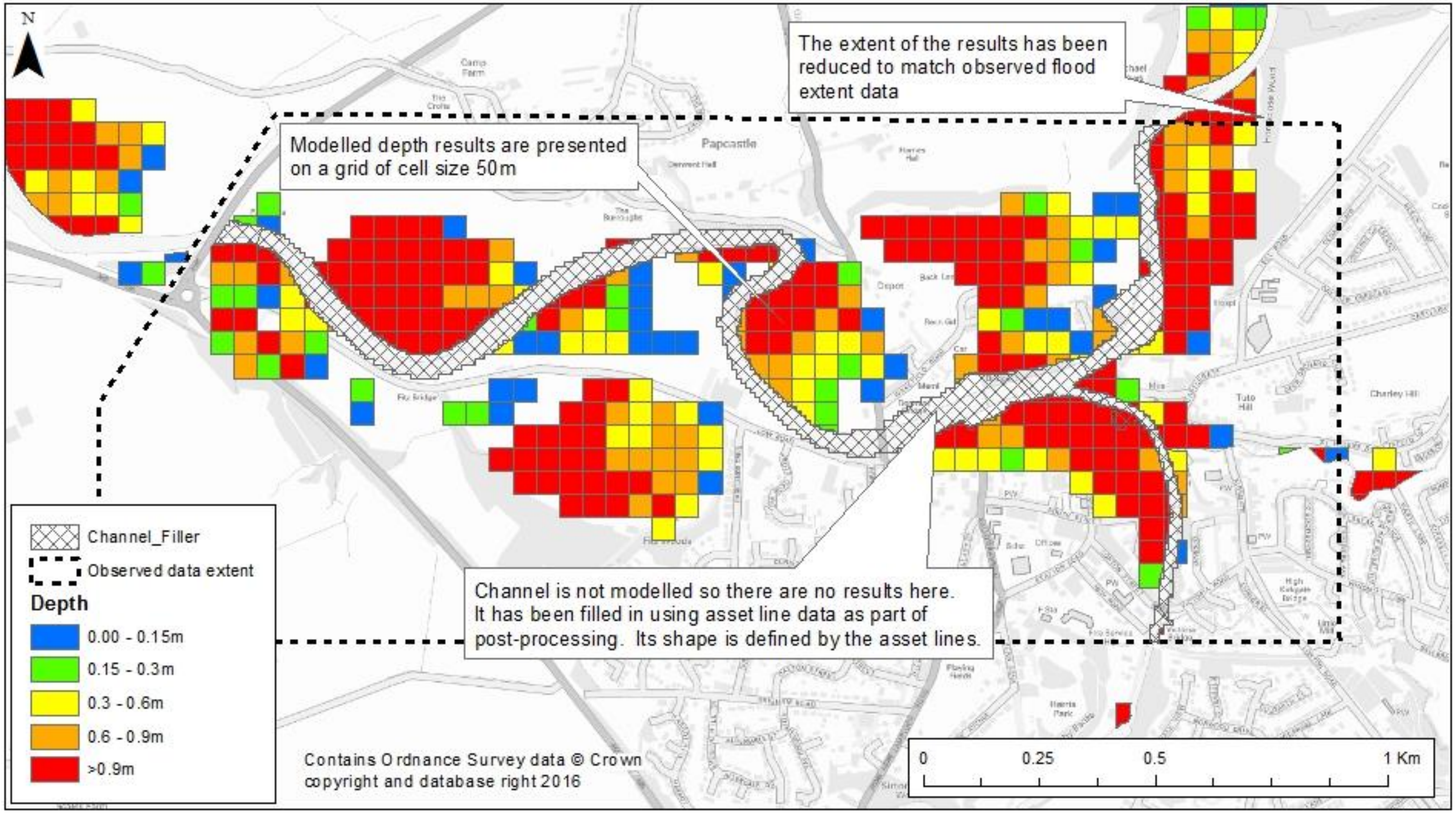


Figure 4.33 Model outputs for Cockermouth event: level inputs

4.4.3 Extent flooded (Test A1)

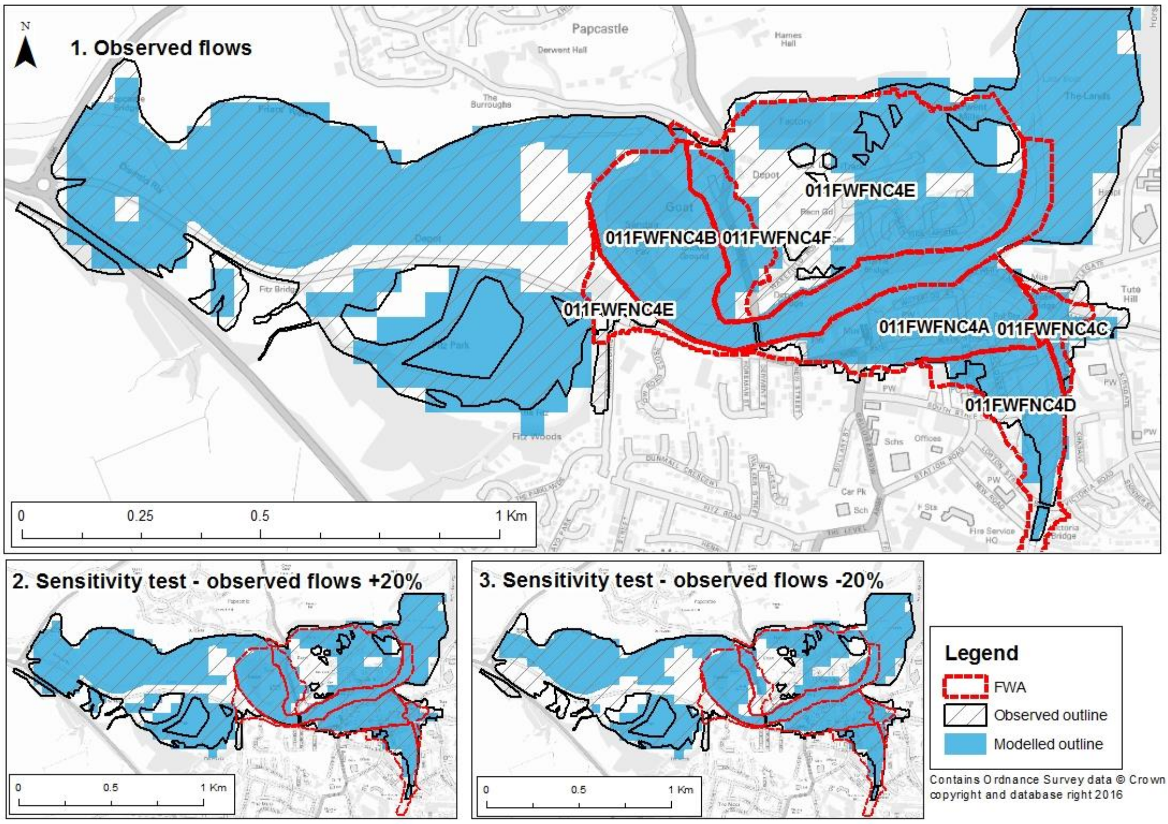


Figure 4.34 Maximum modelled and observed extent flooded: level inputs

Table 4.19 Comparison of modelled and observed area flooded for each Flood Warning Area for Cockermouth event: level inputs

Flood Warning Area (FWA)	Area (m^2)	Area flooded			
		Modelled		Observed	
		m^2	% of FWA	m^2	% of FWA
All	560,039	438,758	78.3	508,774	90.9
011FWFNC4A	73,728	67,874	92.1	70,731	95.9
011FWFNC4B	134,289	132,685	98.8	133,541	99.4
011FWFNC4C	13,362	11,086	83.0	12,788	95.7
011FWFNC4D	57,177	42,159	73.7	37,810	66.1
011FWFNC4E	252,013	158,462	62.9	224,436	89.1
011FWFNC4F	29,469	26,492	89.9	29,469	100.0

Notes: For the purposes of comparison, the areas of the Flood Warning Areas have been trimmed to the extent of the available observed data.

Interpretation

The simulation library output consists of 50m resolution grid cells. There are some cells of irregular size and shape at the boundaries of the channel, where they have been trimmed by the asset lines. Another feature of the results is the tributaries; at Cockermouth, the forecast outline includes a tributary at the eastern end of the tested area, but the flooding here is not significant to the results.

The flood outline is accurate in terms of the extent of flooding, although there are areas of underprediction on parts of the floodplain. The accuracy of the model is comparable to the flows input modelling.

This option is sensitive to a ±20% change in inflow, as was the case in the flows input modelling. However, the accuracy of the overall model outline is not affected; the changes in flood extent are within the areas (or dry islands) of underprediction on the floodplain.

4.4.4 Model performance (Test A2)

Model performance scores were derived by comparison of modelled and observed flood outlines. Percentages were calculated as follows.

- Correct wet: proportion of flood extent that is correctly predicted by the model. Modelled extent = observed extent (blue)
- Overprediction: proportion of flood extent that is overpredicted by the model. Modelled extent > observed extent (green)
- Underprediction: proportion of flood extent that is underpredicted by the model. Modelled extent < observed extent (purple)

Skill and bias scores were calculated using the equations given below. ‘Correct dry’ areas are never included in the scores, as this is heavily dependent on the extent of the model domain.

$$SKILL = \frac{Correct\ Wet}{Correct\ Wet + Overprediction + Underprediction}$$

$$BIAS = \frac{Correct\ Wet + Overprediction}{Correct\ Wet + Underprediction}$$

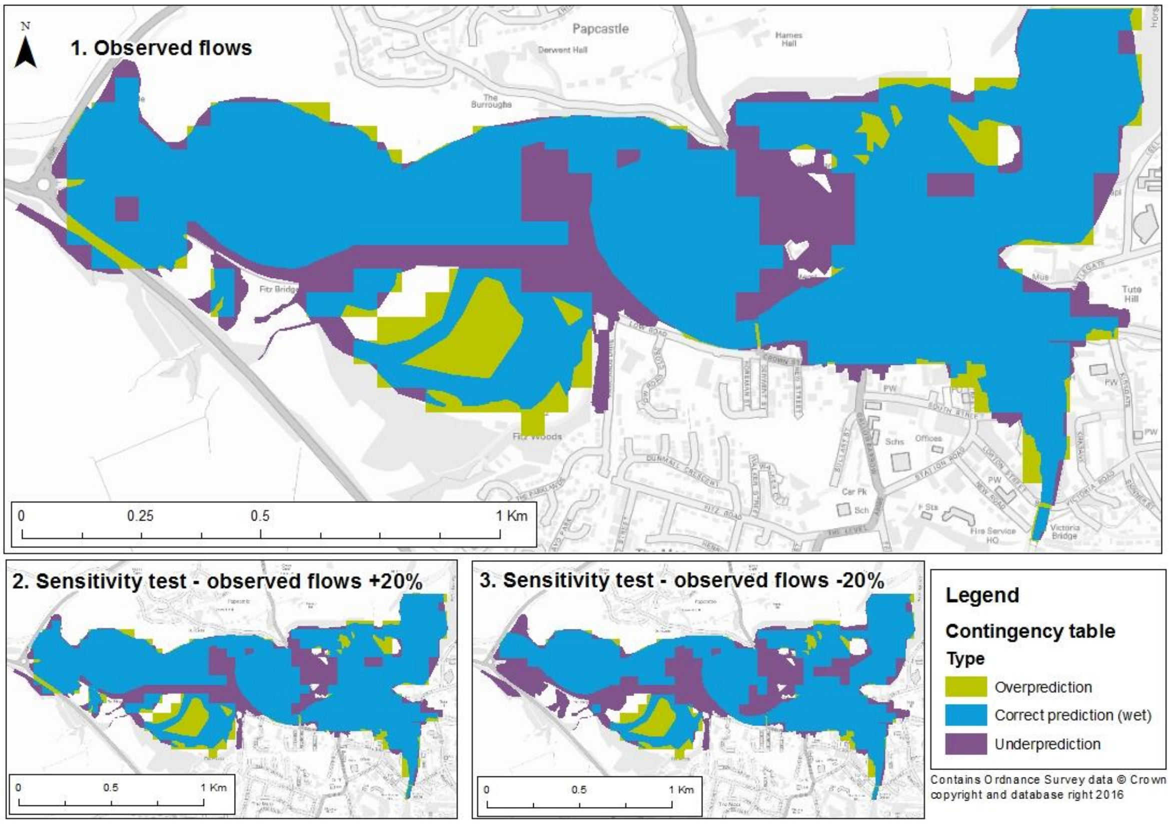


Figure 4.35 Model performance in predicting flooded extent at Cockermouth: level inputs

Table 4.20 Model performance metrics for Cockermouth event: level inputs

Flood Warning Area	Correct wet (%)	Over-prediction (%)	Under-prediction (%)	Skill	Bias
Modelled outline (all)	**73.4**	**8.3**	**18.3**	**0.73**	**0.89**
Modelled outline (within area covered by Flood Warning Areas only)					
011FWFNC4A	95.5	0.2	4.3	0.96	0.96
011FWFNC4B	98.4	0.5	1.1	0.98	0.99
011FWFNC4C	80.5	3.3	16.2	0.81	0.87
011FWFNC4D	78.4	15.6	5.9	0.78	1.12
011FWFNC4E	62.0	5.1	33.0	0.62	0.71
011FWFNC4F	89.9	0.0	10.1	0.90	0.90

Notes: Metrics are reported for the full modelled flood outline first. Subsequent rows of the table report the metrics for the model flood outline within given Flood Warning Areas. This distinguishes between performance across the full model domain and performance in locations where there is known to be flood risk to property.

Interpretation

There is a large proportion of correct prediction in the model results at Cockermouth (73% of total modelled outline). The results are very similar to the flows input results, and they demonstrate some of the same features (see below).

The coarse results grid and the lack of explicit modelling of overland flow in the modelling method are demonstrated in the model results, by the following features.

- The observed outline at Cockermouth includes areas such as the braided floodplain flow to the south of the main floodplain. The 50m model output is not able to predict this, resulting in an area of overprediction.
- At the western end of the flood extent, a road cuts off the floodplain but some flood spreading is observed due to a culvert in the embankment. This floodplain flow is not explicitly modelled in this option, resulting in underprediction here.

4.4.5 Property counts (Test B)

Properties within flood extent

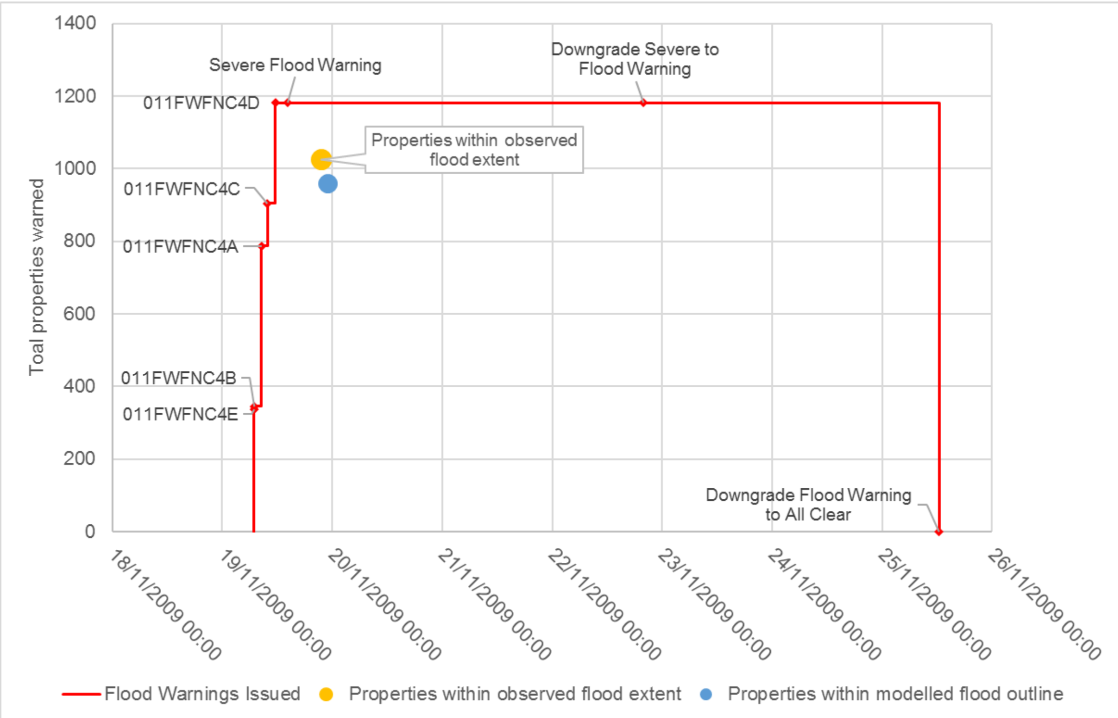


Figure 4.36 Properties within flood extent for Cockermouth event: level inputs

Notes: Properties are mapped below.

Table 4.21 Maximum number of flooded properties for Cockermouth event: level inputs

Flood Warning Area	Properties warned[1]	Observed[2]	Predicted[3]
All	1,180	1,036	961
011FWFNC4A	442	415	392
011FWFNC4B	9	7	9
011FWFNC4C	117	116	103
011FWFNC4D	278	189	236
011FWFNC4E	336	309	221
011FWFNC4F	119	119	72

Notes: [1] Properties warned: counts of properties within each Flood Warning Area that received a flood warning during the event.
[2] Observed is based on the intersection of NRD property points and observed flood outline.
[3] Predicted is based on the intersection of NRD property points with maximum modelled flood outline.
Flood Warning Area F is nested within Flood Warning Area E.

Interpretation

The number of properties within the modelled flood outline is accurate; results are within 10.0% of the number of properties within the observed extent. The number is consistent with the number of properties within the flood outline, when using flow inputs to drive the PoC (see Section 4.3.5).

The final property count (961 properties within Flood Warning Area) is the result of some areas of overprediction and some areas of underprediction. These are shown in Figure 4.37.

This PoC produces a maximum flood outline only and therefore time-stepped results are not available for comparison against the observed property counts.

Properties mapped by model prediction

Figure 4.37 shows NRD property points, colour-coded according to whether the model overpredicts, underpredicts or correctly predicts the observed flood outline. Only properties within the existing Flood Warning Area are considered.

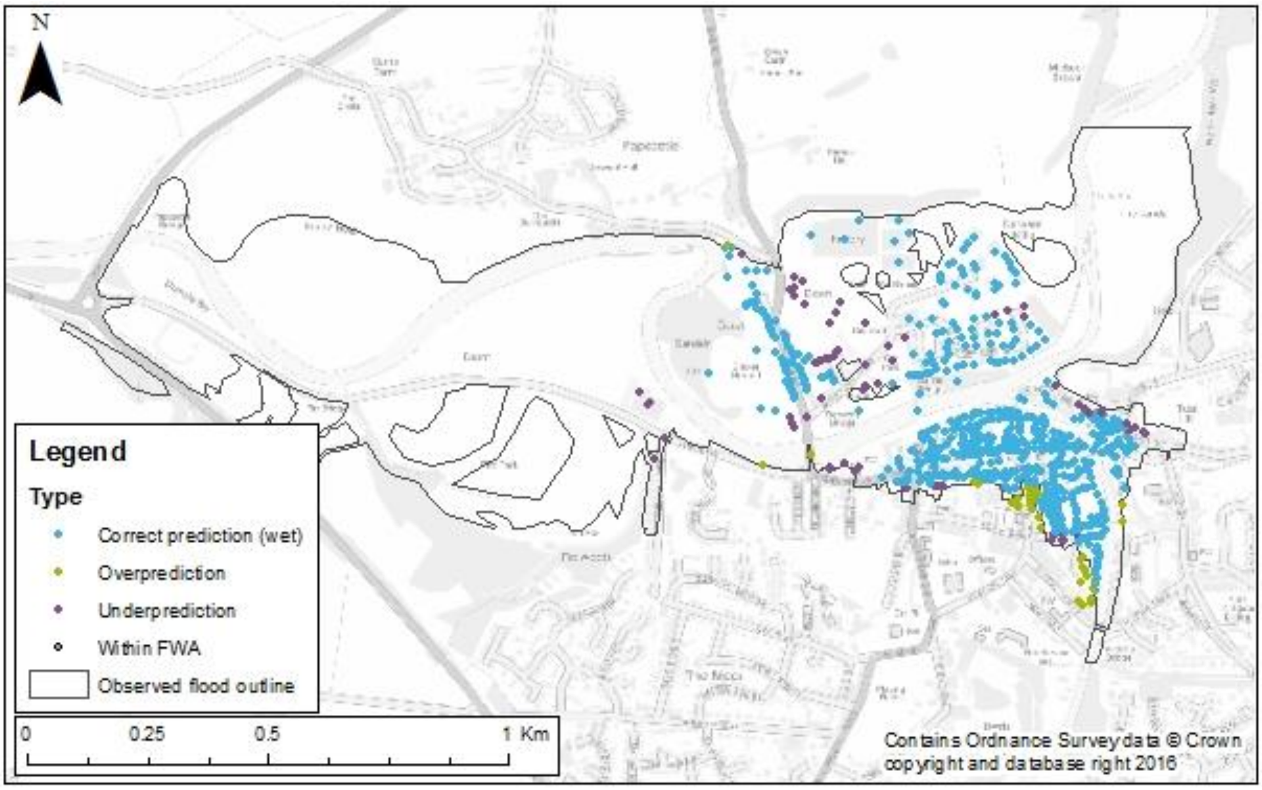


Figure 4.37 Model performance in predicting extent of flooding at Cockermouth: level inputs

4.4.6 Depth analysis (Test C)

Flooded depths

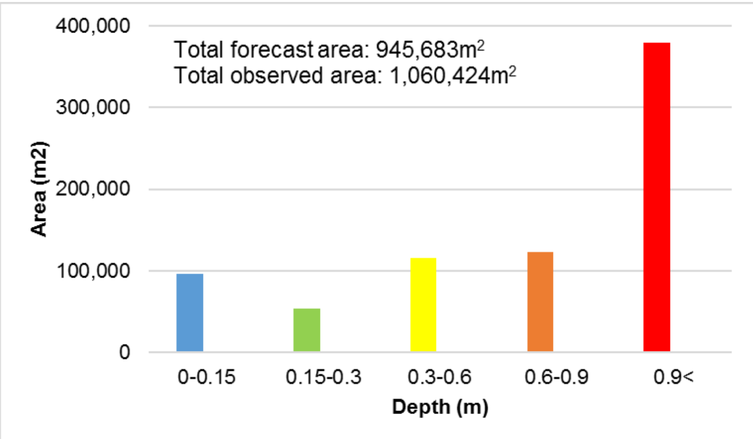


Figure 4.38 Distribution of flooded depth at the peak of the flood at 02:15 on 20 September 2009: level inputs

Notes: Solid bars show modelled depths (from the PoC option); no observed depths are available.
Channel depths are not included in the modelled results and so the observed area would be expected to be greater. Channel area = 178,608m^2
Total areas quoted on each plot include the channel area for both forecast and observed results.

Modelled	Observed	Depth (m)

		0.00–0.15
		0.15–0.30
		0.30–0.60
		0.60–0.90
		>0.90

Interpretation

Observed depth data are not available at Cockermouth and so the depth forecast can only be assessed in terms of model sensibility.

The results for this PoC at Cockermouth are skewed towards the deepest category (>0.90m). This skewed distribution is likely to be more severe if channel depths are taken into account; the channel is not included in the forecast results for this PoC.

In contrast to the flow inputs results, the distribution of flood depths progresses more smoothly from one category to the next, although there is a significant proportion of the shallowest depths (<0.15m).

The flow inputs and level inputs forecasts cannot be compared due to the lack of observed depth data at Cockermouth.

4.5 Case study 3: Thames, February 2014 – flow inputs

4.5.1 Location

The location map in Appendix 6b shows the entire Thames reach considered for analysis in this study.

Inputs to the simplified fluvial model were provided by a detailed 1D–2D hydrodynamic model. The 1D–2D model is fully documented in Appendix 4, the PoC pro-forma for fully dynamic fluvial modelling. At the time of this study, however, the model was in an interim stage of development; in particular, results from the 1D–2D model were only available to the peak of the event and the assessment in this study therefore compares the latest available model outputs with the closest available observed outline (after the peak). Figure 4.39 shows the modelled and observed outlines in relation to the flow hydrograph, recorded at the Walton gauge, towards the downstream extent of the model domain.

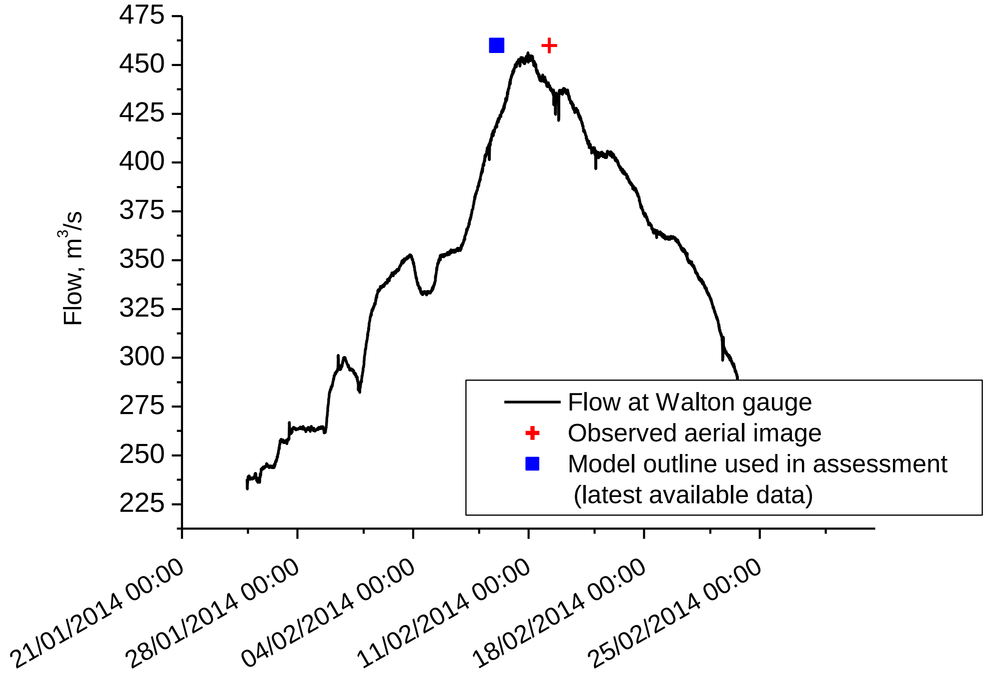


Figure 4.39 Observed flow hydrograph at the Walton gauge

In addition, sensitivity tests (increasing and decreasing model inflows by 20%) were not available within the time constraints of the project.

Although the full extent of model outputs was analysed, for consistency with other PoCs, the pro-forma presents detailed findings from 4 selected insets (highlighted in red in Figure 4.40). These were chosen according to availability of observed and modelled data, and the high concentration of receptors.

Table 4.22 Description of Flood Warning Areas featured in the Thames case study

Flood Warning Target Area Code	JBA code[1]	Name
061FWF23BrneEnd	101	River Thames at Bourne End
061FWF23Chertsey	102	River Thames at Chertsey
061FWF23Cookham	103	River Thames at Cookham
061FWF23Datchet	104	River Thames at Datchet
061FWF23HammCrt	105	River Thames at Hamm Court
061FWF23Horton	106	River Thames at Horton
061FWF23Laleham	107	River Thames at Laleham
061FWF23LHalifrd	108	River Thames at Shepperton and Lower Halliford
061FWF23Mdnhead	109	River Thames at Maidenhead to Windsor and Eton
061FWF23OldWndsr	110	River Thames at Old Windsor
061FWF23ShepGrn	111	River Thames at Shepperton Green
061FWF23Staines	112	River Thames at Staines and Egham
061FWF23Sunbury	113	River Thames at Sunbury
061FWF23Walton	114	River Thames at Walton
061FWF23Wraysbry	115	River Thames at Wraysbury
061FWF23XDatcht	116	Properties closest to the River Thames at Datchet, between Black Potts Bridge and Albert Bridge
061FWF23XLHalif	117	Properties closest to the River Thames from Shepperton Lock to Beasley's Ait
061FWF23XMhead	118	Moorings and properties closest to the River Thames between Maidenhead, Windsor and Eton
061FWF23XOldWnd	119	Properties closest to the River Thames at Old Windsor, from Friday Island to Magna Carta Island
061FWF23XShepG	120	Properties closest to the River Thames between Littleton Lane (Shepperton Green) and Shepperton Lock
061FWF23XStaines	121	Properties closest to the River Thames between Runnymede Pleasure Grounds, Staines and Penton Hook
061FWF23XWrysbry	122	Properties closest to the River Thames at Wraysbury from Old Windsor Weir to Magna Carta Island
061FWF26Binghams	123	Cut at the Binghams
061FWF29Addstne	124	Addlestone Bourne at Addlestone
061FWF29Chertsey	125	Chertsey Bourne at Chertsey

Flood Warning Target Area Code	JBA code[1]	Name
061FWF29ThorpGrn	126	Chertsey Bourne at Thorpe Green
061FWF29XAddstne	127	Properties closest to the Addlestone Bourne at Addlestone
061FWF29XChrtsy	128	Areas of Chertsey closest to the Chertsey Bourne
062FWF28Colnbrk	129	Colne Brook at Colnbrook
062FWF28WDrayton	130	River Colne and Frays River at West Drayton and Stanwell Moor
062FWF31Ashford	131	River Ash at Ashford and Staines
061FWF23Marlow	132	River Thames at Bisham village and Marlow town
061FWF23XMarlow	133	Properties closest to the River Thames from All Saints Church, Bisham to Little Marlow
061FWF23Hurley	134	River Thames at Hurley and Harleyford
061FWF23XSunbry	135	Properties closest to the River Thames at Sunbury
061FWF30Weybrdge	136	River Wey at Weybridge
061FWF23HenMed	137	River Thames for Henley, Remenham and Medmenham

Notes: [1] Due to the size of the reach being analysed, a short three-digit code was assigned by JBA Consulting to all Flood Warning Areas to aid interpretation in later figures.

4.5.2 Context for model outputs

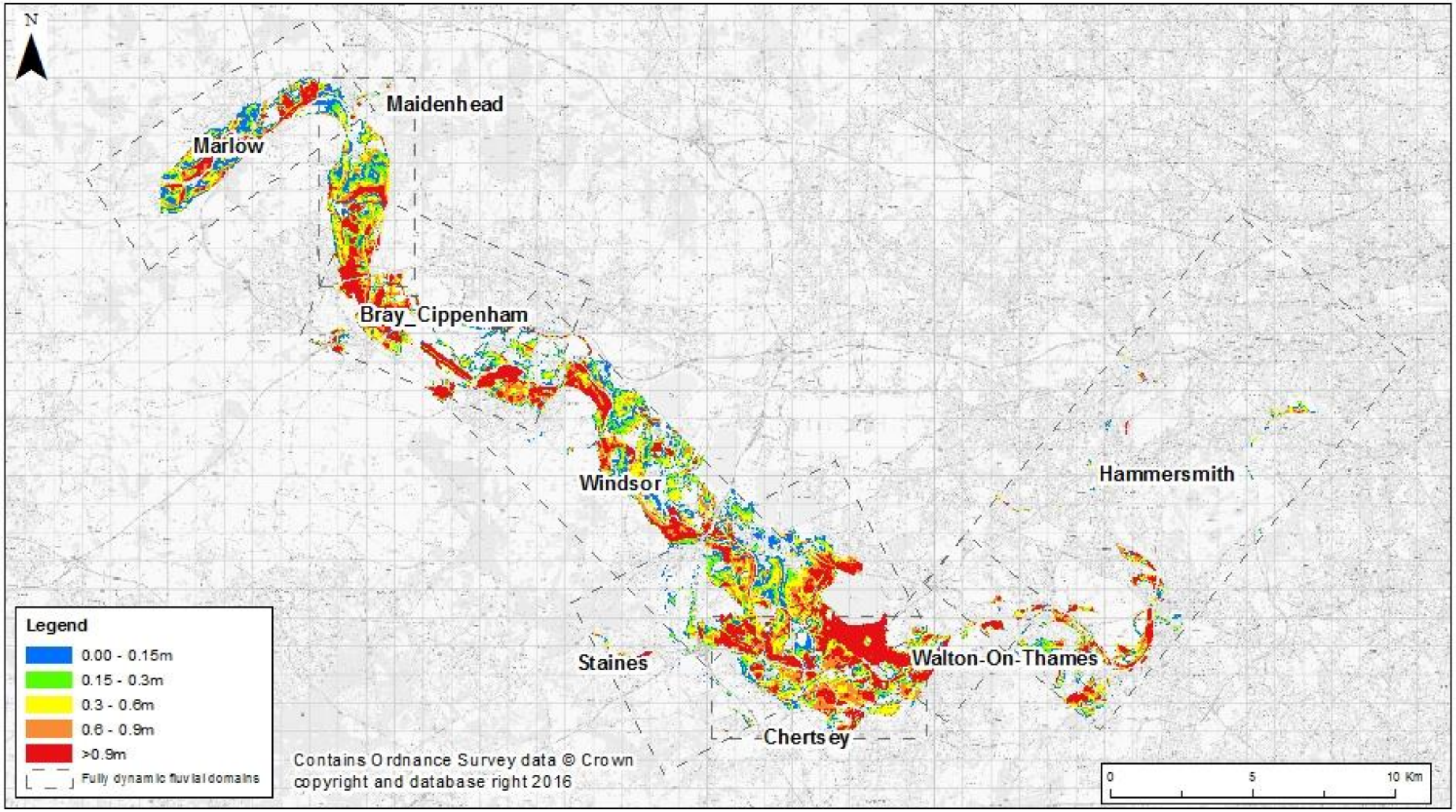


Figure 4.41 Context for model outputs for Thames case study: flow inputs

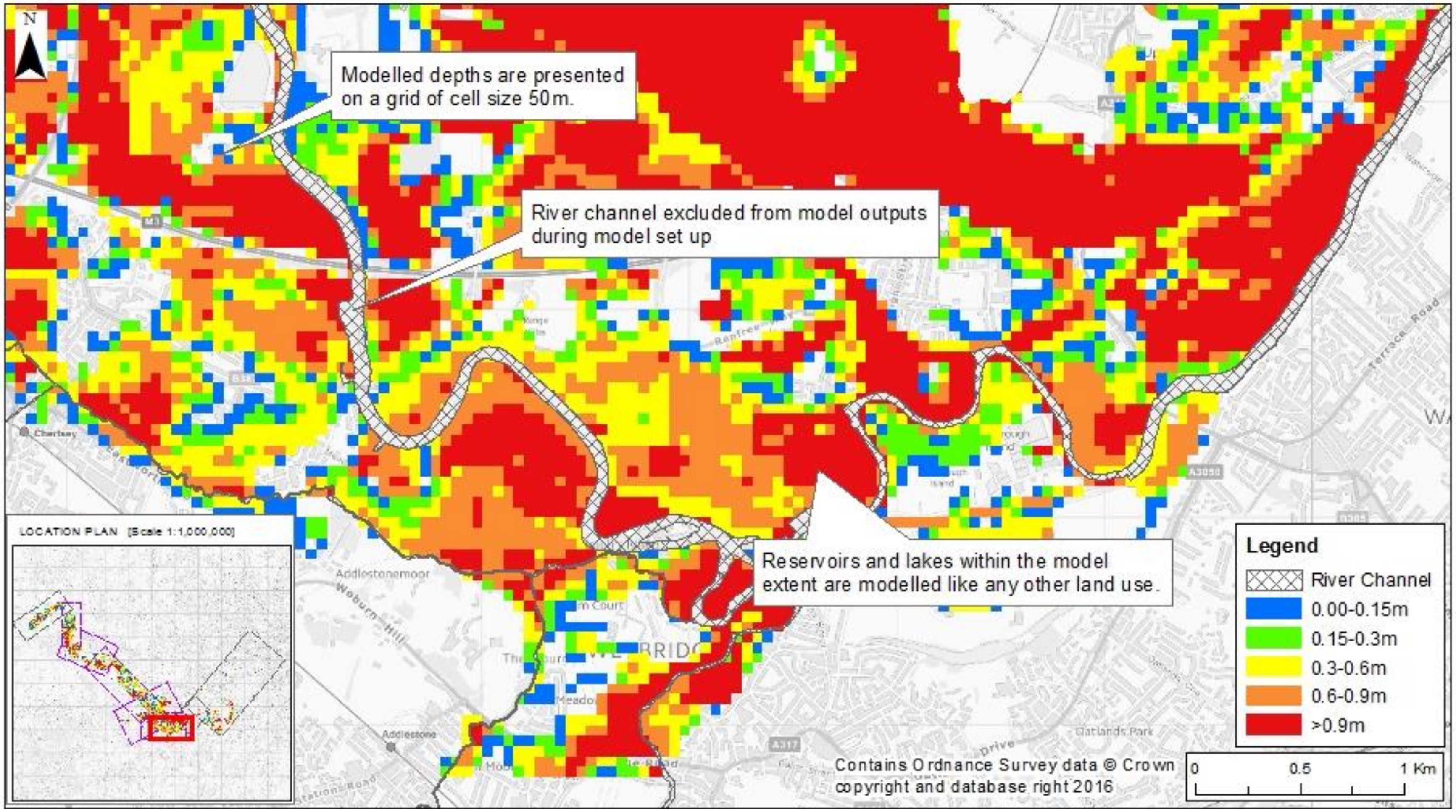


Figure 4.42 Context for model outputs in Chertsey domain: flow inputs

4.5.3 Extent flooded (Test A1)

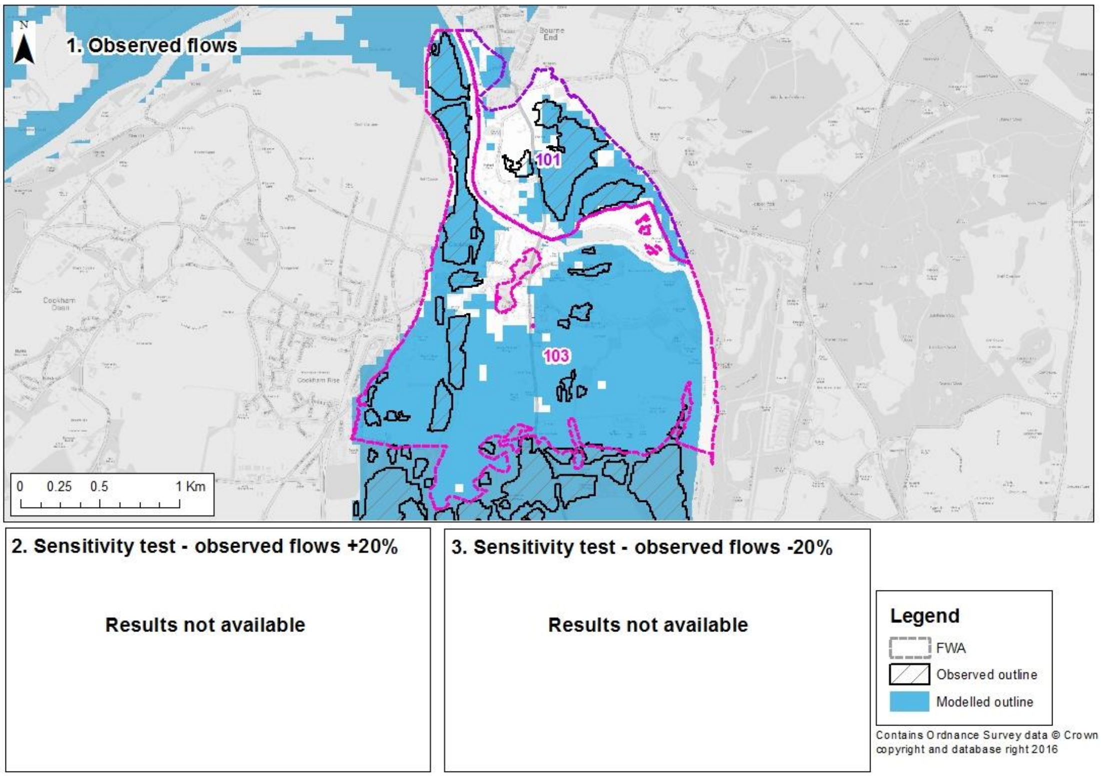


Figure 4.43 Maximum modelled and observed extent flooded for Maidenhead domain (inset 1): flow inputs

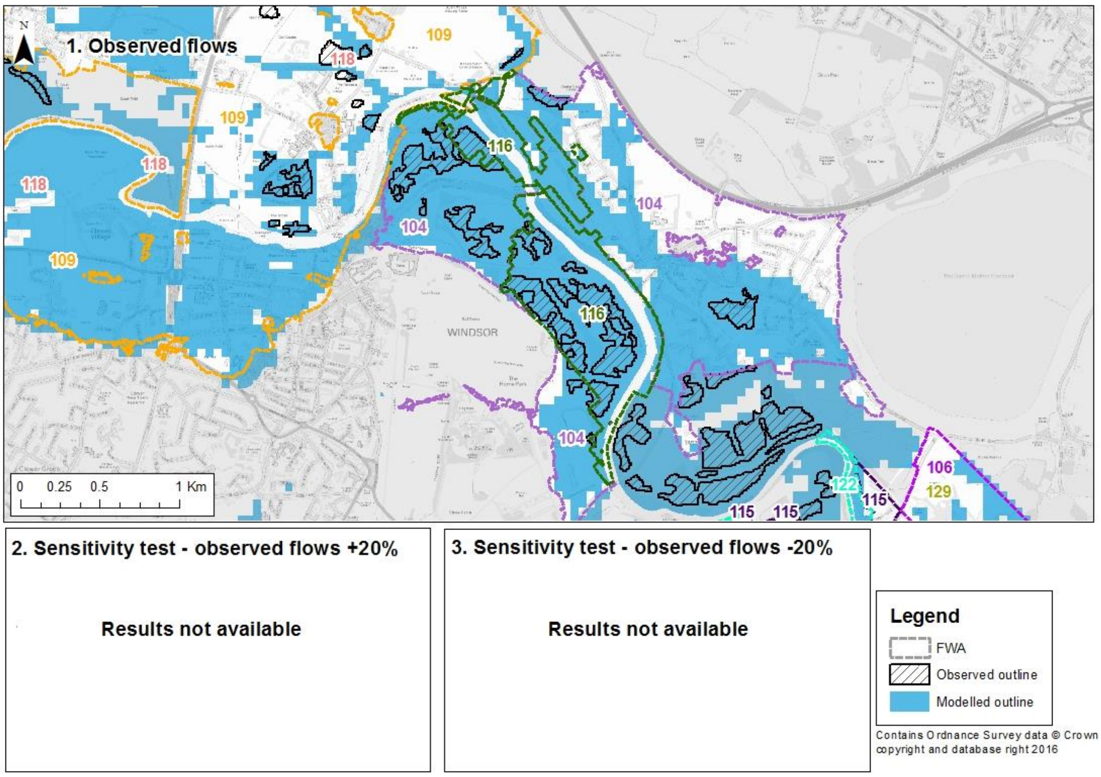


Figure 4.44 Maximum modelled and observed extent flooded for Bray, Cippenham and Windsor domains (inset 2): flow inputs

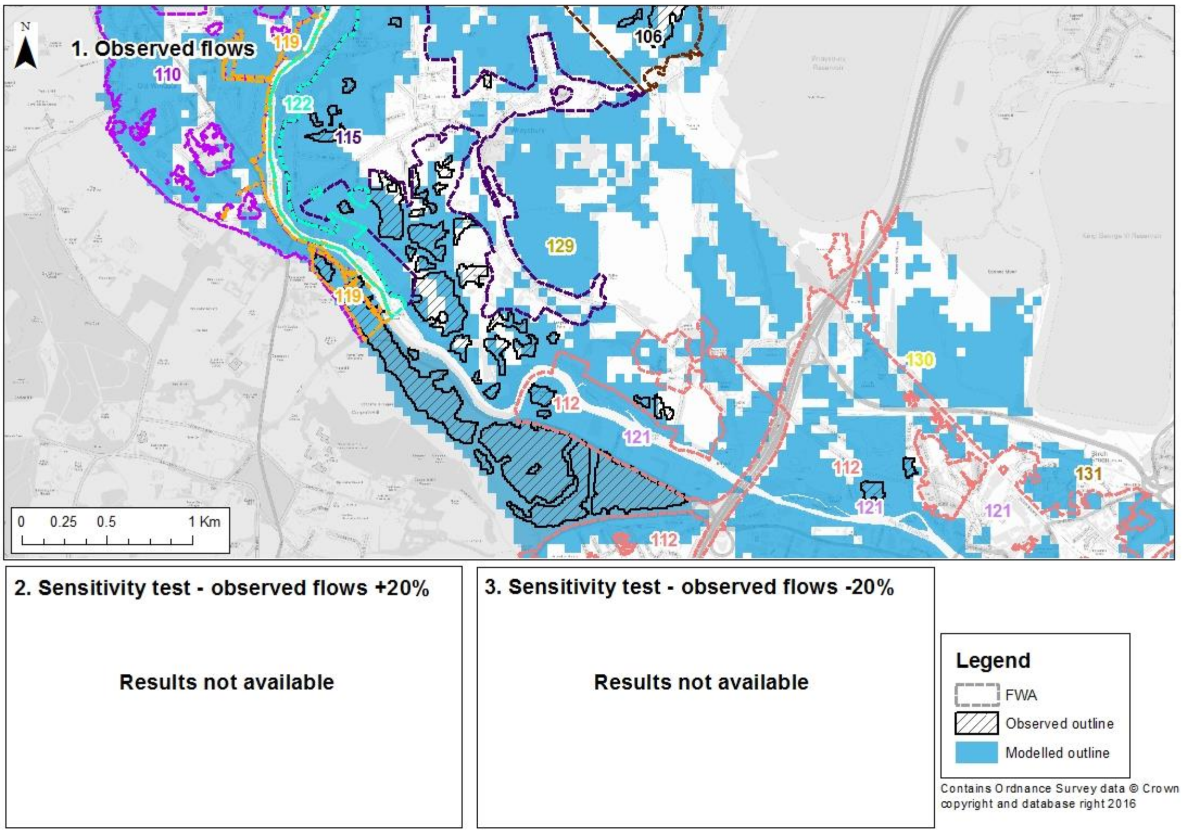


Figure 4.45 Maximum modelled and observed extent flooded for Windsor and Staines domains (inset 3): flow inputs

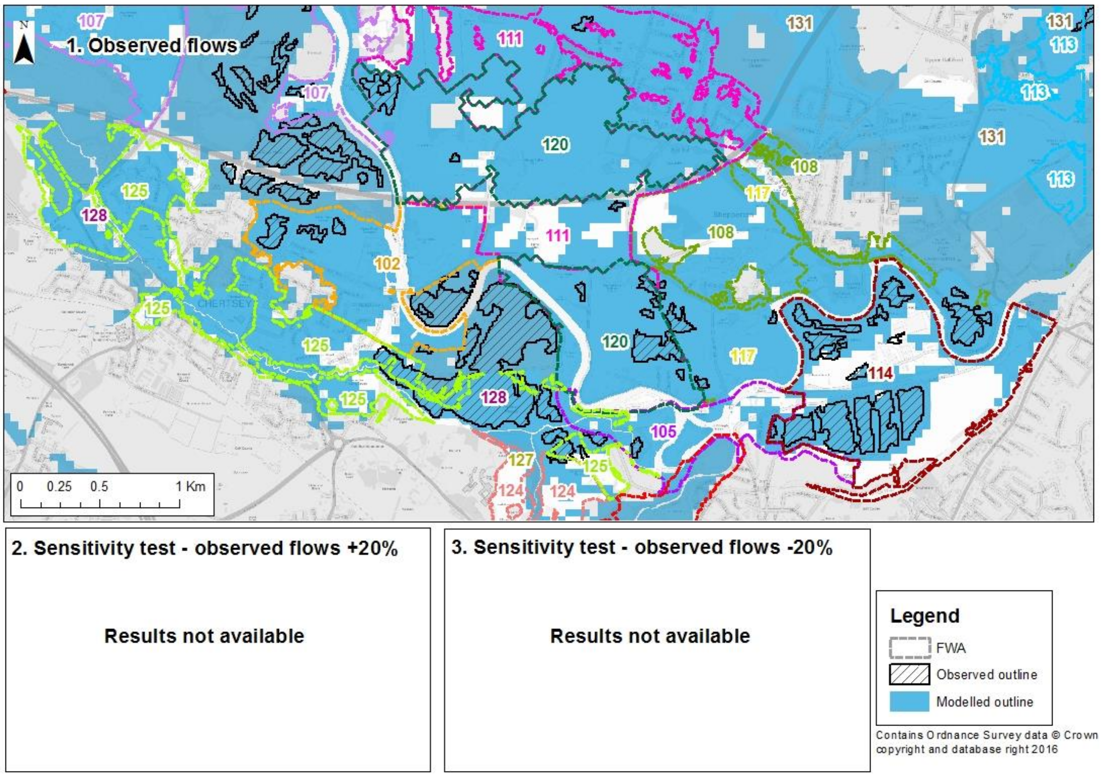


Figure 4.46 Maximum modelled and observed extent flooded for Staines and Chertsey domains (inset 4): flow inputs

Table 4.23 Comparison of modelled and observed area flooded for each Flood Warning Area for Thames event: flow inputs

Flood Warning Area (FWA)	Area (m^2)	Area flooded			
		Modelled		Observed	
		m^2	% of FWA	m^2	% of FWA
Modelled outline (all)	**89,705,096**	**56,491,581**	**63.0**	**3,634,066**	**4.1**
Modelled outline (within area covered by Flood Warning Areas only)					
101	1,435,750	723,998	50.4	218,584	15.2
102	820,307	701,820	85.6	35,655	4.4
103	3,040,090	2,461,770	81.0	368,451	12.1
104	3,749,480	1,952,640	52.1	190,325	5.1
105	476,208	266,371	55.9	6,007	1.3
106	1,577,960	564,905	35.8	53,153	3.4
107	2,701,220	2,156,100	79.8	33,819	1.3
108	1,231,600	1,043,970	84.8	0	0.0
109	17,815,300	9,423,550	52.9	118,934	0.7
110	1,268,770	1,031,580	81.3	2,317	0.2
111	1,609,120	1,290,340	80.2	9,253	0.6
112	10,035,800	6,935,290	69.1	87,325	0.9
113	2,064,880	859,849	40.8	30,295	1.5
114	2,208,480	858,858	38.4	280,953	12.7
115	1,684,260	855,282	50.8	34,100	2.0
116	1,065,900	886,039	83.1	254,917	23.9
117	1,271,140	1,108,890	87.2	72,523	5.7
118	1,431,340	385,836	27.0	36,738	2.6
119	212,519	148,240	69.8	50,135	23.6
120	2,020,080	1,783,990	88.3	93,569	4.6
121	1,272,310	868,897	68.3	31,703	2.5
122	409,355	253,427	61.9	0	0.0
123	160,184	10,096	6.3	0	0.0
124	401,553	194,509	34.2	3,779	0.9

Flood Warning Area (FWA)	Area (m^2)	Area flooded			
		Modelled		Observed	
		m^2	% of FWA	m^2	% of FWA
125	1,115,270	812,056	72.8	71,237	6.4
126	527,197	170,852	32.4	0	0.0
127	20,383	25,154	90.1	0	0.0
128	728,015	660,121	90.7	191,146	26.3
129	8,776,290	4,704,810	53.4	383,117	4.4
130	1,918,490	917,162	35.2	5,747	0.3
131	7,773,590	6,218,620	80.0	12,656	0.2
132	3,661,670	3,025,230	82.6	63,320	1.7
133	2,439,350	1,894,720	77.7	755,003	31.0
134	1,957,330	744,322	38.0	124,854	6.4
135	438,652	228,267	52.0	14,451	3.3
136	385,253	324,020	84.1	0	0.0

Notes: For the purposes of comparison, the areas of the Flood Warning Areas have been trimmed to the extent of the available observed data.

Interpretation

The simulation library output consists of 50m resolution grid cells. There are some cells of irregular size and shape at the boundaries of the channel, where they have been trimmed by the asset lines. Another feature of the results is reservoirs and lakes; on this reach of the Thames, there are several water bodies such as gravel pits. These are forecast in the same way as any other class of land use and are not included in the observed flooding outline.

There are large areas of overprediction throughout this reach of the Thames. The simulation library forecasts flooding far in excess of the recorded flooding – 15 times the recorded area. Similar overprediction is observed in other PoCs and the boundary conditions, which are drawn from the fully dynamic fluvial modelling PoC, may contribute some of the inaccuracy. Further details are provided in Appendix 4, the pro-forma for the fully dynamic fluvial modelling PoC option.

This assessment makes use of observed flood extents derived from satellite imagery, in which there may be inaccuracies. As noted earlier, the available observations of flood extent do not coincide precisely (in time) with the available model outputs. Although the modelled output is very different to the observed flooding, the extent of the Flood Warning Areas should be considered. All forecast flooding in this option is within the extent of the Flood Warning Areas and this serves as a sensibility check on the results.

Sensitivity testing was not carried out for the Thames reach due to the large amount of computing resources that these runs would require and which was not possible within the time constraints of this project.

4.5.4 Model performance (Test A2)

Model performance scores were derived by comparison of modelled and observed flood outlines. Percentages were calculated as follows.

- Correct wet: proportion of flood extent that is correctly predicted by the model. Modelled extent = observed extent (blue)
- Overprediction: proportion of flood extent that is overpredicted by the model. Modelled extent > observed extent (green)
- Underprediction: proportion of flood extent that is underpredicted by the model. Modelled extent < observed extent (purple)

Skill and bias scores were calculated using the equations given below. 'Correct dry' areas are never included in the scores, as this is heavily dependent on the extent of the model domain.

$$SKILL = \frac{Correct\ Wet}{Correct\ Wet + Overprediction + Underprediction}$$

$$BIAS = \frac{Correct\ Wet + Overprediction}{Correct\ Wet + Underprediction}$$

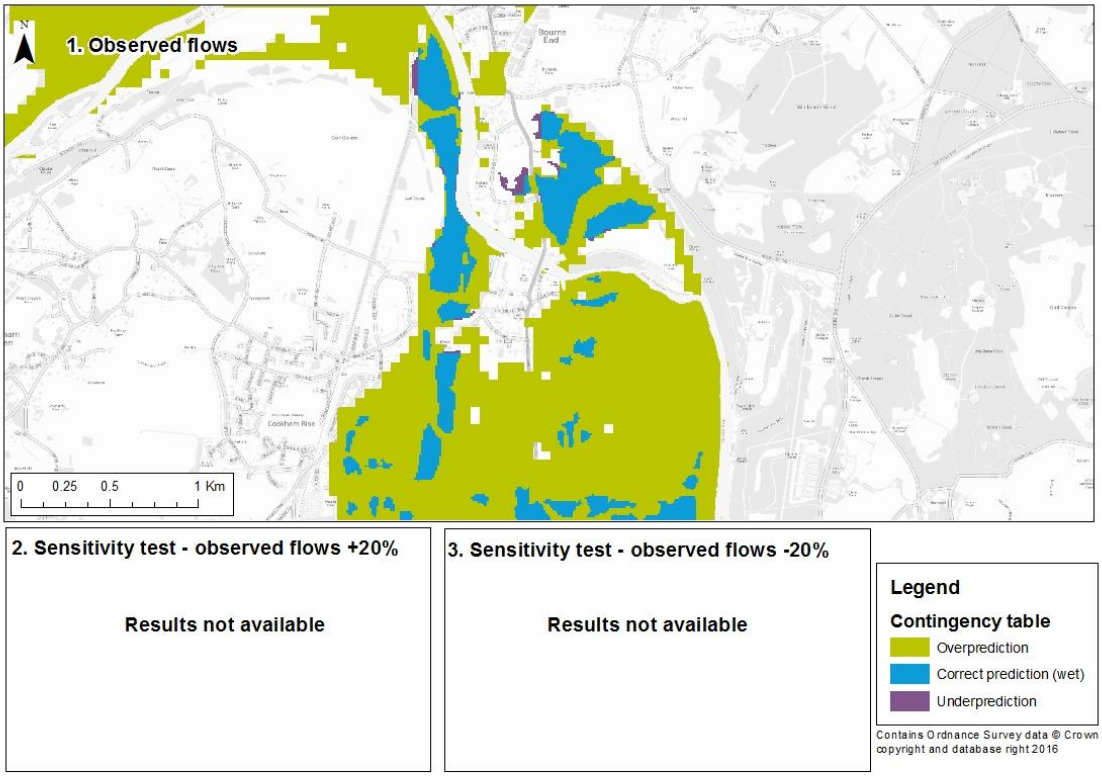


Figure 4.47 Model performance in predicting flooded extent for Maidenhead domain (inset 1): flow inputs

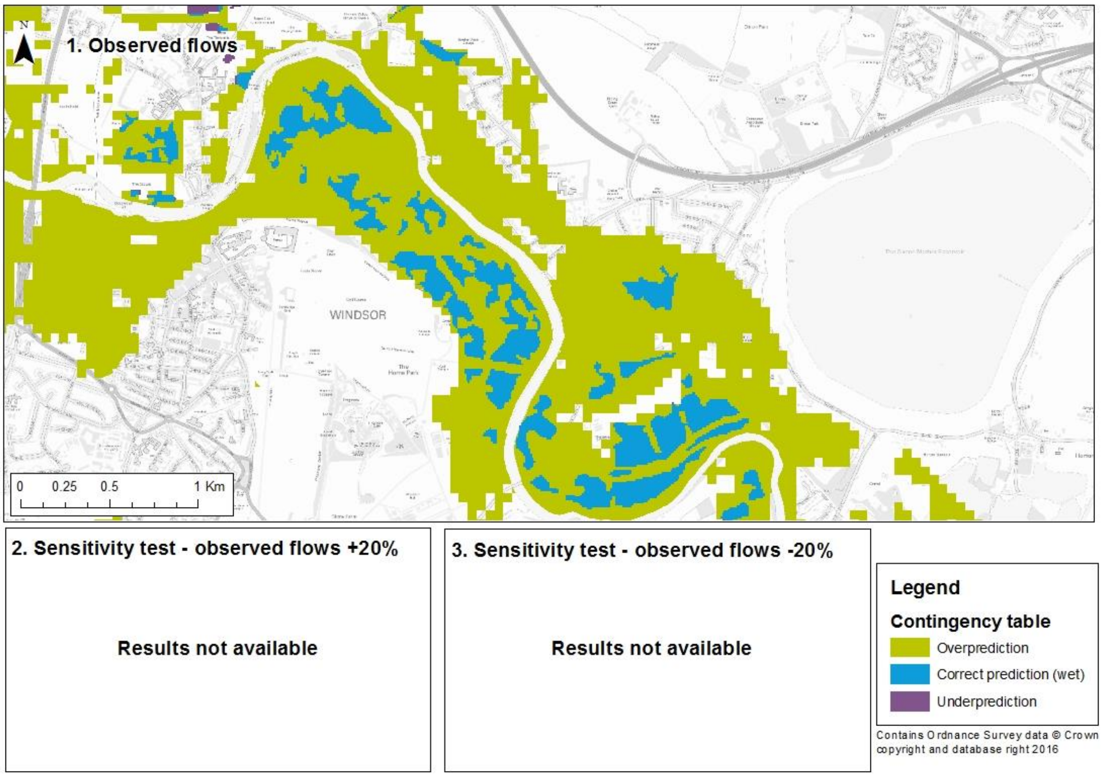


Figure 4.48 Model performance in predicting flooded extent for Bray, Cippenham and Windsor domains (inset 2): flow inputs

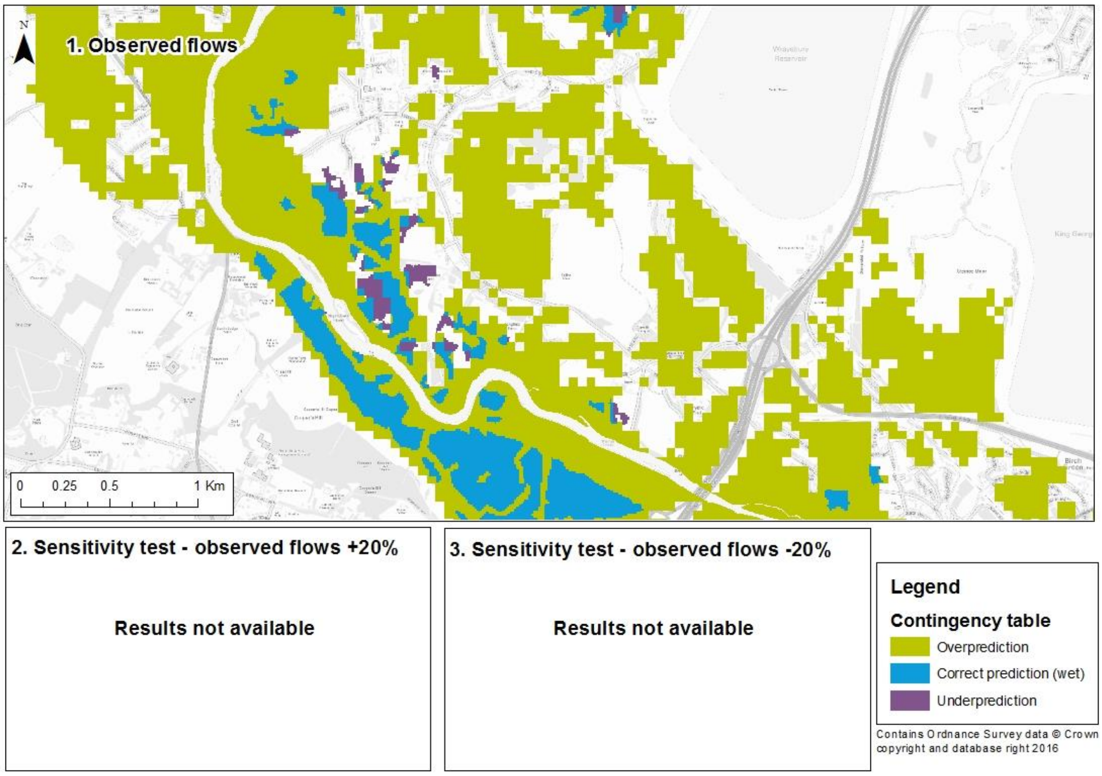


Figure 4.49 Model performance in predicting flooded extent for Windsor and Staines domain (inset 3): flow inputs

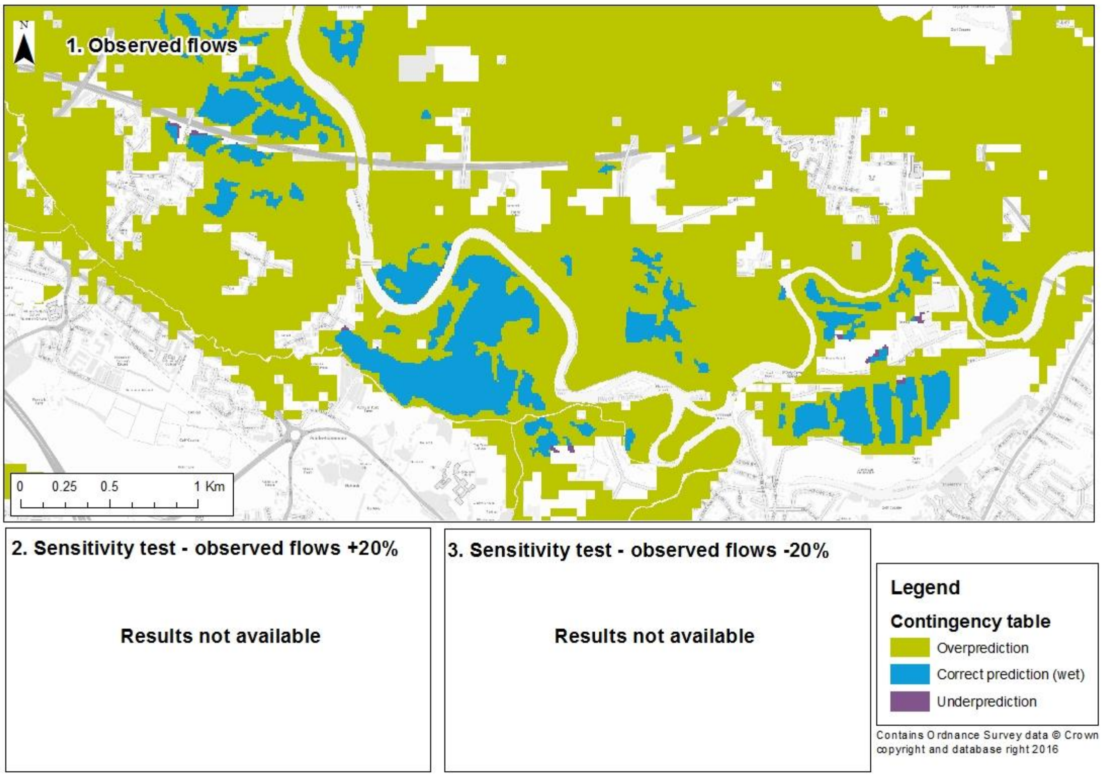


Figure 4.50 Model performance in predicting flooded extent for Staines and Chertsey (inset 4): flow inputs

Table 4.24 Model performance metrics for Thames event: flow inputs

Flood Warning Area	Correct wet (%)	Over-prediction (%)	Under-prediction (%)	Skill	Bias
Modelled outline (all)	**6.2**	**93.4**	**0.4**	**0.06**	**5.50**
Modelled outline (within area covered by Flood Warning Areas only)					
101	25.8	71.7	2.5	0.26	3.45
102	5.0	95.0	0.0	0.05	20.00
103	14.4	85.2	0.4	0.14	6.73
104	9.7	90.3	0.0	0.10	10.31
105	2.1	97.8	0.1	0.02	45.41
106	4.4	90.9	4.7	0.04	10.47
107	1.6	98.4	0.0	0.02	62.50
108	0.0	100.0	0.0	0.00	0.00
109	0.7	98.8	0.6	0.01	76.54
110	0.2	99.8	0.0	0.00	500.00
111	0.7	99.3	0.0	0.01	142.86

Flood Warning Area	Correct wet (%)	Over-prediction (%)	Under-prediction (%)	Skill	Bias
112	1.3	98.7	0.0	0.01	76.92
113	3.5	96.5	0.0	0.04	28.57
114	31.4	67.6	1.0	0.31	3.06
115	3.1	96.0	0.8	0.03	25.41
116	28.9	71.1	0.0	0.29	3.46
117	6.5	93.5	0.0	0.07	15.38
118	3.2	91.1	5.6	0.03	10.72
119	33.4	66.5	0.1	0.33	2.98
120	5.3	94.7	0.0	0.05	18.87
121	3.7	96.3	0.0	0.04	27.03
122	0.0	100.0	0.0	0.00	0.00
123	0.0	100.0	0.0	0.00	0.00
124	1.7	98.1	0.2	0.02	52.53
125	8.3	91.3	0.4	0.08	11.45
126	0.0	100.0	0.0	0.00	0.00
127	0.0	100.0	0.0	0.00	0.00
128	29.0	71.0	0.0	0.29	3.45
129	5.4	91.9	2.7	0.05	12.01
130	0.6	99.4	0.0	0.01	166.67
131	0.2	99.8	0.0	0.00	500.00
132	0.0	100.0	0.0	0.00	0.00
133	0.0	100.0	0.0	0.00	0.00
134	0.0	100.0	0.0	0.00	0.00
135	6.2	93.7	0.1	0.06	15.86
136	0.0	100.0	0.0	0.00	0.00

Notes: Metrics are reported for the full modelled flood outline first. Subsequent rows of the table report the metrics for the model flood outline within given Flood Warning Areas. This distinguishes between performance across the full model domain, and performance in locations where there is known to be flood risk to property.

Interpretation

This PoC option significantly overpredicts in comparison to the observed data (which was derived from satellite imagery). There are small pockets of underprediction, but these are very small in comparison with the extent of overprediction. In some Flood Warning Areas, overprediction reaches up to 100%, meaning that the skill and bias scores cannot be calculated.

Overall, model skill is very low (0.06) and bias is high (5.50). This pattern is seen in the majority of Flood Warning Area, with very high bias scores exceeding 100.0.

The calibration report from the 2015 modelling study undertaken by JBA Consulting highlights the significance of a number of factors on model performance, including overestimation of flows from lateral inflows and design hydrograph shape.

Consideration should also be made regarding the observed outline. It is possible that the data are inaccurate since they were derived from automated digitisation of satellite imagery in this heavily urbanised area.

4.5.5 Property counts (Test B)

Properties within flood extent

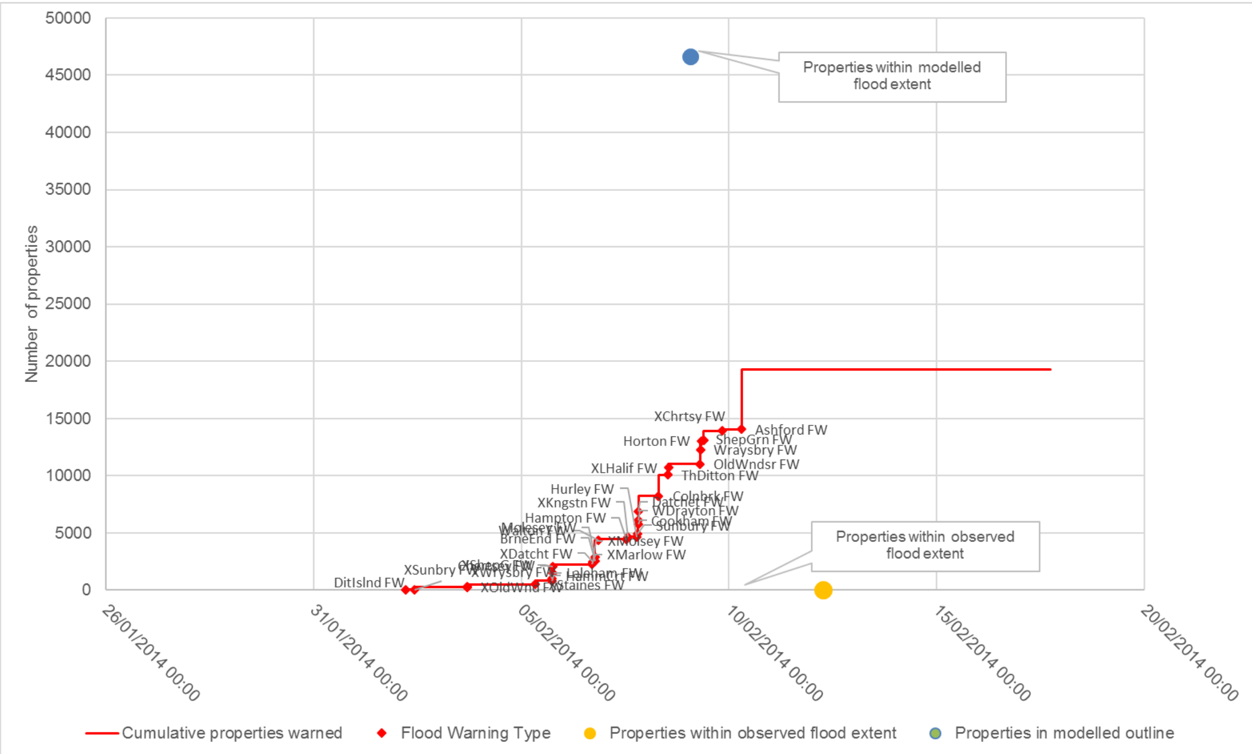


Figure 4.51 Properties within flood extent for Thames event: flow inputs

Notes: Properties are mapped below.

Table 4.25 Maximum number of flooded properties for Thames event: flow inputs

Flood Warning Area	Properties warned[1]	Observed[2]	Predicted[3]
All	**16,827**	**40**	**46,430**
101	376	4	280
102	530	0	861
103	304	4	336
104	1,378	2	1,542
105	171	0	217
106	10	0	2
107	548	2	1,086
108	0	0	1,134
109	0	1	10,411
110	1,240	1	1,739
111	860	1	1,315
112	0	3	11,554
113	838	0	413
114	120	5	45
115	785	0	629
116	11	0	29
117	315	1	427
118	0	0	80
119	26	2	58
120	169	0	381
121	325	3	612
122	218	0	303
123	0	0	0
124	0	0	172
125	0	0	1,940
126	0	0	51
127	0	0	15
128	147	1	234
129	1,850	2	1,447
130	771	0	287

Flood Warning Area	Properties warned[1]	Observed[2]	Predicted[3]
131	5,184	0	6,038
132	0	2	1,446
133	179	5	378
134	278	1	124
135	194	0	222
136	0	0	622

Notes: [1] Properties warned: counts of properties within each Flood Warning Area that received a flood warning during the event.
[2] Observed is based on the intersection of NRD property points and observed flood outline.
[3] Predicted is based on the intersection of NRD property points with maximum modelled flood outline.
Some Flood Warning Areas overlap and, as a result, some properties are double-counted in the totals on the first line of the table. Also some Flood Warning Areas have been trimmed to the modelled extent for display purposes and their dimensions may differ compared with the same Flood Warning Areas in other PoCs.

Interpretation

The number of properties within the modelled flood outline is 46,430 (Table 4.25). This is over twice the number of properties warned during the event. It is also significantly more than the number of properties within the observed extent, which is only 40.

The property counts are a product of the significant overprediction during this event. As discussed previously, model results could be affected by factors including the overprediction of boundary conditions. It is also possible that the observed flood extent is not an accurate representation of flooding at the precise time of the model results.

This PoC produces a maximum flood outline only and therefore time-stepped results are not available for comparison against the observed property counts.

Properties mapped by model prediction

Figures 52 to 55 show NRD property points, colour-coded according to whether the model overpredicts, underpredicts or correctly predicts the observed flood outline. Only properties within the existing Flood Warning Area are considered.

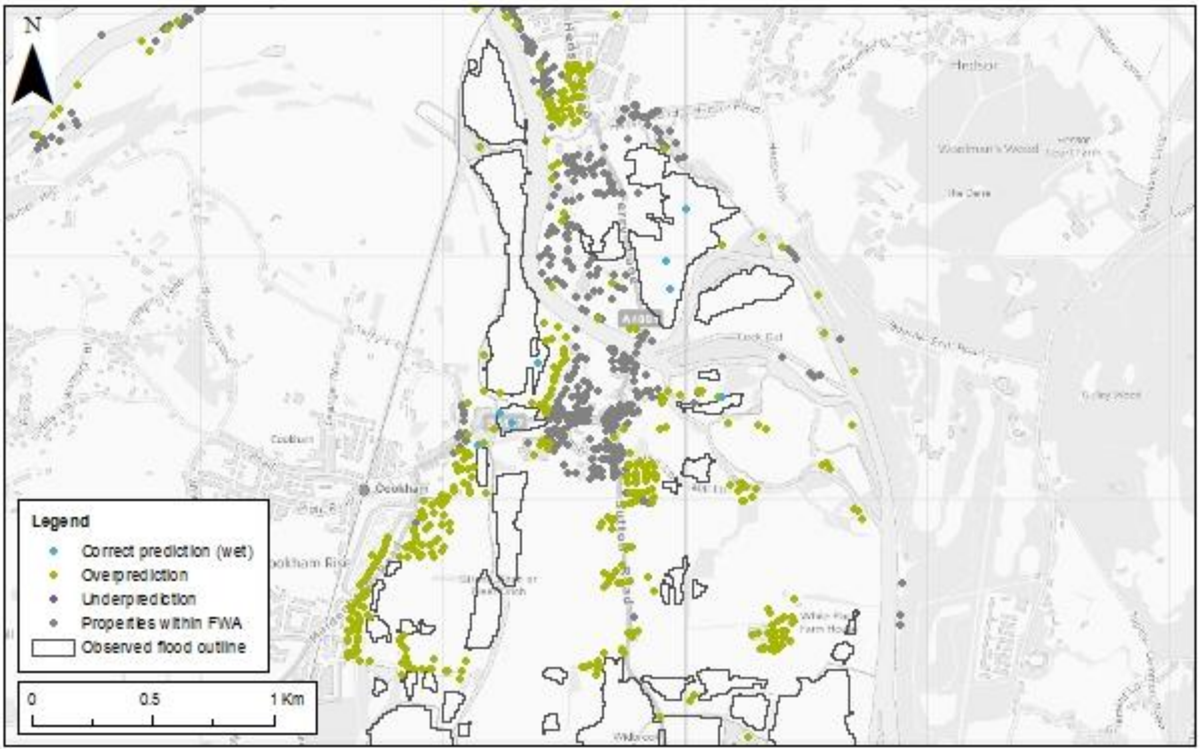


Figure 4.52 Closest modelled time step to validation data for Maidenhead domain (inset 1): flow inputs

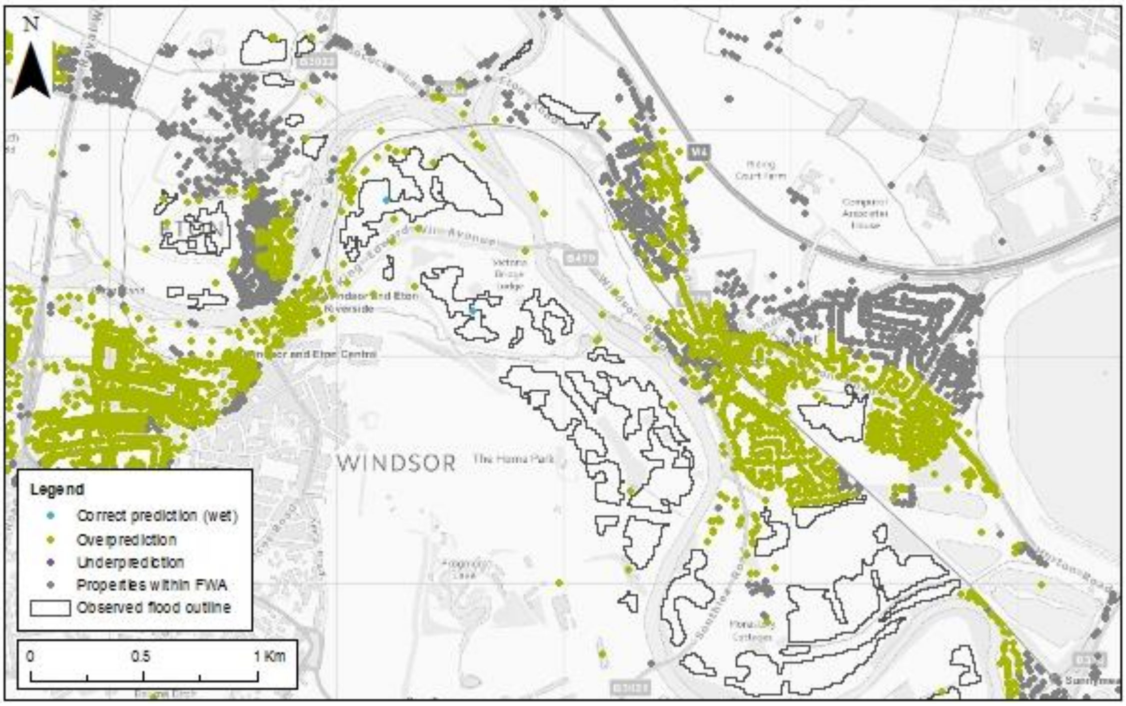


Figure 4.53 Closest modelled time step to validation data for Bray, Cippenham and Windsor domains (inset 2): flow inputs

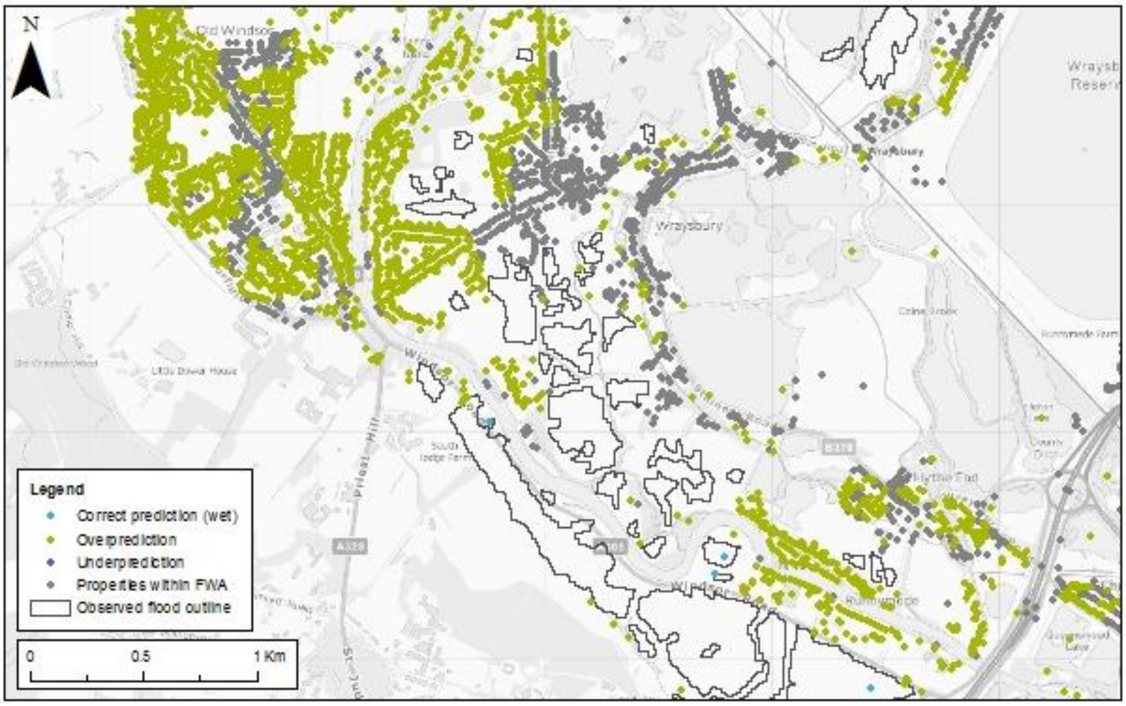


Figure 4.54 Closest modelled time step to validation data for Windsor and Staines domains (inset 3): flow inputs

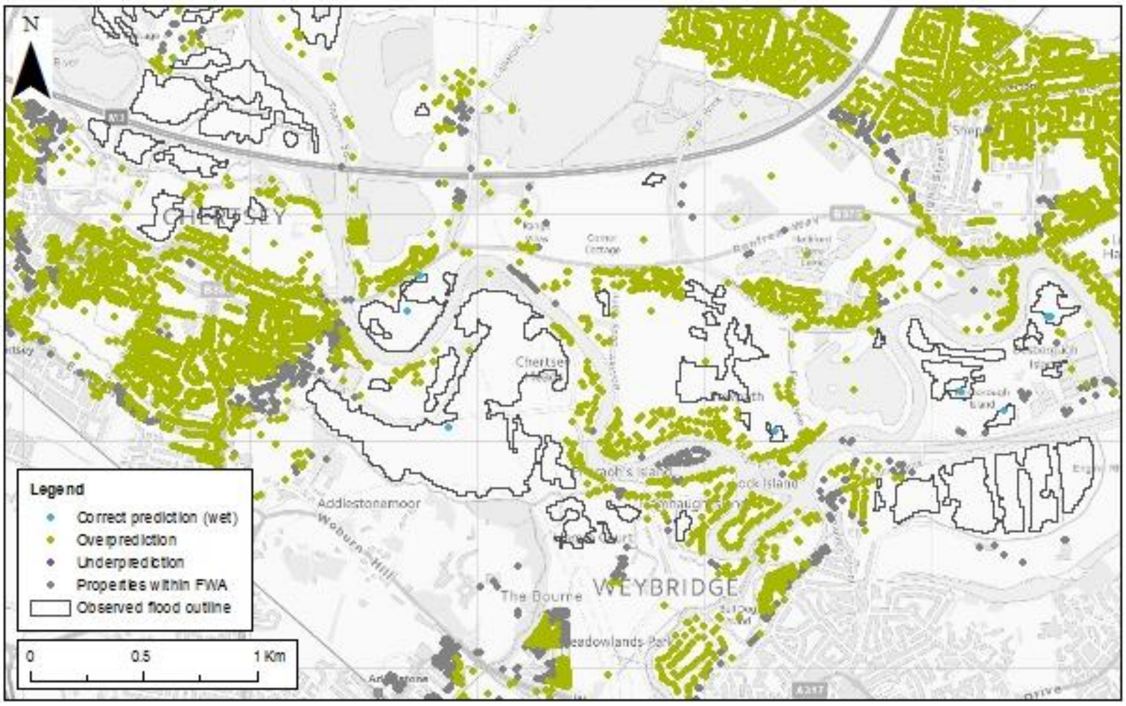


Figure 4.55 Closest modelled time step to validation data for Staines and Chertsey domains (inset 4): flow inputs

4.5.6 Depth analysis (Test C)

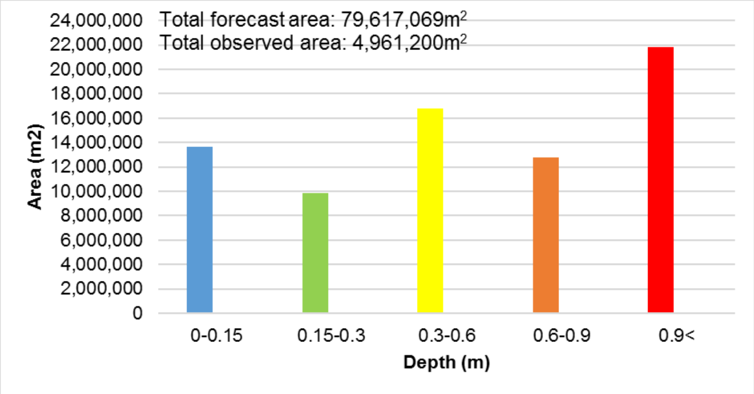


Figure 4.56 Distribution of flooded depths at 02:00 on 9 February 2014: flow inputs

Notes: Peak of the flood was at 01:15 on 10 February 2014 at Reading.
Solid bars show modelled depths (from the PoC option); no observed depths are available.
Channel depths are not included in the modelled results and so the observed area would be expected to be greater. Channel area = 4,744,810m^2
Total areas quoted on each plot include the channel area for both forecast and observed results.

Modelled	Observed	Depth (m)
		0.00–0.15
		0.15–0.30
		0.30–0.60
		0.60–0.90
		>0.90

Interpretation

The distribution of observed depth is not available for the Thames case study, although the primary feature of the forecast results here is the overprediction of the flooded area compared with the observed flood event data used for the assessment.

A brief sensibility assessment can be carried out on these results. The distribution of flood depth is shared between all the depth categories more evenly than in other case studies, although the total flooded area is much larger in the Thames case study.

The frequency distribution does not progress smoothly through the depth categories. Unfortunately, further assessment of these results is not possible due to the lack of observed data.

4.6 Case study 3: Thames, February 2014 – level inputs

4.6.1 Location

See Section 4.5.1 for a discussion of the location map and inputs used for this PoC.

Table 4.26 Description of Flood Warning Areas featured in the Thames case study

Flood Warning Target Area Code	JBA code[1]	Name
061FWF23BrneEnd	101	River Thames at Bourne End
061FWF23Chertsey	102	River Thames at Chertsey
061FWF23Cookham	103	River Thames at Cookham
061FWF23Datchet	104	River Thames at Datchet
061FWF23HammCrt	105	River Thames at Hamm Court
061FWF23Horton	106	River Thames at Horton
061FWF23Laleham	107	River Thames at Laleham
061FWF23LHalifrd	108	River Thames at Shepperton and Lower Halliford
061FWF23Mdnhead	109	River Thames at Maidenhead to Windsor and Eton
061FWF23OldWndsr	110	River Thames at Old Windsor
061FWF23ShepGrn	111	River Thames at Shepperton Green
061FWF23Staines	112	River Thames at Staines and Egham
061FWF23Sunbury	113	River Thames at Sunbury
061FWF23Walton	114	River Thames at Walton
061FWF23Wraysbry	115	River Thames at Wraysbury
061FWF23XDatcht	116	Properties closest to the River Thames at Datchet, between Black Potts Bridge and Albert Bridge
061FWF23XLHalif	117	Properties closest to the River Thames from Shepperton Lock to Beasley's Ait
061FWF23XMhead	118	Moorings and properties closest to the River Thames between Maidenhead, Windsor and Eton
061FWF23XOldWnd	119	Properties closest to the River Thames at Old Windsor, from Friday Island to Magna Carta Island
061FWF23XShepG	120	Properties closest to the River Thames between Littleton Lane (Shepperton Green) and Shepperton Lock
061FWF23XStaines	121	Properties closest to the River Thames between Runnymede Pleasure Grounds, Staines and Penton Hook
061FWF23XWrysbry	122	Properties closest to the River Thames at Wraysbury

Flood Warning Target Area Code	JBA code[1]	Name
		from Old Windsor Weir to Magna Carta Island
061FWF26Binghams	123	Cut at the Binghams
061FWF29Addstne	124	Addlestone Bourne at Addlestone
061FWF29Chertsey	125	Chertsey Bourne at Chertsey
061FWF29ThorpGrn	126	Chertsey Bourne at Thorpe Green
061FWF29XAddstne	127	Properties closest to the Addlestone Bourne at Addlestone
061FWF29XChrtsy	128	Areas of Chertsey closest to the Chertsey Bourne
062FWF28Colnbrk	129	Colne Brook at Colnbrook
062FWF28WDrayton	130	River Colne and Frays River at West Drayton and Stanwell Moor
062FWF31Ashford	131	River Ash at Ashford and Staines
061FWF23Marlow	132	River Thames at Bisham village and Marlow town
061FWF23XMarlow	133	Properties closest to the River Thames from All Saints Church, Bisham to Little Marlow
061FWF23Hurley	134	River Thames at Hurley and Harleyford
061FWF23XSunbry	135	Properties closest to the River Thames at Sunbury
061FWF30Weybrdge	136	River Wey at Weybridge
061FWF23HenMed	137	River Thames for Henley, Remenham and Medmenham

Notes: [1] Due to the size of the reach being analysed, a short three-digit code was assigned by JBA Consulting to all Flood Warning Areas to aid interpretation in later figures.

4.6.2 Context for model outputs

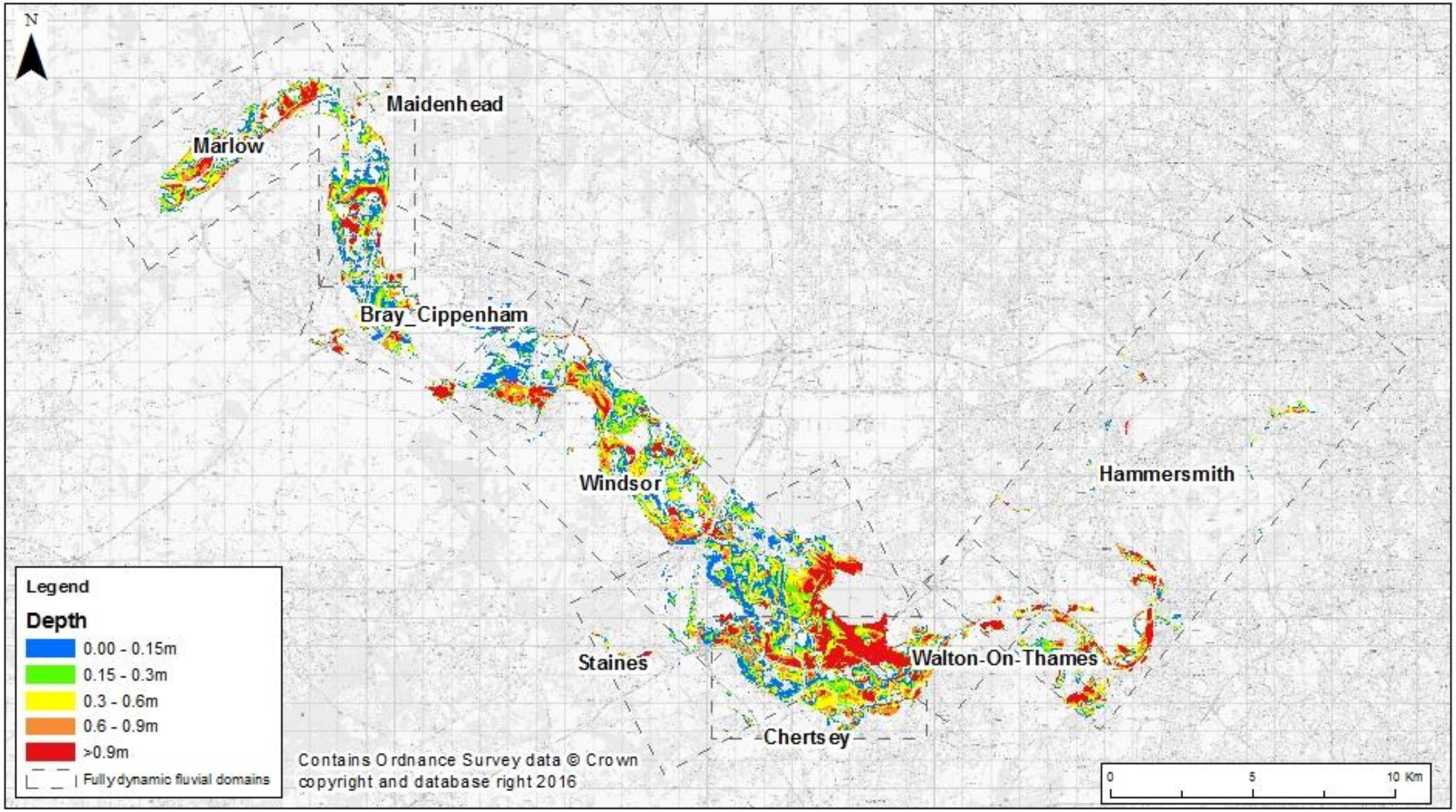


Figure 4.57 Context for model outputs for Thames case study: level inputs

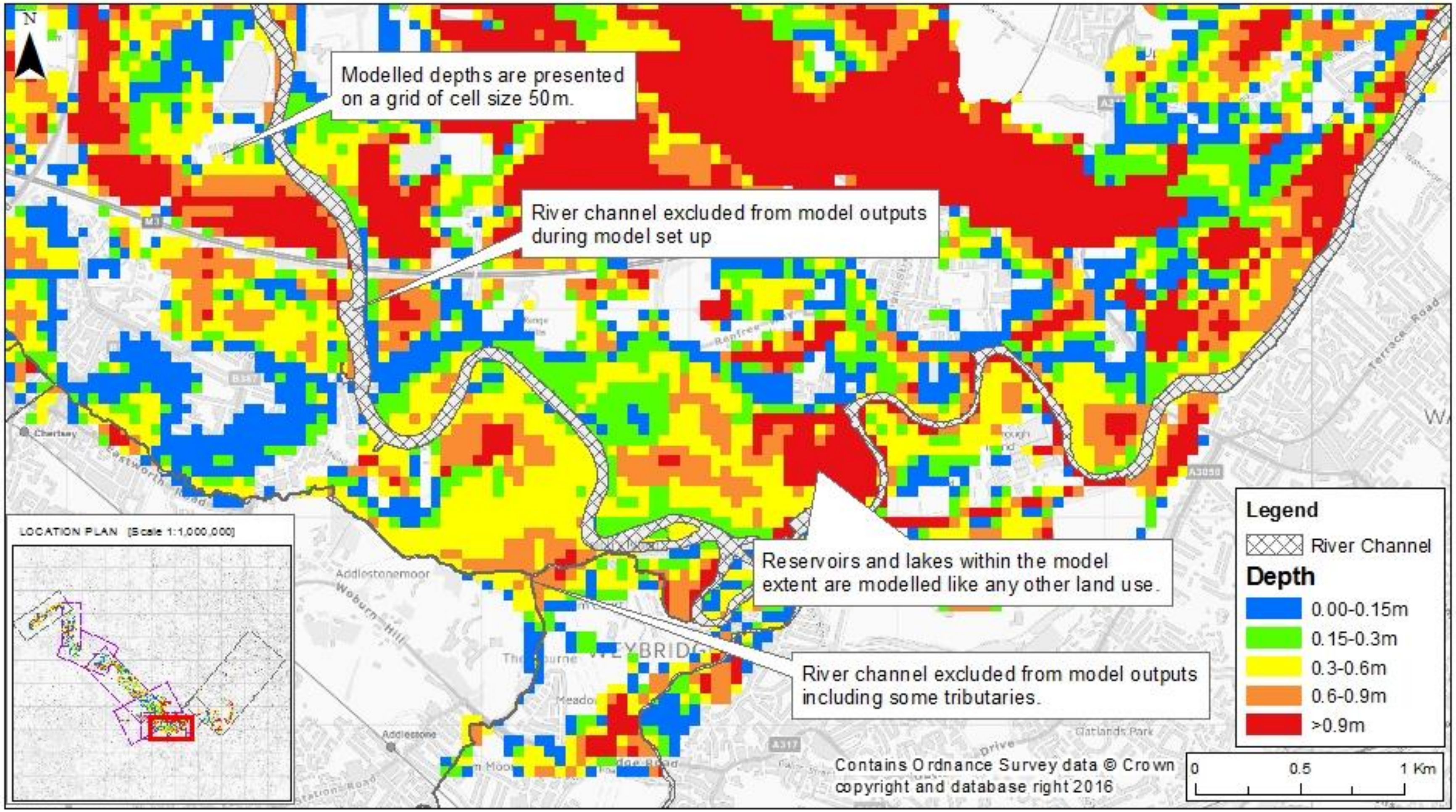


Figure 4.58 Context for model outputs in Chertsey domain: level inputs

4.6.3 Extent flooded (Test A1)

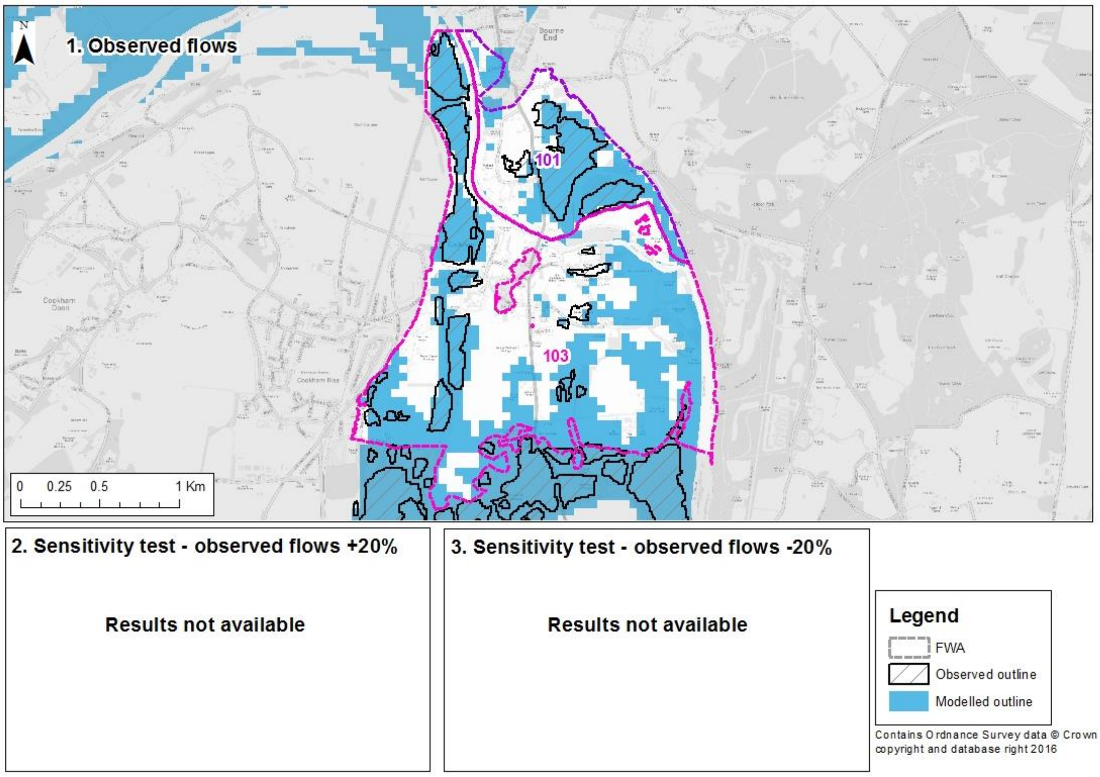


Figure 4.59 Maximum modelled and observed extent flooded for Maidenhead domain (inset 1): level inputs

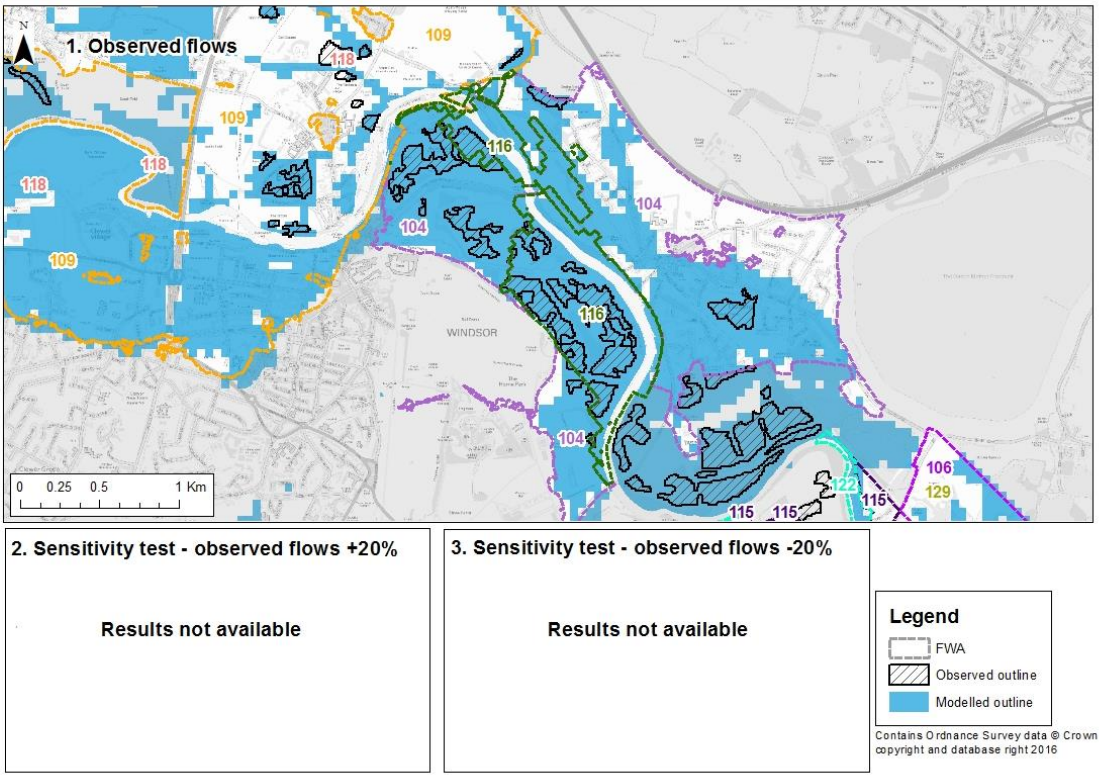


Figure 4.60 Maximum modelled and observed extent flooded for Bray, Cippenham and Windsor domains (inset 2): level inputs

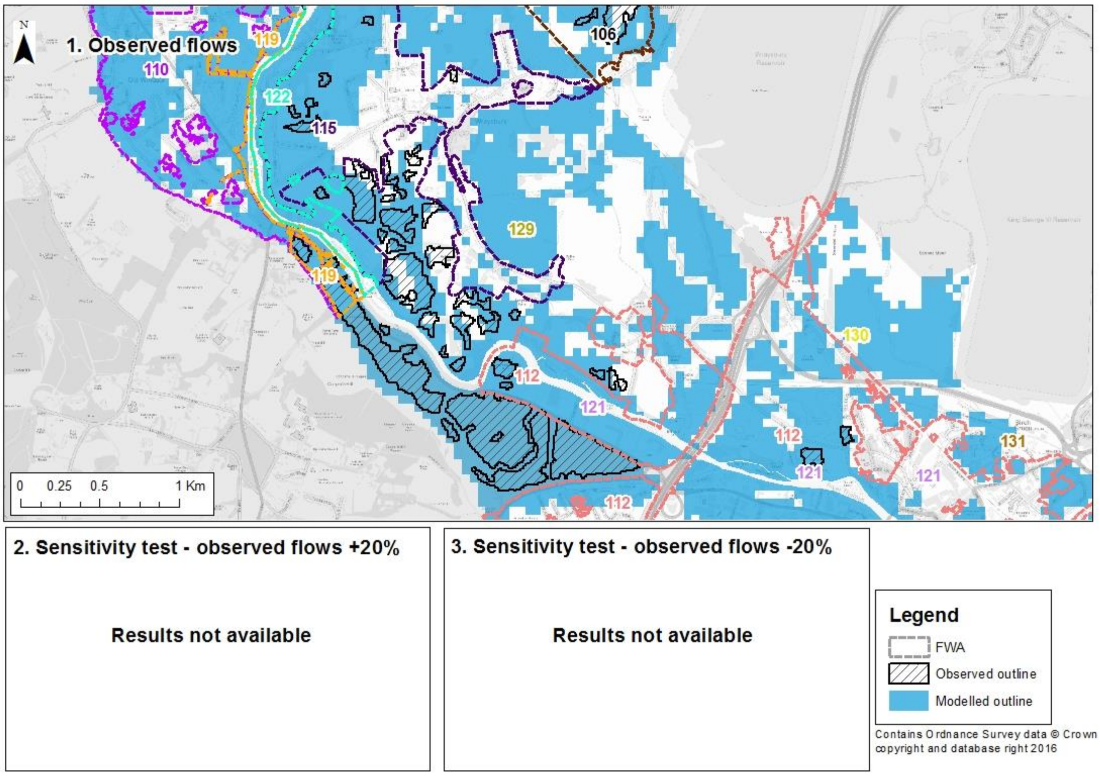


Figure 4.61 Maximum modelled and observed extent flooded for Windsor and Staines domains (inset 3): level inputs

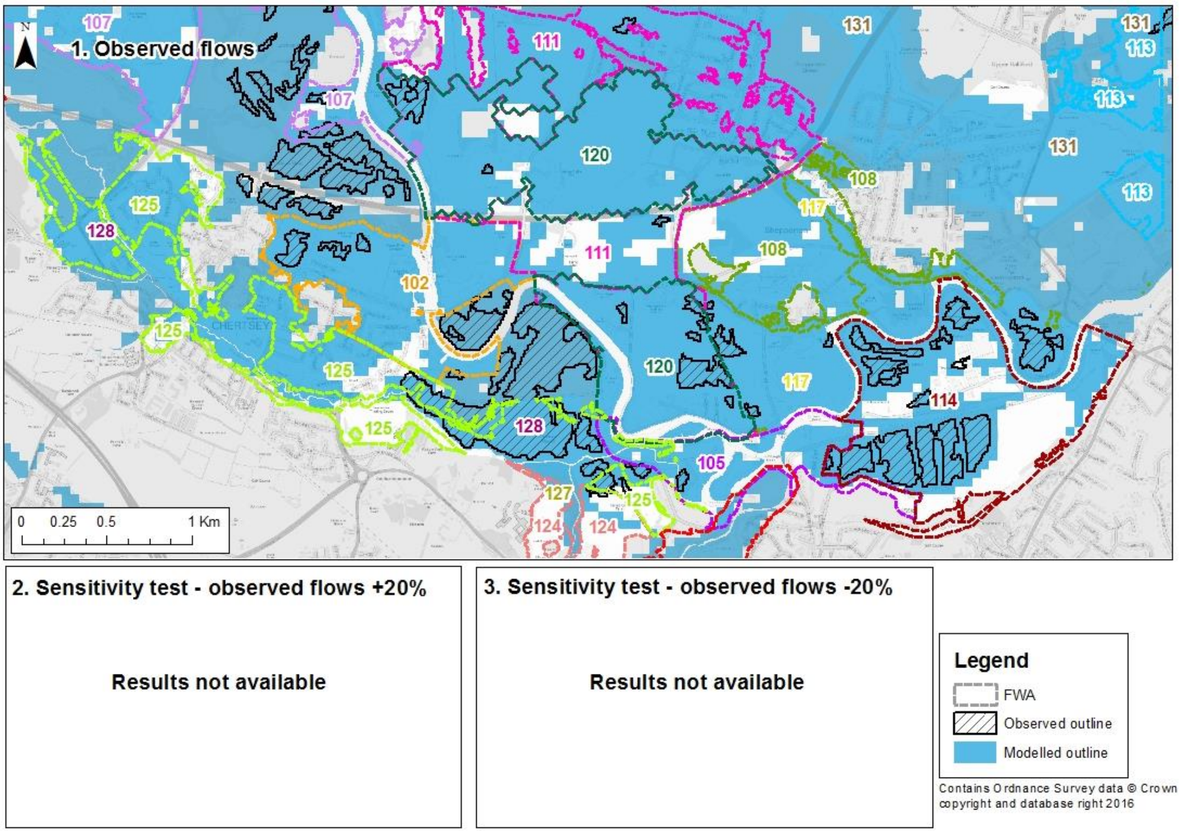


Figure 4.62 Maximum modelled and observed extent flooded for Staines and Chertsey domains (inset 4): level inputs

Table 4.27 Comparison of modelled and observed area flooded for each Flood Warning Area for Thames event: level inputs

Flood Warning Area (FWA)	Area (m^2)	Area flooded			
		Modelled		Observed	
		m^2	% of FWA	m^2	% of FWA
All	**89,705,096**	**52,389,720**	**58.4**	**2, 614, 506**	**3.6**
101	1,435,750	602,651	42.0	218,584	15.2
102	820,307	701,820	85.6	35,655	4.4
103	3,040,090	1,483,090	48.8	368,451	12.1
104	3,749,480	1,952,640	52.1	190,325	5.1
105	476,208	289,354	60.8	6,007	1.3
106	1,577,960	564,905	35.8	53,153	3.4
107	2,701,220	2,186,260	80.9	33,819	1.3
108	1,231,600	1,043,970	84.8	0	0.0
109	17,815,300	7,380,240	41.4	118,934	0.7
110	1,268,770	1,031,580	81.3	2,317	0.2
111	1,609,120	1,290,340	80.2	9,253	0.6
112	10,035,800	6,926,450	69.0	87,325	0.9
113	2,064,880	863,248	41.0	30,295	1.5
114	2,208,480	917,474	41.1	280,953	12.7
115	1,684,260	844,354	50.1	34,100	2.0
116	1,065,900	886,039	83.1	254,917	23.9
117	1,271,140	1,108,890	87.2	72,523	5.7
118	1,431,340	405,467	28.3	36,738	2.6
119	212,519	148,240	69.8	50,135	23.6
120	2,020,080	1,799,320	89.1	93,569	4.6
121	1,272,310	860,061	67.6	31,703	2.5
122	409,355	237,881	58.1	0	0.0
123	160,184	2,852	1.8	0	0.0
124	401,553	128,486	22.6	3,779	0.9
125	1,115,270	753,321	67.5	71,237	6.4
126	527,197	170,500	32.3	0	0.0
127	20,383	21,385	76.6	0	0.0

Flood Warning Area (FWA)	Area (m^2)	Area flooded			
		Modelled		Observed	
		m^2	% of FWA	m^2	% of FWA
128	728,015	650,404	89.3	191,146	26.3
129	8,776,290	4,689,170	53.2	383,117	4.4
130	1,918,490	917,162	35.2	5,747	0.3
131	7,773,590	6,218,620	80.0	12,656	0.2
132	3,661,670	2,222,160	60.7	63,320	1.7
133	2,439,350	1,865,050	76.5	755,003	31.0
134	1,957,330	672,376	34.4	124,854	6.4
135	438,652	244,998	55.9	14,451	3.3
136	385,253	308,962	80.2	0	0.0

Notes: For the purposes of comparison, the areas of the Flood Warning Areas have been trimmed to the extent of the available observed data.

Interpretation

The simulation library output consists of 50m resolution grid cells. There are some cells of irregular size and shape at the boundaries of the channel, where they have been trimmed by the asset lines. Another feature of the results is reservoirs and lakes; on this reach of the Thames, there are several water bodies such as gravel pits. These are forecast in the same way as any other class of land use and are not included in the observed flooding outline.

There are large areas of overprediction throughout this reach of the Thames. The simulation library forecasts flooding far in excess of the recorded flooding – 14 times the recorded area. Similar overprediction has been observed in other PoCs on this reach and the boundary conditions, which are drawn from the fully dynamic fluvial modelling PoC, may contribute some of the inaccuracy. Further details are provided in Appendix 4, the pro-forma for the fully dynamic fluvial modelling PoC option.

This assessment makes use of observed flooding data derived from satellite imagery, in which there may be inaccuracies. Although the modelled output is very different to the observed flooding, the extent of the Flood Warning Areas should be considered. All forecast flooding in this option is within the extent of the Flood Warning Areas and this serves as a sensibility check on the results.

Sensitivity testing was not carried out for the Thames reach due to the large amount of computing resources that these runs would require and which was not possible within the time constraints of this study.

4.6.4 Model performance (Test A2)

Model performance scores were derived by comparison of modelled and observed flood outlines. Percentages were calculated as follows.

- Correct wet: proportion of flood extent that is correctly predicted by the model. Modelled extent = observed extent (blue)
- Overprediction: proportion of flood extent that is overpredicted by the model. Modelled extent > observed extent (green)
- Underprediction: proportion of flood extent that is underpredicted by the model. Modelled extent < observed extent (purple)

Skill and bias scores were calculated using the equations given below. ‘Correct dry’ areas are never included in the scores, as this is heavily dependent on the extent of the model domain.

$$SKILL = \frac{Correct\ Wet}{Correct\ Wet + Overprediction + Underprediction}$$

$$BIAS = \frac{Correct\ Wet + Overprediction}{Correct\ Wet + Underprediction}$$

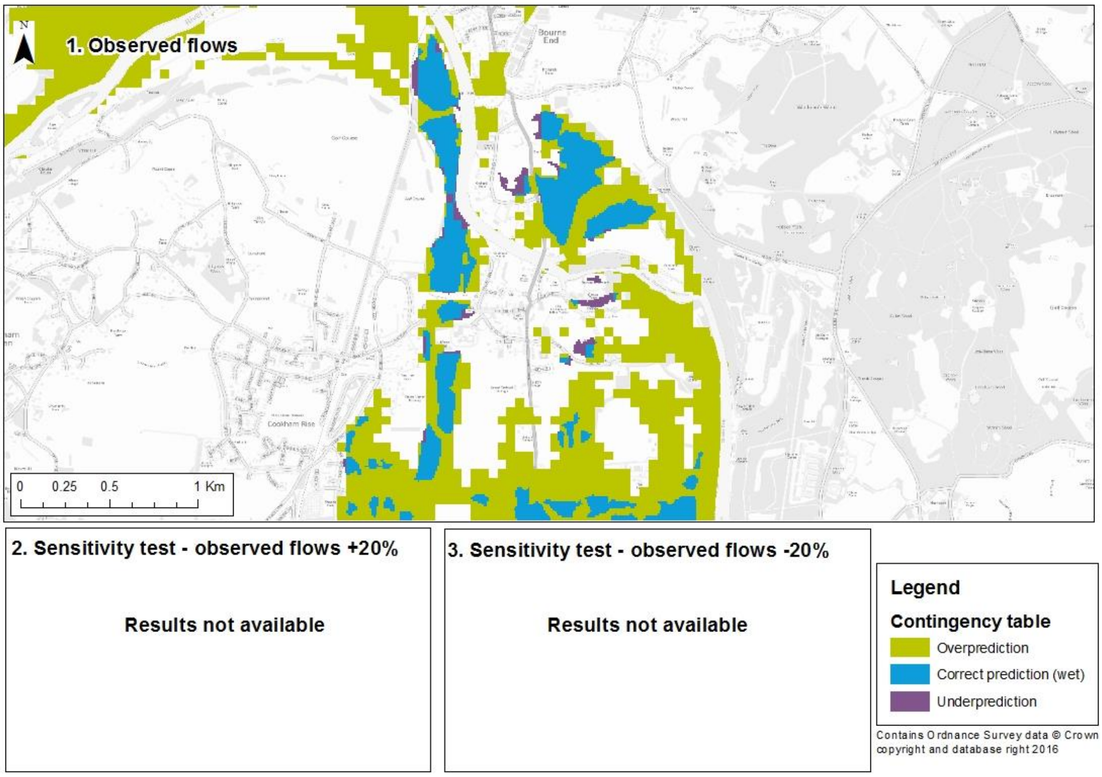


Figure 4.63 Model performance in predicting flooded extent for Maidenhead domain (inset 1): level inputs

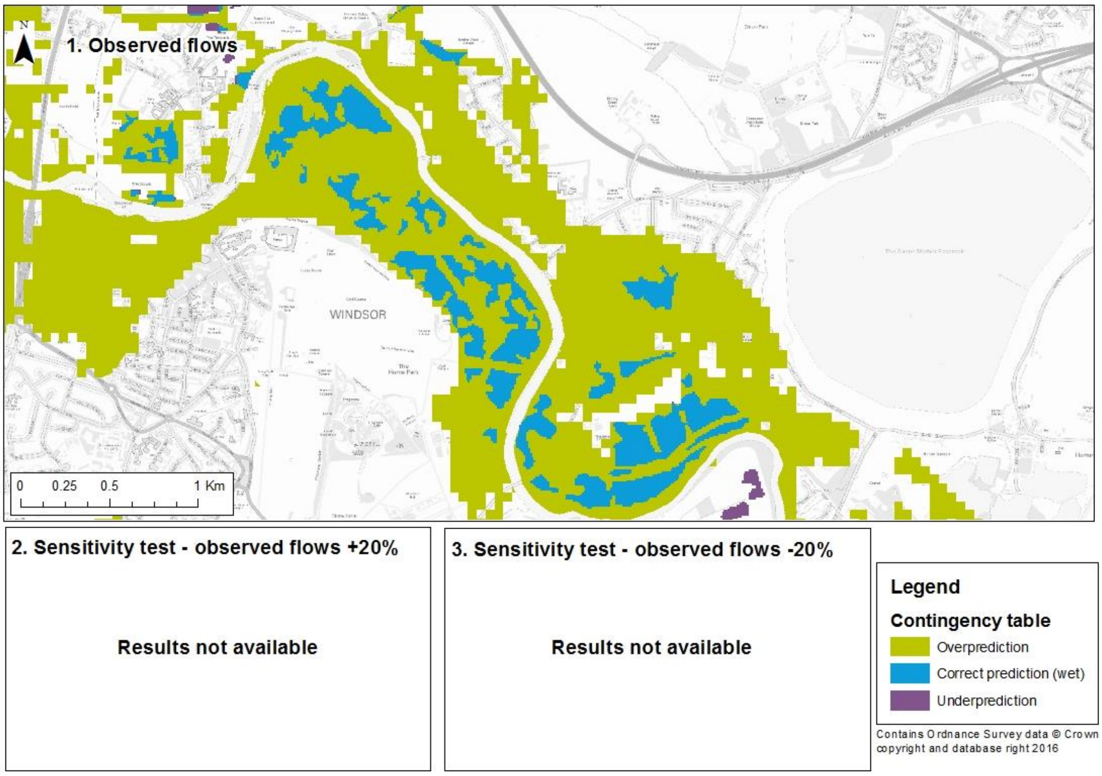


Figure 4.64 Model performance in predicting flooded extent for Bray, Cippenham and Windsor domains (inset 2): level inputs

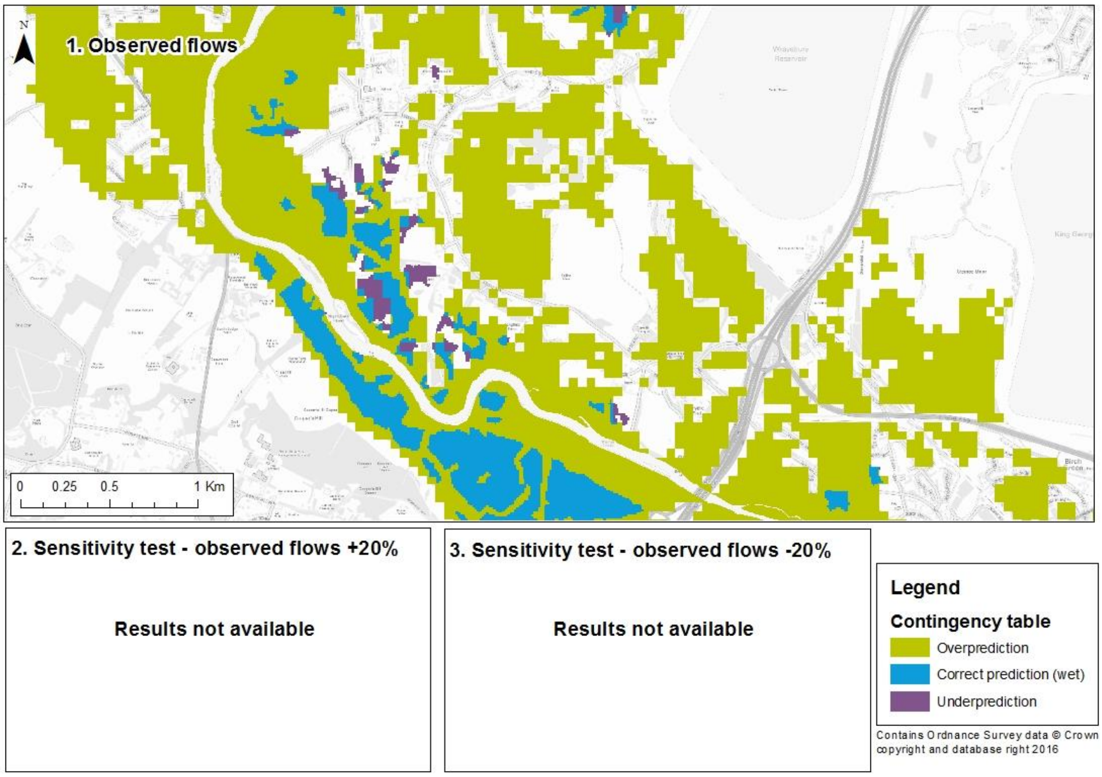


Figure 4.65 Model performance in predicting flooded extent for Windsor and Staines domain (inset 3): level inputs

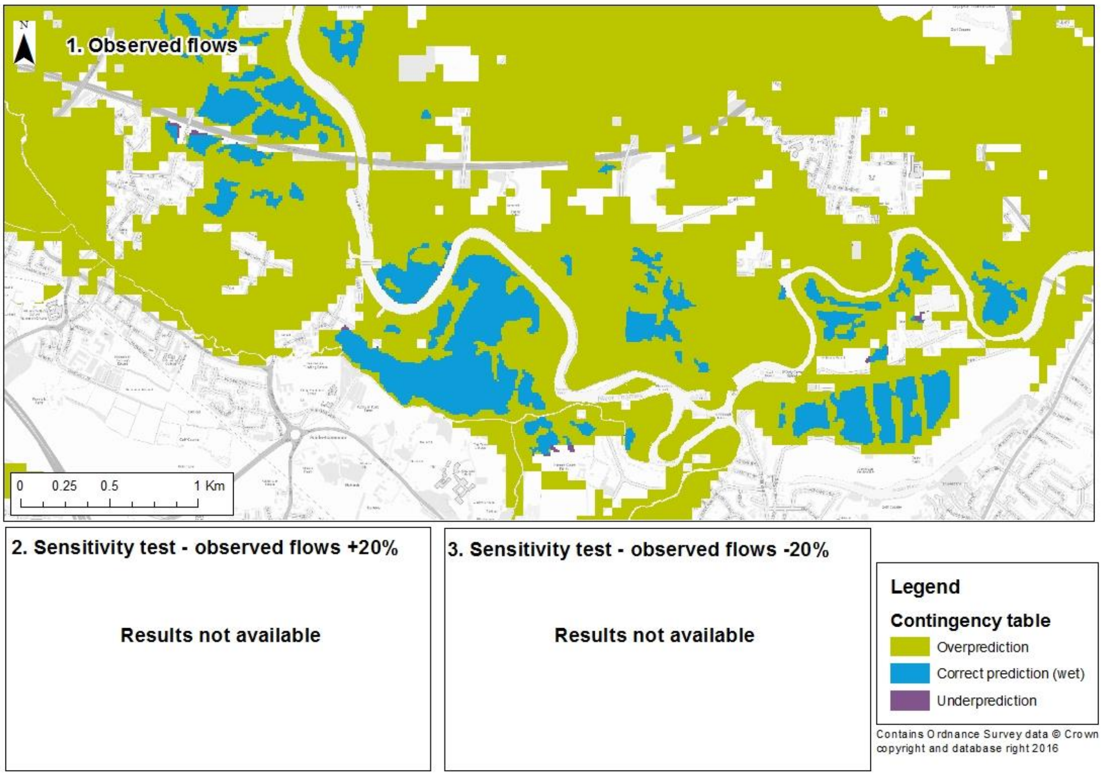


Figure 4.66 Model performance in predicting flooded extent for Staines and Chertsey (inset 4): level inputs

Table 4.28 Model performance metrics for Thames event: level inputs

Flood Warning Area	Correct wet (%)	Over-prediction (%)	Under-prediction (%)	Skill	Bias
Modelled outline (all)	**6.5**	**92.9**	**0.6**	**0.07**	**14.00**
Modelled outline (within area covered by FWAs only)	**6.4**	**93.0**	**0.6**	**0.06**	**14.25**
101	30.9	66.2	3.0	0.31	2.86
102	5.0	95.0	0.0	0.05	20.00
103	20.8	76.1	3.1	0.21	4.05
104	9.7	90.3	0.0	0.10	10.31
105	2.0	98.0	0.1	0.02	47.62
106	4.4	90.9	4.7	0.04	10.47
107	1.5	98.5	0.0	0.02	66.67
108	0.0	100.0	0.0	0.00	0.00
109	1.0	98.4	0.6	0.01	62.13

Flood Warning Area	Correct wet (%)	Over-prediction (%)	Under-prediction (%)	Skill	Bias
110	0.2	99.8	0.0	0.00	500.00
111	0.7	99.3	0.0	0.01	142.86
112	1.3	98.7	0.0	0.01	76.92
113	3.5	96.5	0.0	0.04	28.57
114	30.0	69.5	0.5	0.30	3.26
115	3.1	96.0	0.9	0.03	24.78
116	28.9	71.1	0.0	0.29	3.46
117	6.5	93.5	0.0	0.07	15.38
118	3.1	91.5	5.4	0.03	11.13
119	33.4	66.5	0.1	0.33	2.98
120	5.2	94.8	0.0	0.05	19.23
121	3.7	96.3	0.0	0.04	27.03
122	0.0	100.0	0.0	0.00	0.00
123	0.0	100.0	0.0	0.00	0.00
124	2.2	97.1	0.7	0.02	34.24
125	9.0	90.6	0.4	0.09	10.60
126	0.0	100.0	0.0	0.00	0.00
127	0.0	100.0	0.0	0.00	0.00
128	29.4	70.6	0.0	0.29	3.40
129	5.3	91.9	2.7	0.05	12.15
130	0.6	99.4	0.0	0.01	166.67
131	0.2	99.8	0.0	0.00	500.00
132	0.0	100.0	0.0	0.00	0.00
133	0.0	100.0	0.0	0.00	0.00
134	0.0	100.0	0.0	0.00	0.00
135	5.8	94.2	0.0	0.06	17.24
136	0.0	100.0	0.0	0.00	0.00

Notes: Metrics are reported for the full modelled flood outline first. Subsequent rows of the table report the metrics for the model flood outline within given Flood Warning Areas. This distinguishes between performance across the full model domain, and performance in locations where there is known to be flood risk to property.

Interpretation

This PoC option significantly overpredicts compared with the observed data, which were derived from satellite images. There are small pockets of underprediction, but these are very small compared with the extent of overprediction. In some Flood Warning Area, overprediction reaches 100%, meaning that the skill and bias scores cannot be calculated.

The results for this option are similar to those from the flows input option. Overall, model skill is very low (0.07) and bias is very high (14.00). This pattern is seen in the majority of Flood Warning Area, with very high bias scores.

The calibration report from the 2015 modelling study undertaken by JBA Consulting highlights the significance of a number of factors on model performance, including overestimation of flows from lateral inflows and design hydrograph shape.

Consideration should also be made regarding the observed outline. It is possible that the data are inaccurate since they were derived from automated digitisation of satellite imagery in this heavily urbanised area.

4.6.5 Property counts (Test B)

Properties within flood extent

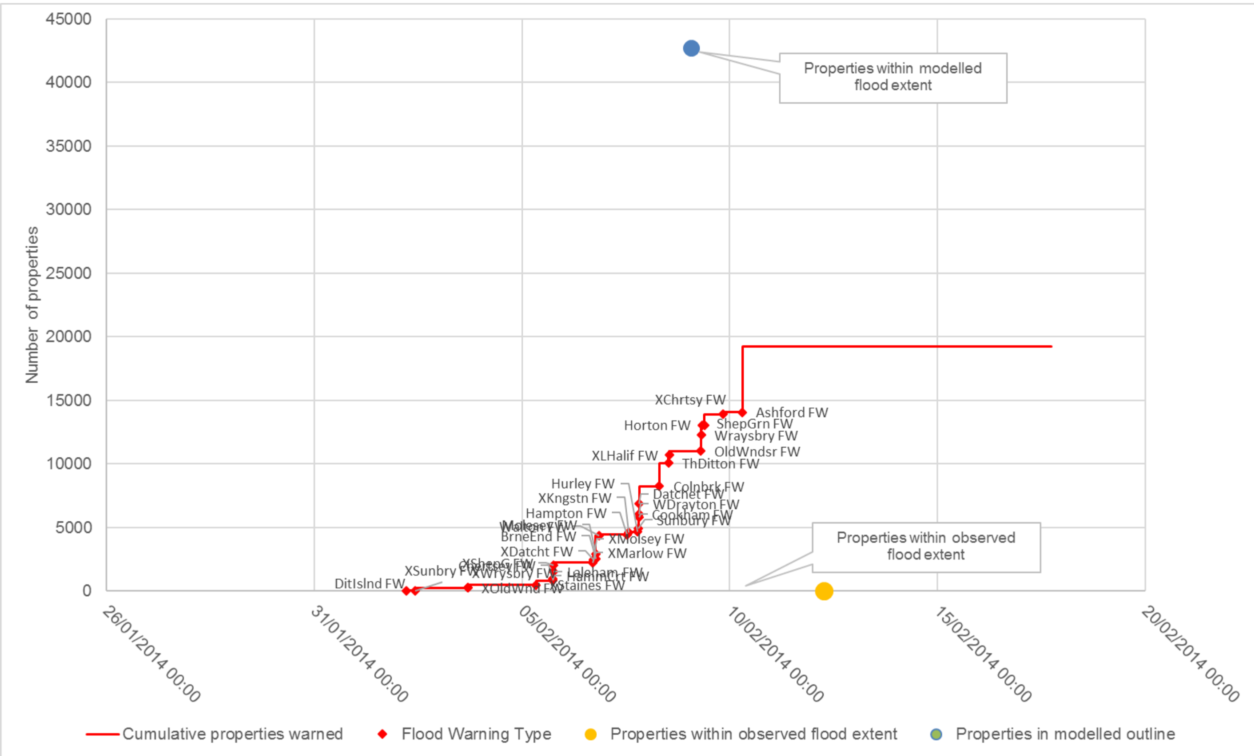


Figure 4.67 Properties within flood extent for Thames event: level inputs

Notes: Properties are mapped below.

Table 4.29 Maximum number of flooded properties for Thames event: level inputs

Flood Warning Area	Properties warned[1]	Observed[2]	Predicted[3]
All	**16,827**	**40**	**42,539**
101	376	4	201
102	530	0	861
103	304	4	115
104	1,378	2	1,542
105	171	0	227
106	10	0	2
107	548	2	1,086
108	0	0	1,134
109	0	1	7,787
110	1,240	1	1,739
111	860	1	1,315
112	0	3	11,545
113	838	0	414
114	120	5	49
115	785	0	618
116	11	0	29
117	315	1	427
118	0	0	85
119	26	2	58
120	169	0	407
121	325	3	603
122	218	0	275
123	0	0	0
124	0	0	82
125	0	0	1,843
126	0	0	51
127	0	0	14
128	147	1	203
129	1,850	2	1,438

Flood Warning Area	Properties warned[1]	Observed[2]	Predicted[3]
130	771	0	287
131	5,184	0	6,038
132	0	2	789
133	179	5	340
134	278	1	103
135	194	0	252
136	0	0	580

Notes: [1] Properties warned: counts of properties within each Flood Warning Area that received a flood warning during the event.
[2] Observed is based on the intersection of NRD property points and observed flood outline.
[3] Predicted is based on the intersection of NRD property points with maximum modelled flood outline.
Some Flood Warning Areas overlap and, as a result, some properties are double-counted in the totals on the first line of the table. Also some Flood Warning Areas have been trimmed to the modelled extent for display purposes and their dimensions may differ compared with the same Flood Warning Areas in other PoCs.

Interpretation

The number of properties within the modelled flood outline is 42,539 (Table 4.29). This is over twice the number of properties warned during the event. It is also significantly more than the number of properties within the observed extent, which is only 40.

As discussed previously, model results could be affected by factors including the overprediction of boundary conditions. It is also possible that the observed flood extent is not an accurate representation of flooding at the precise time of the model results. This PoC produces a maximum flood outline only, and therefore time-stepped results are not available for comparison against the observed property counts.

Properties mapped by model prediction

Figures 67 to 70 show NRD property points, colour-coded according to whether the model overpredicts, underpredicts or correctly predicts the observed flood outline. Only properties within the existing Flood Warning Area are considered.

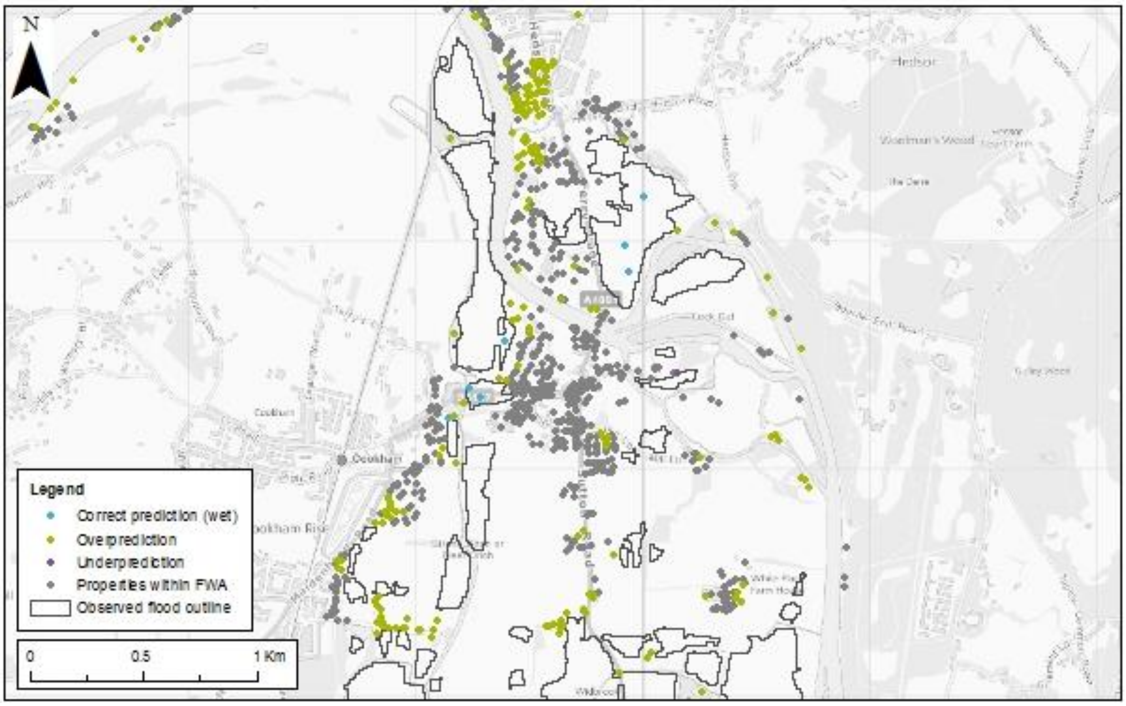


Figure 4.68 Closest modelled time step to validation data for Maidenhead domain (inset 1): level inputs

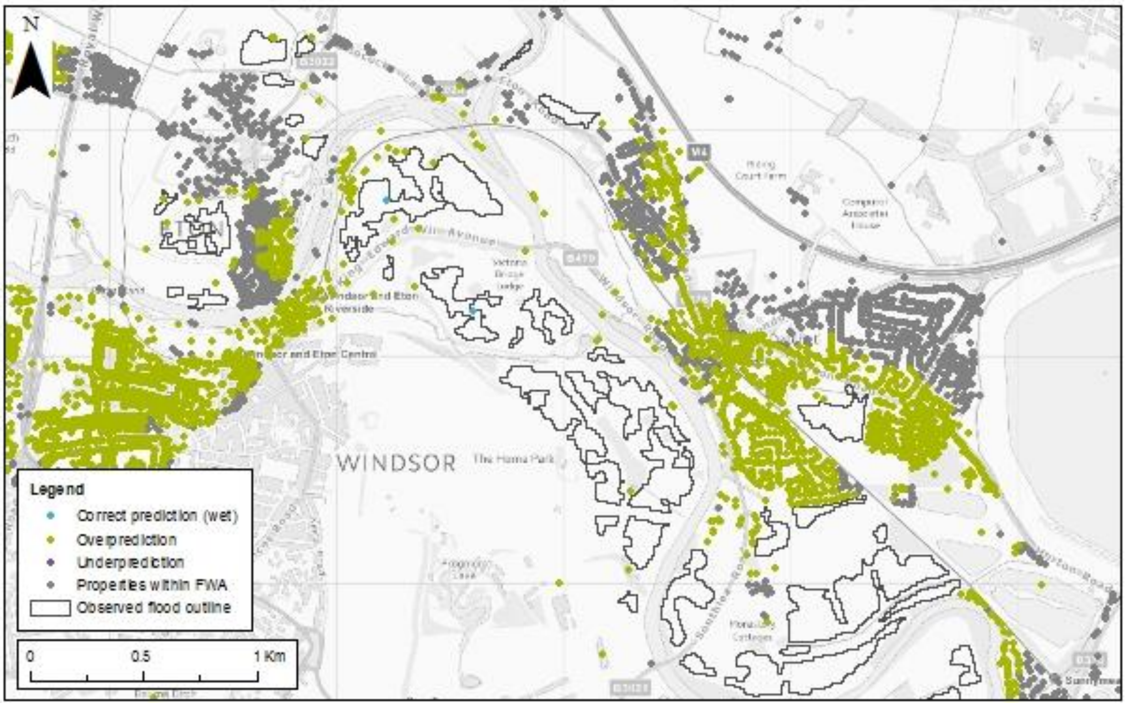


Figure 4.69 Closest modelled time step to validation data for Bray, Cippenham and Windsor domains (inset 2): level inputs

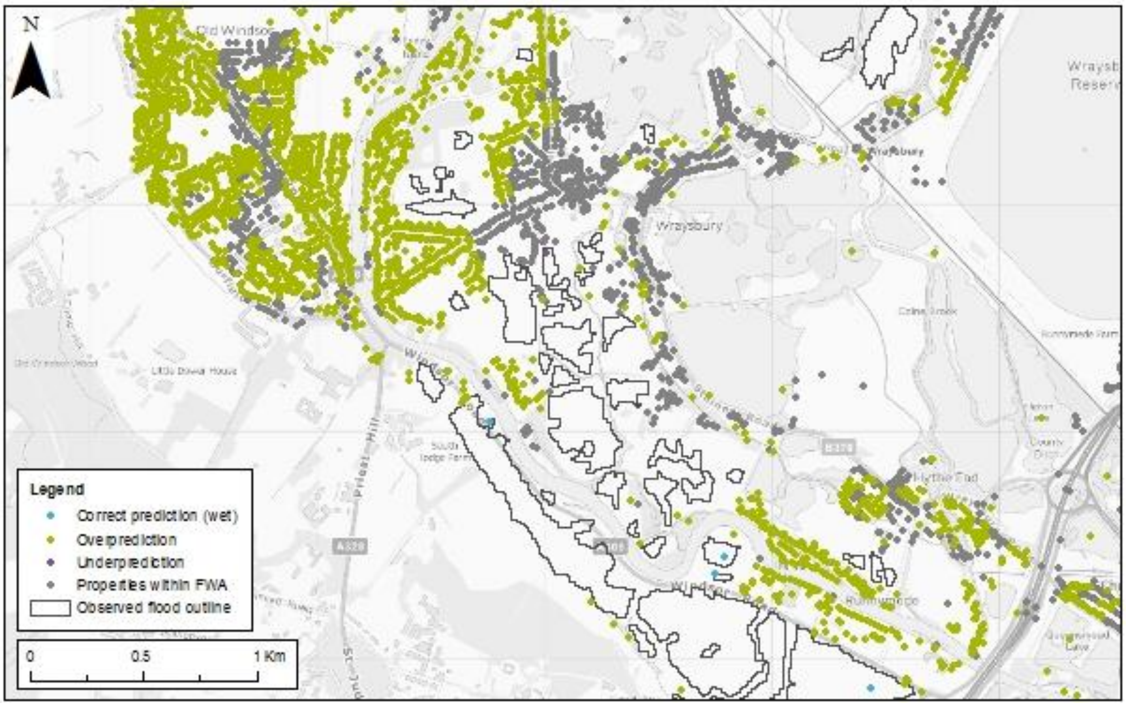


Figure 4.70 Closest modelled time step to validation data for Windsor and Staines domains (inset 3): level inputs

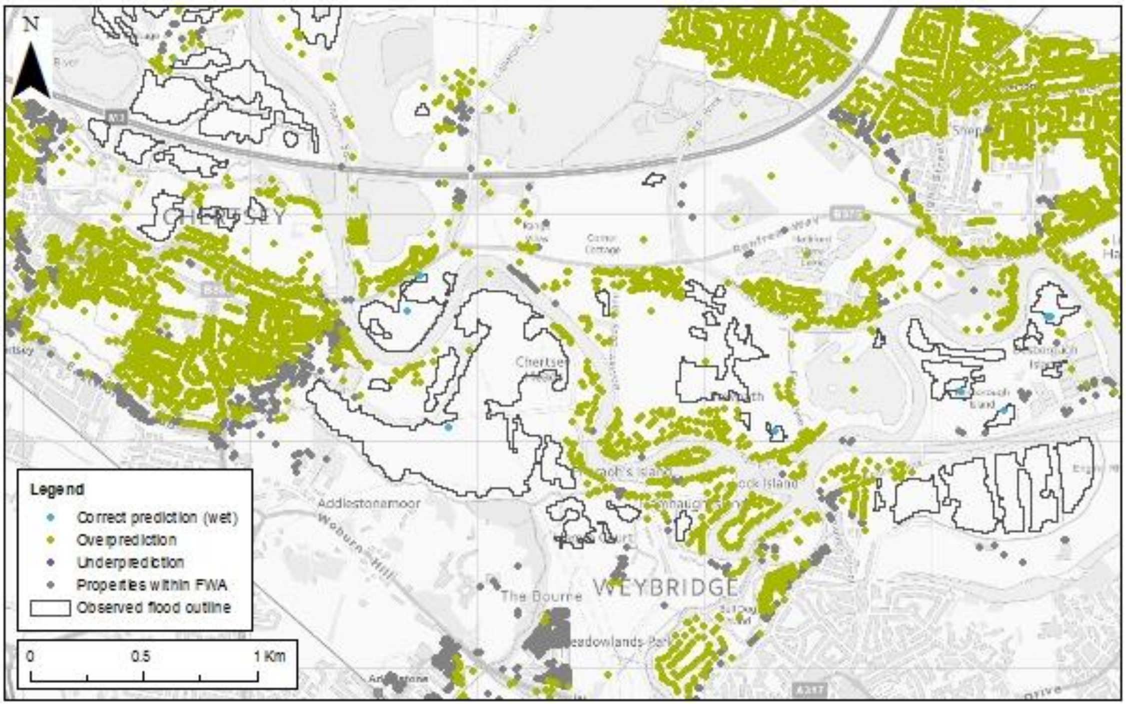


Figure 4.71 Closest modelled time step to validation data for Staines and Chertsey domains (inset 4): level inputs

4.6.6 Depth analysis (Test C)

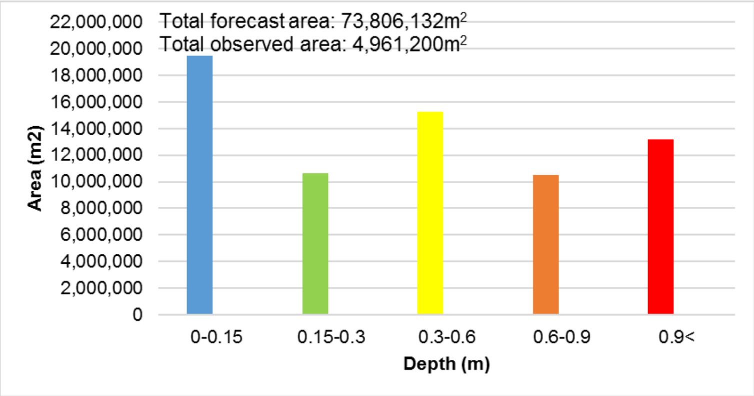


Figure 4.72 Distribution of flooded depths: level inputs

Notes: Solid bars show modelled depths (from the PoC option); no observed depths are available.
Channel depths are not included in the modelled results and so the observed area would be expected to be greater. Channel area = 4,744,810m^2
Total areas quoted on each plot include the channel area for both forecast and observed results.

Modelled	Observed	Depth (m)
		0.00–0.15
		0.15–0.30
		0.30–0.60
		0.60–0.90
		>0.90

Interpretation

Although the distribution of observed depth is not available for the Thames case study, the primary feature of the forecast results is the overprediction of the flooded area, according to the observed flood event data which were used for the assessment.

In contrast to the flow inputs results, the depth results are slightly skewed towards the shallowest category (<0.15m). However, the frequency distribution does not progress smoothly through the depth categories. Further assessment of these results is not possible due to the lack of observed data.

5 Implementation considerations

This section presents items to be considered by the Environment Agency if this PoC option is developed further towards operational use.

Section 5.1 details technical considerations (input data, intermediate processing and outputs provided) beyond the specifics of the PoC testing undertaken by this project. The flow chart from Section 2 showing the steps involved in running the system is reproduced as Figure 5.1. Each step is discussed in turn.

Section 5.2 discusses the skills, cost and effort that might be required to implement and maintain the system.

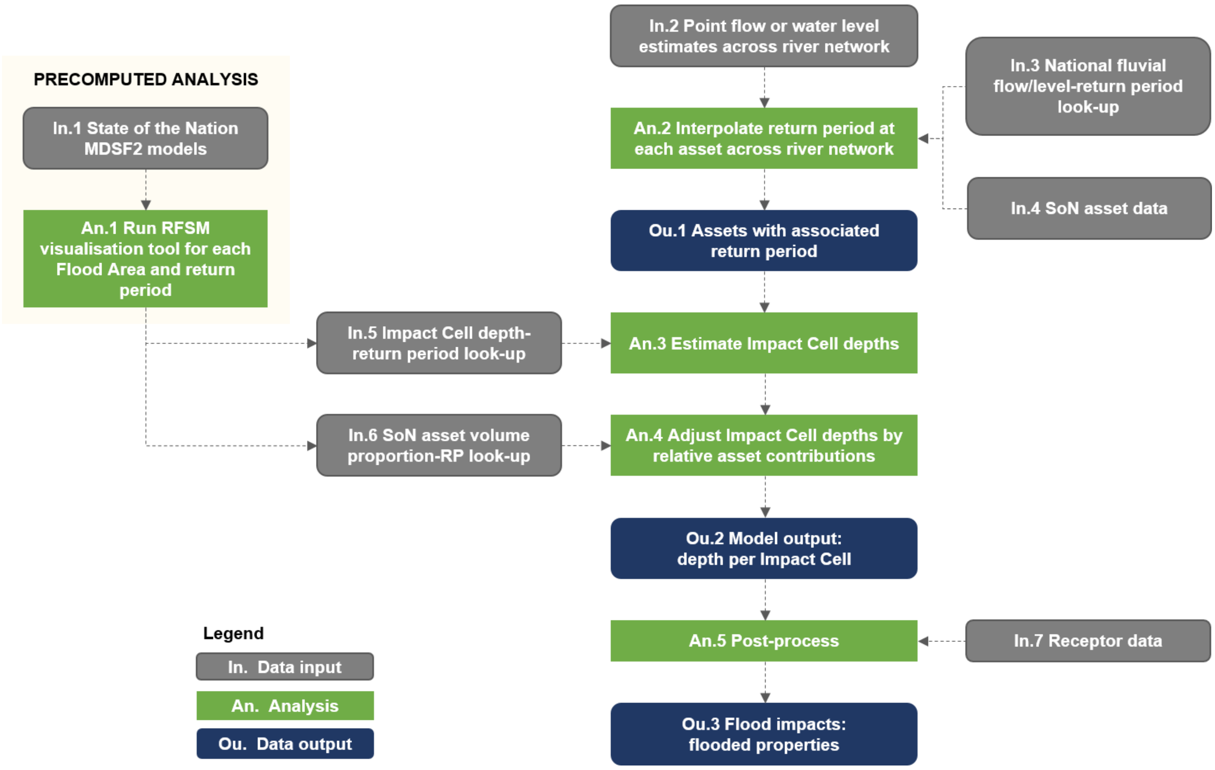


Figure 5.1 Flow chart showing PoC workflow for simulation library

5.1 Operating the system

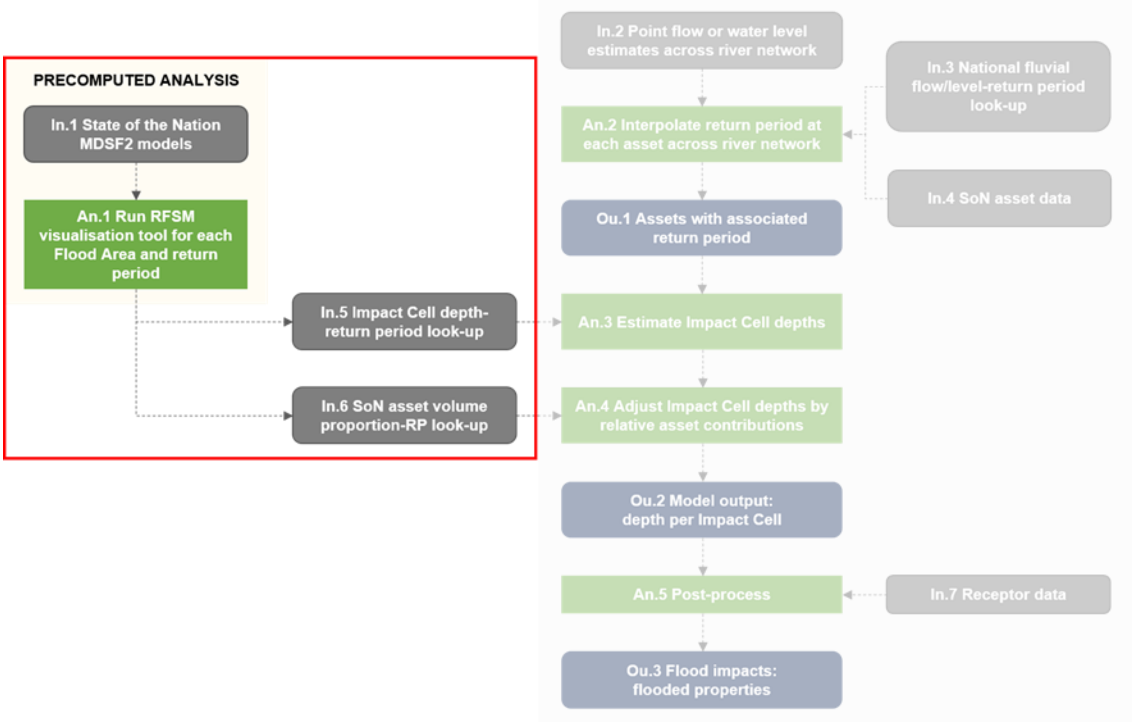
Table 5.1 Key considerations in using this option within an operational forecasting system

Description	Priority
Acceptable run times for use in operational forecasting. Run times for this PoC are feasible for use in real time, with plenty of additional scope for optimising data pre-processing/loading and execution across multiple Flood Areas. PoC does not require specialist hardware (for example, graphics processing units, GPUs) to achieve acceptable run times.	High
Transfer of simulation results – each execution produces a single 2D grid	High

Description	Priority
of flood depth at 50m × 50m resolution.	
Appropriate sources of real-time boundary conditions. PoC is driven by a snapshot of return periods across the river network. A robust relationship is required to convert telemetered flow/level into return period at each gauging station.	High
Integration within forecasting systems (for example, general adapters or application programming interfaces, APIs) is required to populate model boundaries and execute the model run).	Medium
Post-processing of model runs will require GIS routines to intersect modelled flood outlines/depths with receptors (for example, properties). These routines may be time-consuming to run for large and/or multiple Flood Areas.	Medium

Table 5.2 Detailed considerations

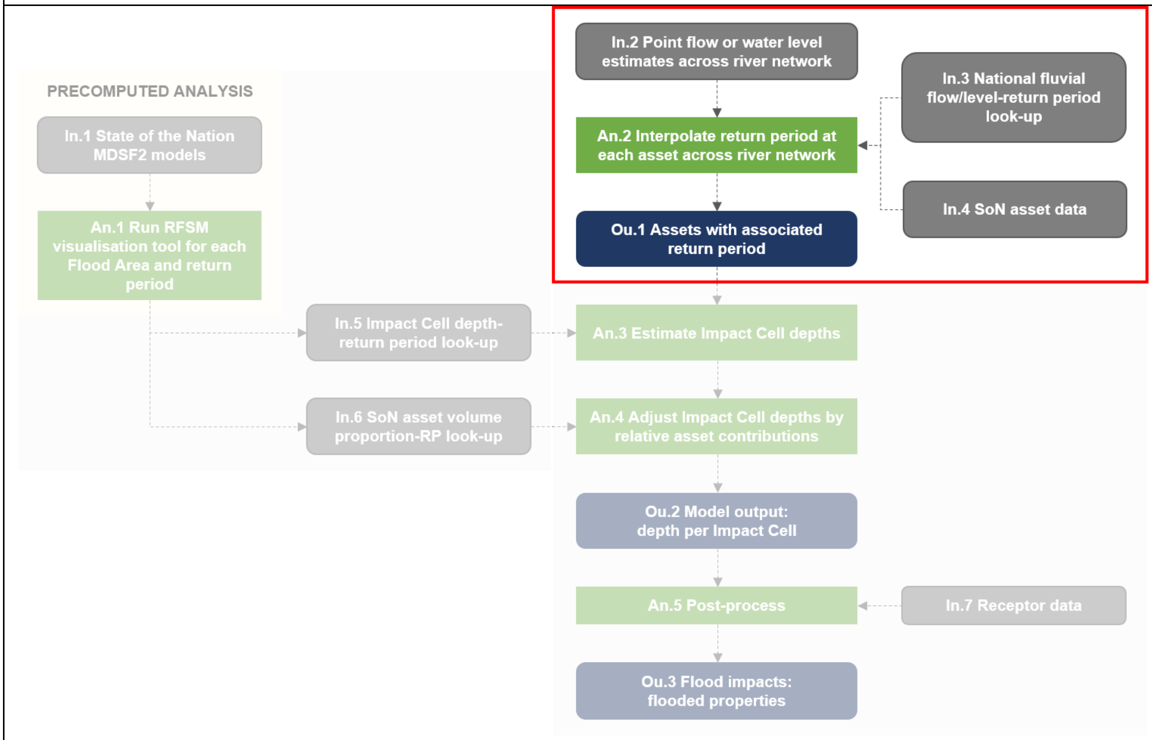
Pre-computed analysis to produce underlying look-ups (In.1, An.1, In.5, In.6)



Description	State of the Nation MDSF2 baseline models are run offline within the RFSM visualisation engine to produce the look-ups that underpin the simulation library PoC. Data values within the look-ups are subject to the same method and data caveats as standard 'MDSF2 for NaFRA' risk modelling.
Data overheads	High – look-ups for PoC development were supplied in .csv format for expediency and many options exist to reduce these file sizes considerably. Data structure, format and file size should be considered alongside their efficiency for use within an operational

	system.
Run times	Look-up production is an entirely automatable process that can be scaled across multiple processing units as required. Run times for look-up production do not affect real-time operation.
Software	Functionality to produce the required look-ups is not currently available ‘as standard’ within the RFSM visualisation engine.
Hardware	Look-up production does not require specialist hardware.

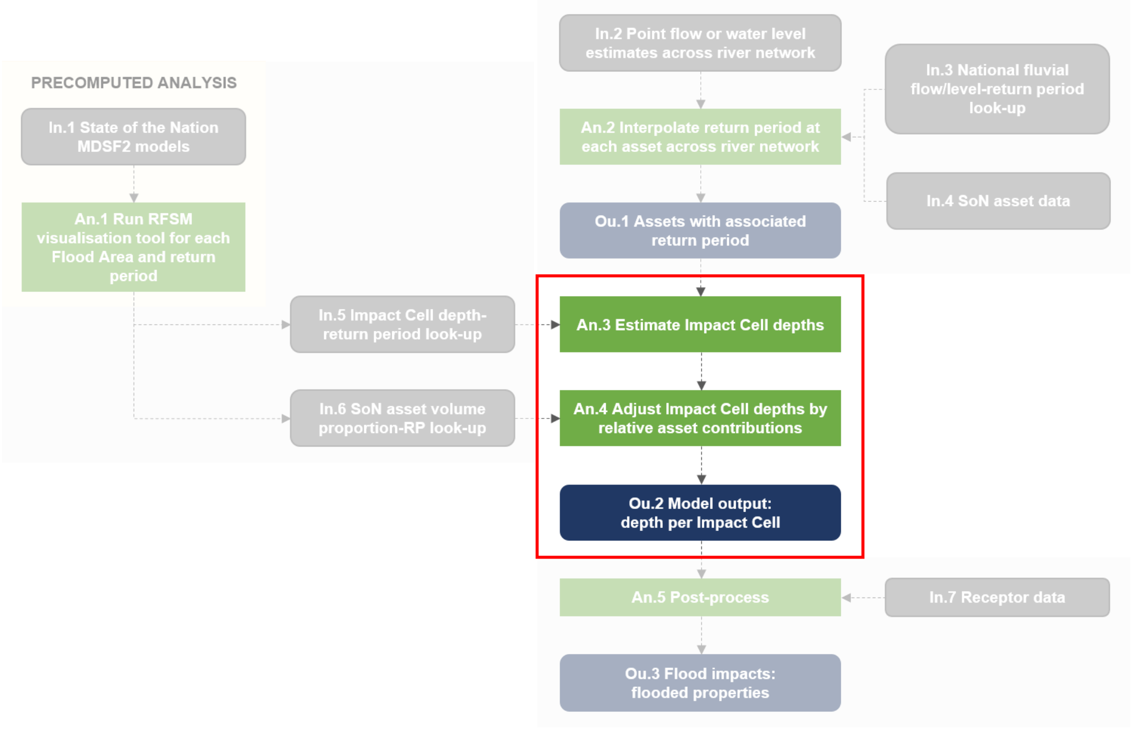
‘At-an-instant’ return period assigned to each asset along channel–floodplain interface across river network (In.2, In.3, In.4, An.2, Ou.1)



Description	Flow/level information, already collected in real time through the telemetered monitoring network, is converted to return period and interpolated across the river network to derive a return period at each asset along the channel–floodplain interface. An average return period across the Flood Area is then calculated from the per asset information. Accurate flow/level information and robust relationships for return period conversion are key inputs to the interpolation process. Moreover, as with any interpolation process, the result across the river network will be sensitive to the choice of a particular method and the parameters therein. However, there has been very little work done to date comparing different methods for this type of interpolation.
Data overheads	Low – single flow/level/return period values stored at each gauging station location Updated asset data 100KB to 10MB depending on the simulation

	extent
Run times	Low – run times are very short as all associations between gauge locations, flow/level–return period look-ups and assets are pre-determined offline.
Software	Spatial relationships can be pre-determined using standard GIS functionality. Bespoke scripts/software will need to be developed to run the interpolation and output the updated asset data.
Hardware	Return period look-up and interpolation does not require specialist hardware.

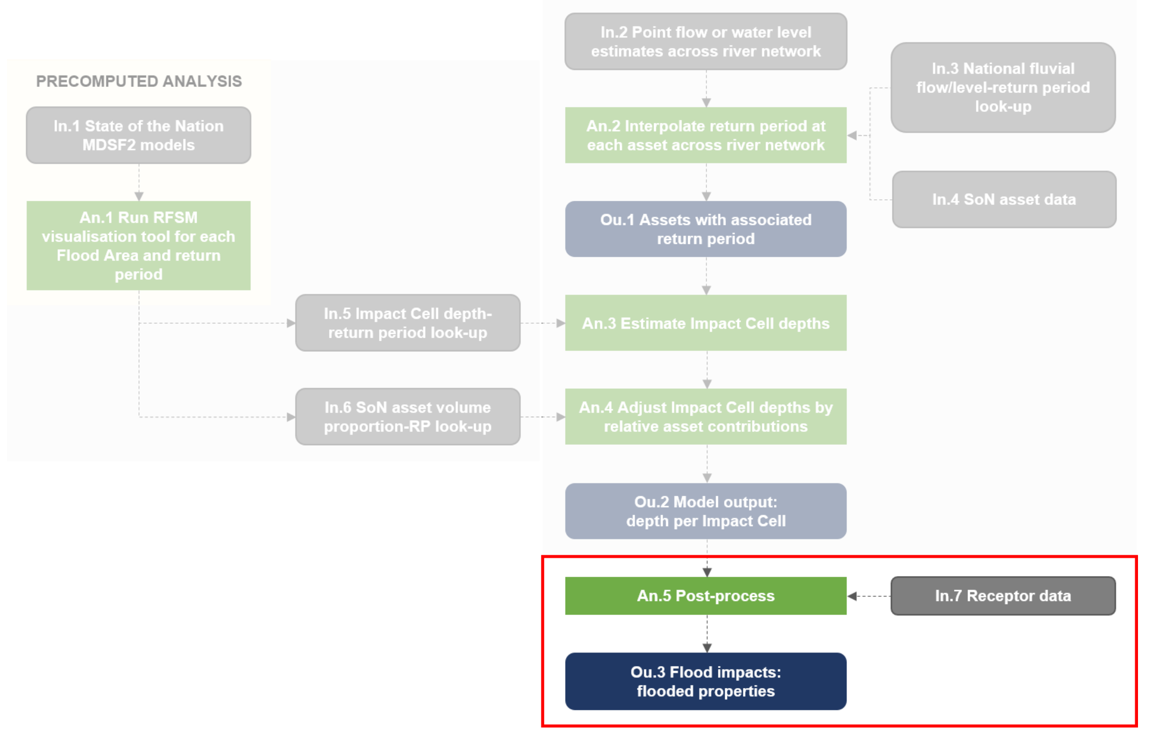
Apply look-ups to derive ‘at-an-instant’ flood depth for each Impact Cell (An.3, An.4, Ou.2)



Description	The Flood Area averaged return period is combined with the pre-computed look-ups to determine a depth of flooding in each Impact Cell at that moment in time.
Data overheads	Look-ups can potentially be large depending on the simulation extent, but data sizes could be managed efficiently in an operational system by evaluating flood depths on a Flood Area by Flood Area basis. In other words, look-ups could be organised and accessed one Flood Area at a time. Output file size is very small as each execution produces only a single 2D grid of flood depth at 50m × 50m resolution.
Run times	Low – run times are in the order of 1–10 minutes and potentially much less if run on a Flood Area by Flood Area basis across multiple processing units.

Software	Bespoke scripts/software will need to be developed. Look-up process is relatively straightforward and so development effort is more likely to focus on optimisation for real-time use.
Hardware	Specialist hardware not required but will be run most efficiently across a multicore/CPU system.

Undertake and report flood impacts analysis (In.7, An.5 and Ou.3)



Description	Output flood depth map is combined with information on receptors (for example, contained within the NRD) to understand the potential consequences of flooding at that moment in time. Use of flood map data for impacts analysis is well documented in other sources and so is not considered further here.
Data overheads	Low – for a single inundation snapshot, but largely dependent on the number of metrics calculated and how the results of the impacts analysis are stored (for example, as summary tables or as depth-attributed individual receptor features).
Run times	Low – impact analyses are typically very quick for low resolution model outputs even over large areas.
Software	GIS software is required to intersect model outputs with receptor data and perform the impacts calculations.
Hardware	Flood impacts analysis based on low resolution model outputs are unlikely to require specialist hardware.

5.2 Implementation and ongoing maintenance of an operational system

<table>
<tr><td colspan="4">Overview</td></tr>
<tr><td colspan="4">This option will require look-up tables to be generated, albeit automatically, for all Flood Areas across England from the State of the Nation MDSF2 models. It will also require further testing and development of methods and tools for interpolating return periods across the river network. Finally, flow/level–return period relations at telemetered gauging stations will need to produced or collated (if available from previous studies).

The look-up tables required to support a nationwide implementation are potentially very large datasets and will require careful organisation to be used efficiently within an operational system. Although specialist hardware is not required to achieve acceptable run times for a single execution across small areas, care should be taken when designing any future software implementation to ensure that multiple Flood Areas can be processed simultaneously.

Ongoing maintenance will only be required where new MDSF2 modelling is undertaken. However, assuming the MDSF2 software is updated to allow automatic production of the required look-ups, new data can be swapped in/out very efficiently on a Flood Area by Flood Area basis, potentially as part of the NaFRA quarterly update process.</td></tr>
<tr><td colspan="4">Implementation</td></tr>
<tr><td rowspan="2">Change required</td><td>Low</td><td>Moderate</td><td>Significant</td></tr>
<tr><td colspan="3">The option represents a significant step change away from how flood extent/depth information is typically produced within the Environment Agency. However, simulation library outputs of flood depth/extent (and associated impacts) will be familiar to most users.

Look-ups are based on MDSF2 modelling that is not always trusted at the local level (despite the considerable effort put into State of the Nation model preparation). Relevant limitations (that is, conceptual, data) of the underlying MDSF2 modelling will require careful explanation to ensure that the limitations of the approach and outputs are understood.

Implementation would require bespoke software to be written that could interface with the telemetry network via the Flood Early Warning System (FEWS) – the forecasting software that underpins the Environment Agency’s National Flood Forecasting Service (NFFS). Potentially very large look-up table datasets would need to be stored and accessed efficiently by the software.</td></tr>
<tr><td rowspan="2">Cost to implement</td><td>Low</td><td>Moderate</td><td>Significant</td></tr>
<tr><td colspan="3">Existing models and software are used to derive the look-up tables that underpin this option. However, the look-up tables are not produced by default within the current version of the RFSM visualisation engine and so changes to the MDSF2 software would be required to enable this in the future.

The option is conceptually straightforward and a basic workflow has been established through this study. However, the current</td></tr>
</table>

	approach would require further refinement and optimisation for any subsequent operational implementation.		
Skills required to implement	Knowledge of MDSF2 software, models and data Software development within FEWS/NFFS		
Time/effort to implement	6–12 months		
Ongoing maintenance			
Difficulty in accommodating change	**Low**	Moderate	Significant
	Look-ups would need to be re-generated when new MDSF2 modelling is undertaken in the future. However, updating can be done very efficiently on a Flood Area by Flood Area basis and the new data requested as part of the standard suite of deliverables from an MDSF2 modelling project (providing the software is updated to enable this).		
Cost to maintain	**Low**	Moderate	Significant
	Updated look-ups could be swapped in/out very efficiently on a Flood Area by Flood Area basis, potentially as part of the NaFRA quarterly update process.		
Skills required to maintain	Working knowledge of operational implementation within FEWS/NFFS		
Time/effort to maintain	Around 0.5 days per quarter		

6 Scope for further development

Table 6.1 Future data and model improvements that may benefit this option

Description	Impact	Recent examples
Extension to tidal and coastal systems	Complete national coverage for all sources of flooding for which the Environment Agency has direct responsibility	Current coastal flood forecasting methods are already predominantly look-up based (for example, TRITON)
Re-configure underlying MDSF2 models that contain very large Flood Areas	Reduce size of look-ups for largest Flood Areas to enable faster execution times and limit the effect of uniform return period assumption	–
Extension to consider breaching	Would remove the current assumption that all flood defences are in place and have not failed	–

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