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Real-time flood impacts mapping

Appendix 4a: Fully dynamic fluvial modelling

SC120023/A4

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Professor Doug Wilson
Director, Research, Analysis and Evaluation

Contents

1	**Pro-forma summary**	**1**
2	**Proof of concept overview**	**2**
2.1	About this option	2
2.2	Functional requirements	2
2.3	Workflow	3
3	**Proof of concept testing**	**5**
3.1	Case studies	5
3.2	Testing the PoC option	6
4	**Proof of concept evaluation**	**10**
4.1	Case study 1: Morpeth, September 2008	11
4.2	Case study 2: Cockermouth, November 2009	33
4.3	Case study 3: Thames, February 2014	46
5	**Implementation considerations**	**67**
5.1	Operating the system	68
5.2	Implementation and ongoing maintenance of an operational system	71
6	**Scope for further development**	**73**

List of tables and figures

Table 3.1	Summary of available case study data	5
Table 3.2	Input data (flow chart: In.1, An.1)	6
Table 3.3	Intermediate processing (flow chart: An.2)	7
Table 3.4	Output data (flow chart: Ou.1)	8
Table 4.1	Summary of PoC findings	10
Table 4.2	Description of Flood Warning Areas featured in the Morpeth case study	11
Table 4.3	Comparison of modelled and observed area flooded for each Flood Warning Area for Morpeth event	13
Table 4.4	Model performance metrics for Morpeth event	15
Table 4.5	Temporal evaluation of model performance at Morpeth on 6 September 2008	16
Table 4.6	Maximum number of flooded properties for Morpeth event	20
Table 4.7	Details of available G2G data for Morpeth event	26
Table 4.8	Number of NRD property points within the flood outlines for Morpeth event	30
Table 4.9	Temporal evolution of observed and G2G modelled flood extent and property counts, 6 September 2008	30
Table 4.10	Description of Flood Warning Areas featured in the Cockermouth case study	33
Table 4.11	Comparison of modelled and observed area flooded for each Flood Warning Area for Cockermouth event	35
Table 4.12	Model performance metrics for Cockermouth event	37
Table 4.13	Maximum number of flooded properties for Cockermouth event	39
Table 4.14	Details of available G2G data for Cockermouth event	41
Table 4.15	Number of NRD property points within the flood outlines for Cockermouth event	46
Table 4.16	Description of Flood Warning Areas featured in the Thames case study	48
Table 4.17	Comparison of modelled and observed area flooded for each Flood Warning Area for Thames event	54
Table 4.18	Model performance metrics for Thames event	59
Table 4.19	Maximum number of flooded properties for Thames event	61
Table 5.1	Key considerations in using this option within an operational forecasting system	68
Table 5.2	Detailed considerations	68
Table 5.3	Summary of implementation and maintenance issues for an operational system	71
Table 6.1	Future data and model improvements that may benefit this option	73
Figure 2.1	Evaluation matrix: fully dynamic fluvial modelling	3
Figure 2.2	Flow chart showing PoC workflow for fully dynamic fluvial modelling	4
Figure 4.1	Location map for Morpeth case study	11
Figure 4.2	Model outputs for the Morpeth case study	12

Figure 4.3	Maximum modelled and observed extent flooded (17:00 on 6 September 2008)	13
Figure 4.4	Model performance in predicting flooded extent at Morpeth (17:00 on 6 September 2008)	15
Figure 4.5	Available data for evaluation of model's temporal performance for Morpeth flood event	16
Figure 4.6	Properties within flood extent for Morpeth event	19
Figure 4.7	Model performance in predicting extent of flooding at Morpeth between 11:00 and 17:00 on 6 September 2008	24
Figure 4.8	Modelled and observed flooded depths at Morpeth between 11:00 and 17:00 on 6 September 2008	25
Figure 4.9	Hydrograph for the River Wansbeck	27
Figure 4.10	Observed and G2G simulated maximum flood extent for Morpeth event	27
Figure 4.11	G2G ensemble members: inflows to hydraulic model for Morpeth event	28
Figure 4.12	Maximum observed and maximum G2G simulation of flood extent for Morpeth event	29
Figure 4.13	Location map for Cockermouth case study	33
Figure 4.14	Model outputs for Cockermouth event	34
Figure 4.15	Maximum modelled extent compared with maximum available observed extent	35
Figure 4.16	Model performance in predicting flooded extent at Cockermouth	37
Figure 4.17	Properties within flood extent for Cockermouth event	38
Figure 4.18	Model performance in predicting extent of flooding at Cockermouth	40
Figure 4.19	Distribution of flooded depth at the peak of the flood at 02:15 on 20 September 2009	40
Figure 4.20	River Derwent hydrograph	42
Figure 4.21	River Cocker hydrograph	42
Figure 4.22	Observed and G2G simulated maximum flood extent for Cockermouth event	43
Figure 4.23	River Derwent inflows to hydraulic model	44
Figure 4.24	River Cocker inflows to hydraulic model	44
Figure 4.25	Maximum observed and maximum G2G simulation of flood extent for Cockermouth event	45
Figure 4.26	Observed and modelled outlines used to assess the PoC	47
Figure 4.27	Observed flow hydrograph at the Walton gauge	48
Figure 4.28	Context for model outputs for Thames case study	50
Figure 4.29	Context for model outputs in Chertsey domain	51
Figure 4.30	Best available maximum modelled extent compared with maximum available observed extent for Maidenhead domain (inset 1 in Figure 4.26)	52
Figure 4.31	Best available maximum modelled extent compared with maximum available observed extent for Bray, Cippenham and Windsor domains domain (inset 2 in Figure 4.26)	52
Figure 4.32	Best available maximum modelled extent compared with maximum available observed extent for Windsor and Staines domains (inset 3 in Figure 4.26)	53
Figure 4.33	Best available maximum modelled extent compared with maximum available observed extent for Staines and Chertsey domains domain (inset 4 in Figure 4.26)	53
Figure 4.34	Model performance in predicting flooded extent for Maidenhead domain (inset 1 in Figure 4.26)	56
Figure 4.35	Model performance in predicting flooded extent for Bray, Cippenham and Windsor domains (inset 2 in Figure 4.26)	57
Figure 4.36	Model performance in predicting flooded extent for Windsor and Staines domains (inset 3 in Figure 4.26)	57
Figure 4.37	Model performance in predicting flooded extent for Staines and Chertsey domains (inset 4 in Figure 4.26)	58
Figure 4.38	Properties within flood extent for Thames event	61
Figure 4.39	Closest modelled time step to validation data for Maidenhead domain (inset 1)	63
Figure 4.40	Closest modelled time step to validation data for Bray, Cippenham and Windsor domains (inset 2)	64
Figure 4.41	Closest modelled time step to validation data for Windsor and Staines domains (inset 3)	64
Figure 4.42	Closest modelled time step to validation data for Staines and Chertsey domains (inset 4)	65
Figure 4.43	Distribution of flooded depths (02:00 on 9 February 2014)	65
Figure 5.1	Flow chart showing PoC workflow for fully dynamic fluvial modelling	67

1 Pro-forma summary

This option applies fully dynamic fluvial models to predict extents, depths, hazard and velocity. These models provide the most detailed available flood mapping that is routinely available to the Environment Agency in terms of both the level of topographic detail and representation of flow processes (solving the 1D and 2D shallow water equations). Fully dynamic models are widely used by the Environment Agency and other organisations to produce detailed floodplain mapping for a range of applications including:

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

They therefore meet all the technical user requirements for real-time flood impacts mapping identified in the consultation for this project (see Appendix 1).

However, fully dynamic fluvial modelling of the type typically available to the Environment Agency is computationally expensive and does not meet the run time constraints of forecasting in real time.[1] This is not an inherent limitation of the software or data. Shorter run times could be obtained in future, given appropriate hardware and considerations over the level of complexity incorporated into the model.

Fully dynamic fluvial modelling was added as an option at the proof of concept (PoC) stage of the project (that is, after the Technical Options Report was written[2]) as 'Option 14' – a baseline option to compare the PoC options against. As a technology in operational use today, the option is essentially a representation of the best information available, though it cannot be the preferred option for real-time flood impacts mapping for the reasons given above.

[1] In operational use for static mapping (that is, non-real time), model run times are typically days to weeks, when seconds to minutes are required for real-time mapping.
[2] The report is provided as Appendix 2 for completeness to describe the findings of an important early stage of the project and to present useful evidence, data and assessments.

2 Proof of concept overview

2.1 About this option

Name in Technical Options Report: not applicable (see Section 1)

Number in Technical Options Report: not applicable

This option applies a linked 1D–2D hydrodynamic model to generate maps of flood extent and depths. River channels are simulated in 1D modelling software and are dynamically linked to a 2D model of the floodplain.

Flow time series are applied at upstream model boundaries. Levels may also be applied, for example, at a tidal downstream boundary. In the PoC, observed time series at gauging stations are used to provide model boundary conditions. Operationally, forecast flows from the National Flood Forecasting System (NFFS) or Grid-to-Grid (G2G) could be used instead.

1D–2D modelling is widely used by the Environment Agency and other organisations to produce detailed floodplain mapping in terms of both the level of topographic detail (typically high resolution Digital Terrain Models (DTMs), with the possibility to represent defences and other structures) and representation of flow processes (the 1D and 2D shallow water equations).

In 1D–2D models, a range of approaches are used to represent buildings, which may influence how flood impacts are assessed. For example, a building represented as a footprint raised to a surveyed threshold level may not be shown as flooded until water levels exceed the threshold (as in the Morpeth case study in Section 4.1), whereas a building represented as a ‘flat’ semi-porous footprint may appear to be within the modelled flood extent (as in the Cockermouth and Thames case studies in Sections 0 and 4.3 respectively). Both are standard approaches to building representation, but may require consideration in post-processing of model results to derive flood extent outlines.

As the most detailed flood mapping tool routinely available to the Environment Agency, outputs from 1D-2D models were used in this project as a baseline against which other options could be compared. All the case studies reuse existing models that have been calibrated, validated and accepted for use by the Environment Agency.

2.2 Functional requirements

The Technical Options Report (provided as Appendix 2) 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	Y		
FLOOD HAZARD	1D water levels	2D flood extents	2D flood depths / water levels	2D velocities and / or hazard rating	
	Y	Y	Y	Y	
TEMPORAL INFORMATION	Onset of floodplain inundation	Time of maximum inundation	Duration of flooding	Dynamic representation of floodplain drying	
	Y	Y	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	Y	Y
ASSET REPRESENTATION	Flood defences	Culverts and bridges	Other structures (e.g. gates, sluices, storage areas, pumping stations)		
	Y	Y	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	
	Y	Y	Y	Y	
TRANSPARENCY	Individual components can be interrogated / evaluated	Closed system, simplified model-wide confidence statements			
	Y				

Figure 2.1 Evaluation matrix: fully dynamic fluvial modelling

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)

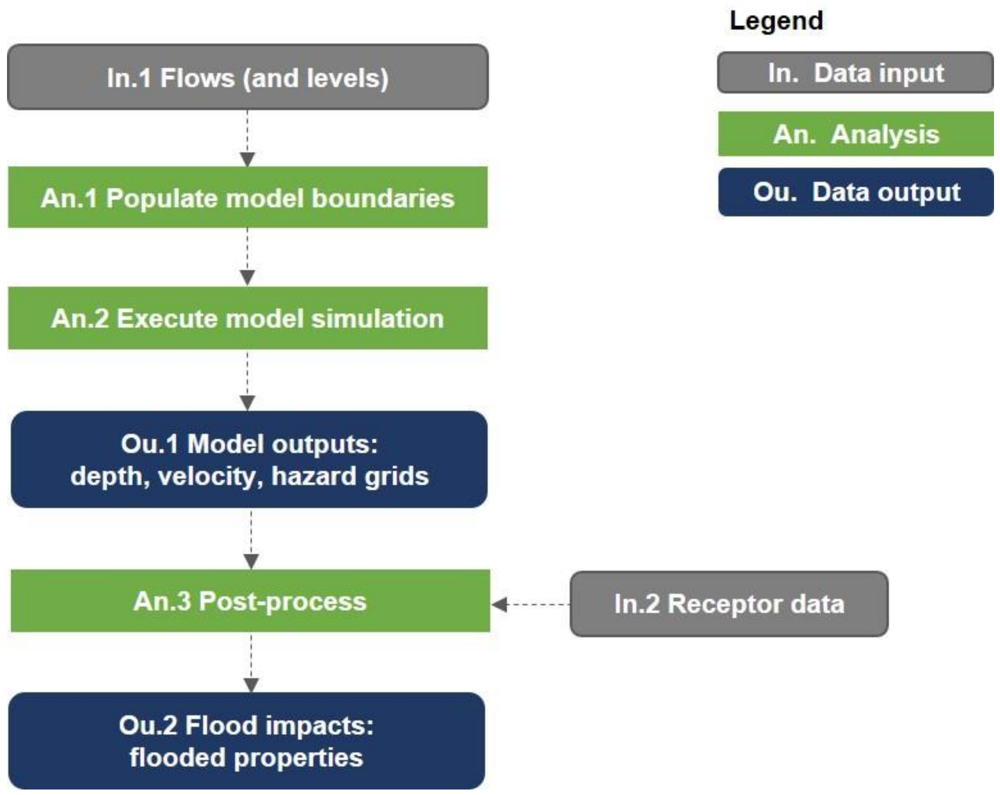


Figure 2.2 Flow chart showing PoC workflow for fully dynamic fluvial modelling

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	06–17 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[1]	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% performed 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.

3.2 Testing the PoC option

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

3.2.1 Input data

Table 3.2 Input data (flow chart: In.1, An.1)

Model files and source	**Morpeth:** Wansbeck Flood Alleviation Scheme (JBA Consulting report, 2011) LIDAR DTM flown in 2009 MOR_117_AM_2008_B0.tcf MOR_117_AM_2008_B0.ecf **Cockermouth:** River Derwent model update (Capita URS report, 2014) LIDAR DTM flown in 2009 Cockermouth_v1.dat Coc_Nov09_V2.ief Coc_Nov09_v2.tcf Coc_Nov09_v2.ecf **Thames:** Lower River Thames Flood Modelling Study (JBA Consulting report, 2015) LIDAR DTM flown in 2009 Master_Thames_DM_031_D.dat THAMES_CAL_2014 (FEB)_A.ief Thames_005_Review.tcf
Required inputs	Flow–time series are the main boundary condition to this option. Where time series from gauging stations have been used, their NaFRA ID is given in parentheses. **Morpeth** (22007) Mitford gauging station. Design flow time series on 3 burns derived using the Flood Estimation Handbook (see Wansbeck Flood Alleviation Scheme report for details of ungauged inflows) **Cockermouth** (75003) Ouse Bridge gauging station (75004) South Bridge gauging station 6 Revitalised Flood Hydrograph (ReFH) boundaries scaled

	to flood estimates 24 unscaled ReFH boundaries representing tributary inflows 28 ReFH boundaries representing lateral inflows. (see River Derwent model update report for details of ungauged inflows) **Thames** (39128) Addlestone (no ID) Chertsey Bourne (39001) Kingston (no ID) Maidlow[1] (39130) Reading (39111) Staines (no ID) Staines Moor (no ID) Staines Trading Estate (no ID) Thorpe (39121) Walton (39079) Weybridge (39072) Royal Windsor Park 64 flow–time boundaries representing lateral inflows, sweetening flows and ungauged inflows (see Lower River Thames Flood Modelling Study report for details of ungauged inflows)
File formats	Flow and/or level time series used to populate ISIS model event files (*.ied)
Data overheads	Input files are of negligible size (around 200)

Notes: [1] A combination of flows from the Maidenhead and Taplow sluices

3.2.2 Intermediate processing

Table 3.3 Intermediate processing (flow chart: An.2)

Software	
ISIS-TUFLOW (Thames, Cockermouth) and ESTRY-TUFLOW (Morpeth) Requires licences for use of ISIS, TUFLOW and ISIS-TUFLOW linking.	
Hardware	
Description	Runs were made on PCs with 3.20–3.60GHz CPUs and 16–32GB of RAM.

	Morpeth: 3.60GHz, 16GB RAM Cockermouth: 3.20GHz, 32GB RAM Thames: 3.40GHz, 16GB RAM
Size of model files (excluding outputs)	For 1D–2D hydraulic models, the constituent files include model geometry (DTM, GIS files) and run files (typically in plain text format). Morpeth: 1.75GB Cockermouth: 192MB Thames: 3.54GB
Network logistics	Intermediate run files were stored on the local hard drive of each PC.
Run times	Morpeth: 22.90 hours for 55 hours of simulation data Cockermouth: 15.64 hours for 400 hours of simulation data Thames: 382.77 hours for 205 hours of simulation data
Size of model domain	Morpeth: 5.62km^2; 2m resolution; 1,410,400 grid cells Cockermouth: 9.46km^2; 5m resolution; 380,000 grid cells Thames: 443km^2 total area designated for modelling (of which 59.5km^2 is covered by 1D cross-sections only); 10m resolution; 3,835,200 grid cells
Building representation	Morpeth: raised to threshold or by 0.3m where no surveyed threshold levels available Cockermouth: 'flat' semi-porous Manning's n 1.0 Thames: 'flat' semi-porous Manning's n 0.5

3.2.3 Output data

Table 3.4 Output data (flow chart: Ou.1)

Outputs provided	1D time series of flow and level in csv format In the Cockermouth and Morpeth studies, 1D results are also mapped using water level lines to interpolate model results between cross-sections for display in a 2D domain. 2D grids of overbank depth, velocity and hazard rating as .xmdf/.dat – can be subsequently converted into ASCII format	
File sizes	Results in .xmdf format (for the full event)	A single ASCII grid (for a single time interval)
Morpeth	1.7GB	51.8MB
Cockermouth	835MB	1.83MB
Thames	5.2GB	184MB

3.2.4 Post-processing

Flow chart: In.2, An.3, Ou.2

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 findings are summarised in Table 4.1.

Table 4.1 Summary of PoC findings

Case study	Findings
Morpeth	Overall, predictions of flood extent provide a good fit to available observations (skill score = 0.76 when comparing the maximum modelled and observed flood extents, see Section 4.1.4 below for definition). Overall, bias towards underprediction or overprediction is limited, ranging between 0.82 and 1.22 across 7 separate hourly time intervals through the event. However, there are a number of residential locations where the model underpredicts and, as a result, the model appears to underpredict flood impacts. In these areas, surface water flooding was known to contribute to the observed flood extent and thus may help to explain the apparent underprediction by the model (which only simulates fluvial flooding). There are also fewer wrack marks available in these locations, particularly in the Allery Banks area, which may add some uncertainty to observed depths.
Cockermouth	Predictions of flood extent match well with the observed. Bias ranges between 0.79 and 1.00, with underprediction in some residential locations such as the Derwentside Gardens area to the north-east of Cockermouth town centre. However, this may also be associated with uncertainties in the observed outline, which was manually digitised from aerial photography.
Thames	Predictions of flood extent demonstrate bias towards overprediction, particularly in built-up locations including Datchet, Old Windsor and Staines-upon-Thames. This may be associated with uncertainties in the observed outline, which was digitised from satellite radar. There is some limited underprediction in less developed areas. This may be attributed to small drainage channels not being represented explicitly in the model. This is generally appropriate, given that larger channels are the dominant drivers of fluvial flood risk to property and introducing small drainage channels has the potential to cause model stability issues, given the relatively coarse model grid resolution.

4.1 Case study 1: Morpeth, September 2008

4.1.1 Location

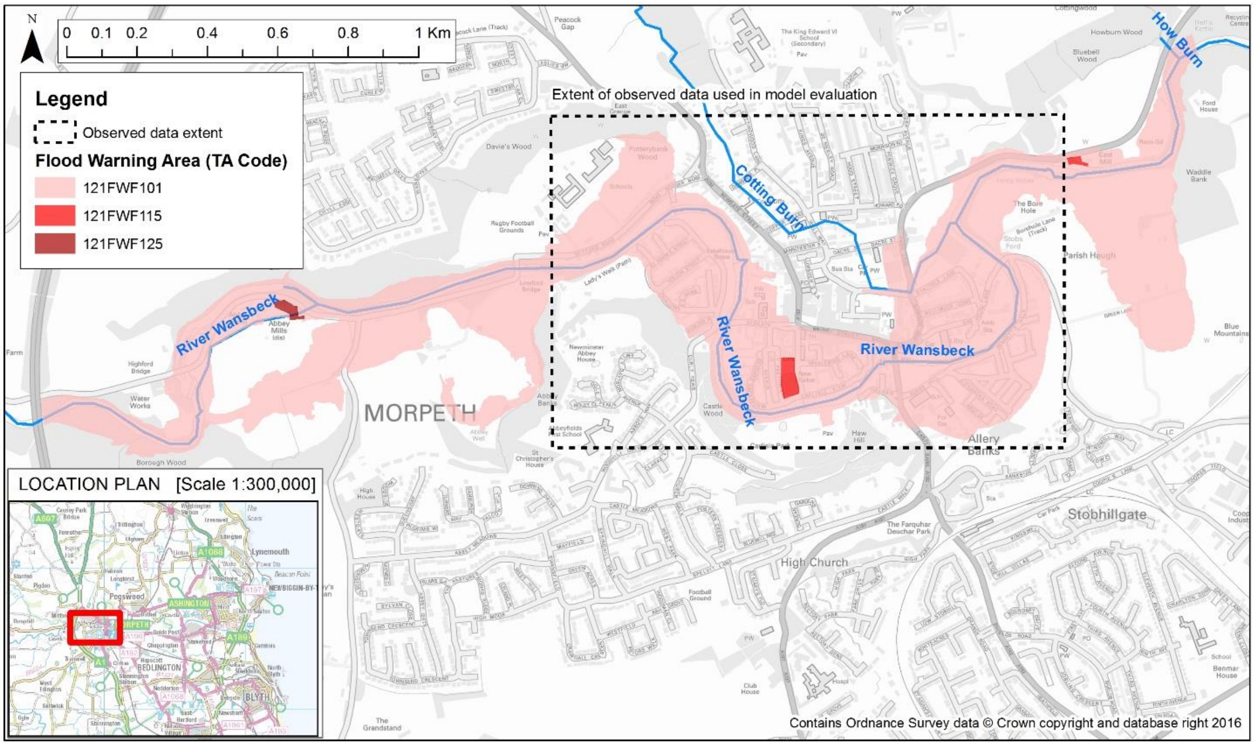


Figure 4.1 Location map for Morpeth case study

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

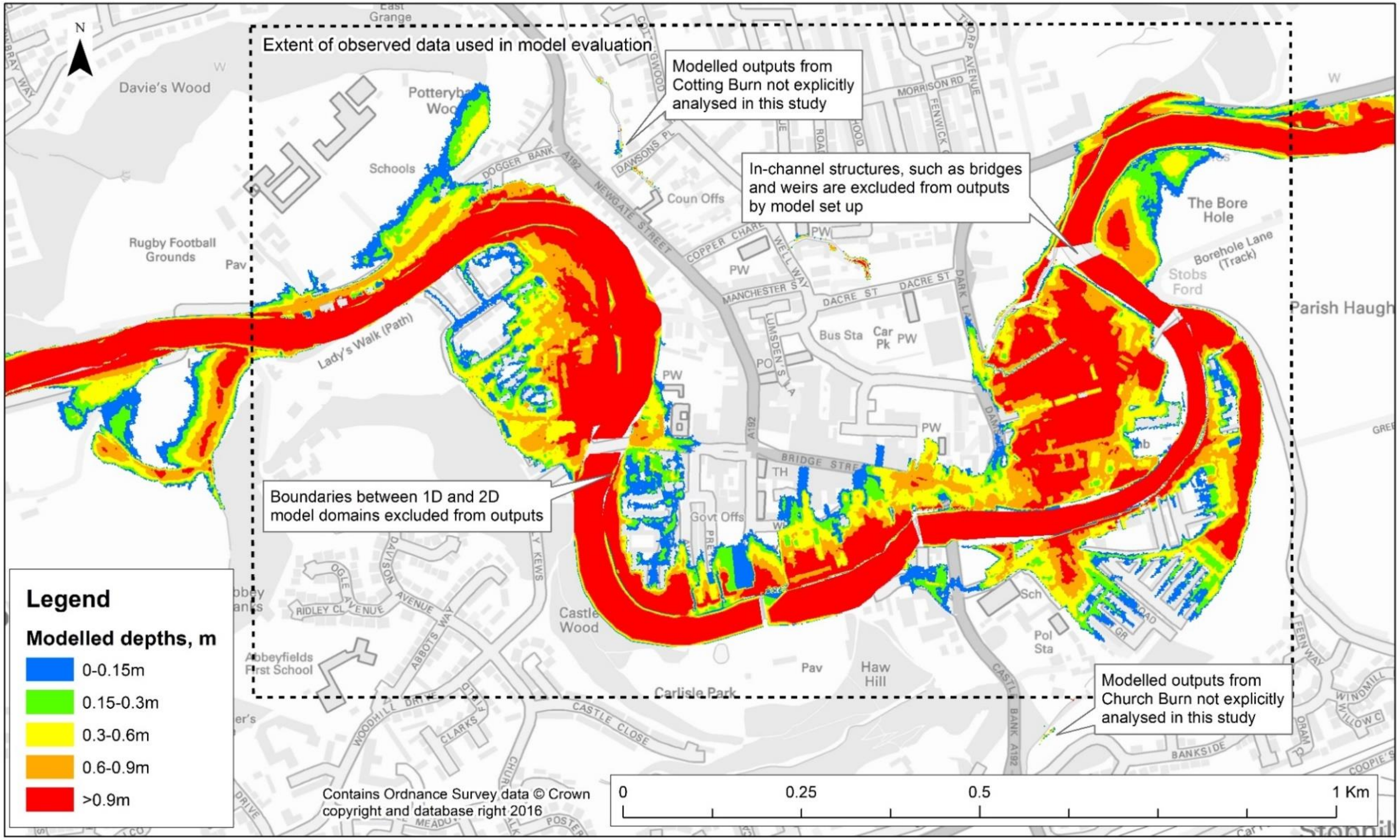


Figure 4.2 Model outputs for the Morpeth case study

4.1.3 Extent flooded (Test A1)

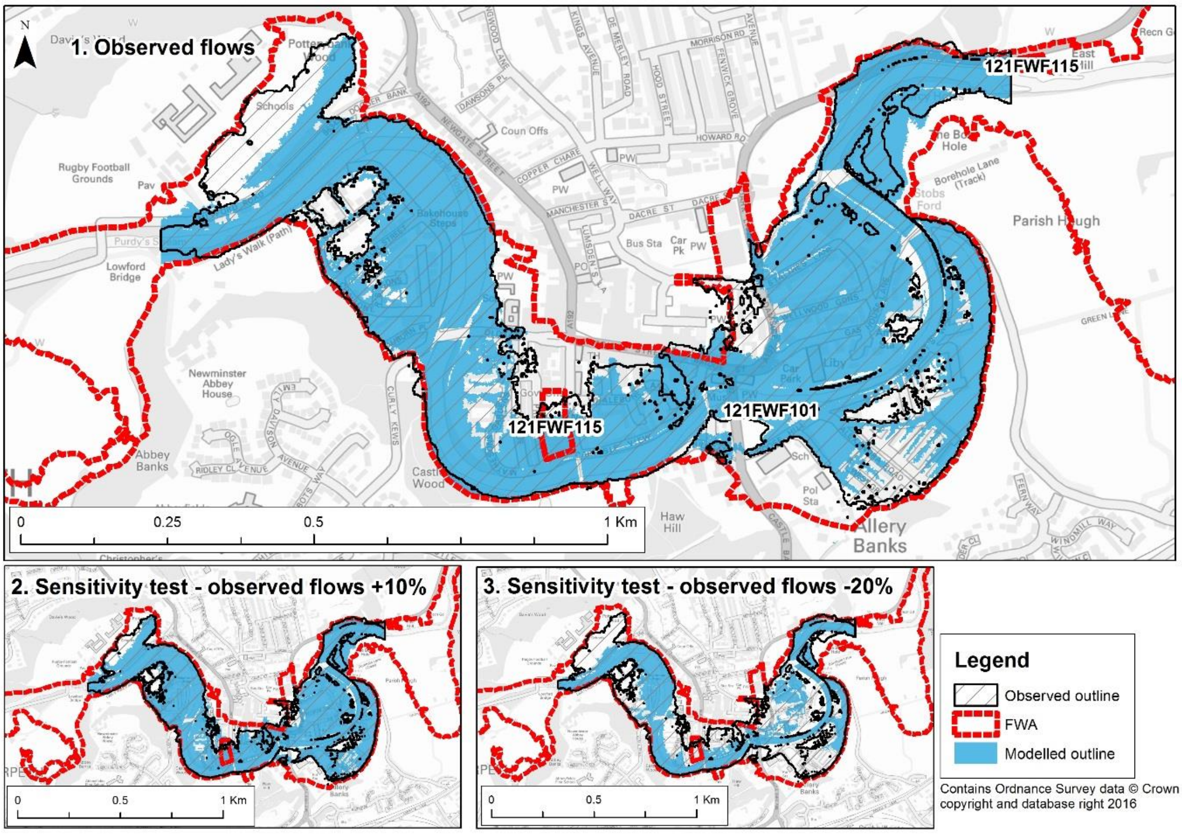


Figure 4.3 Maximum modelled and observed extent flooded (17:00 on 6 September 2008)

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

Flood Warning Area (FWA)	Area (m^2)	Area flooded			
		Modelled		Observed	
		m^2	% of FWA	m^2	% of FWA
All	586,998	386,443	65.83	439,788	74.92
121FWF101	582,260	383,295	65.83	435,947	74.87
121FWF115	4,738	3,148	66.44	3,841	81.07
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

Overall, the model performs well, accurately replicating the observed flood extent in most areas. Note that the model results have been trimmed to the extent of observed data for display purposes. Underprediction of flood extent in the Allery Banks area and to the school fields on Mitford Road is likely to be due to surface water flooding, which is not modelled in this PoC. This hydraulic only model simulates fluvial flooding.

The modelled flood outline is particularly sensitive to variations in flow (see sensitivity tests). Accurately quantifying flow inputs to the system is therefore required for accurate prediction of flood extent.

The model's sensitivity was increased by increasing flows by 10%. Initially, an increase of 20% was tested, but this resulted in model instability. Operational implementation of this option (discussed in Section 5) would therefore need to consider the robustness of 1D–2D models to high flow events, particularly those beyond the standard range of design AEPs.

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.

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

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

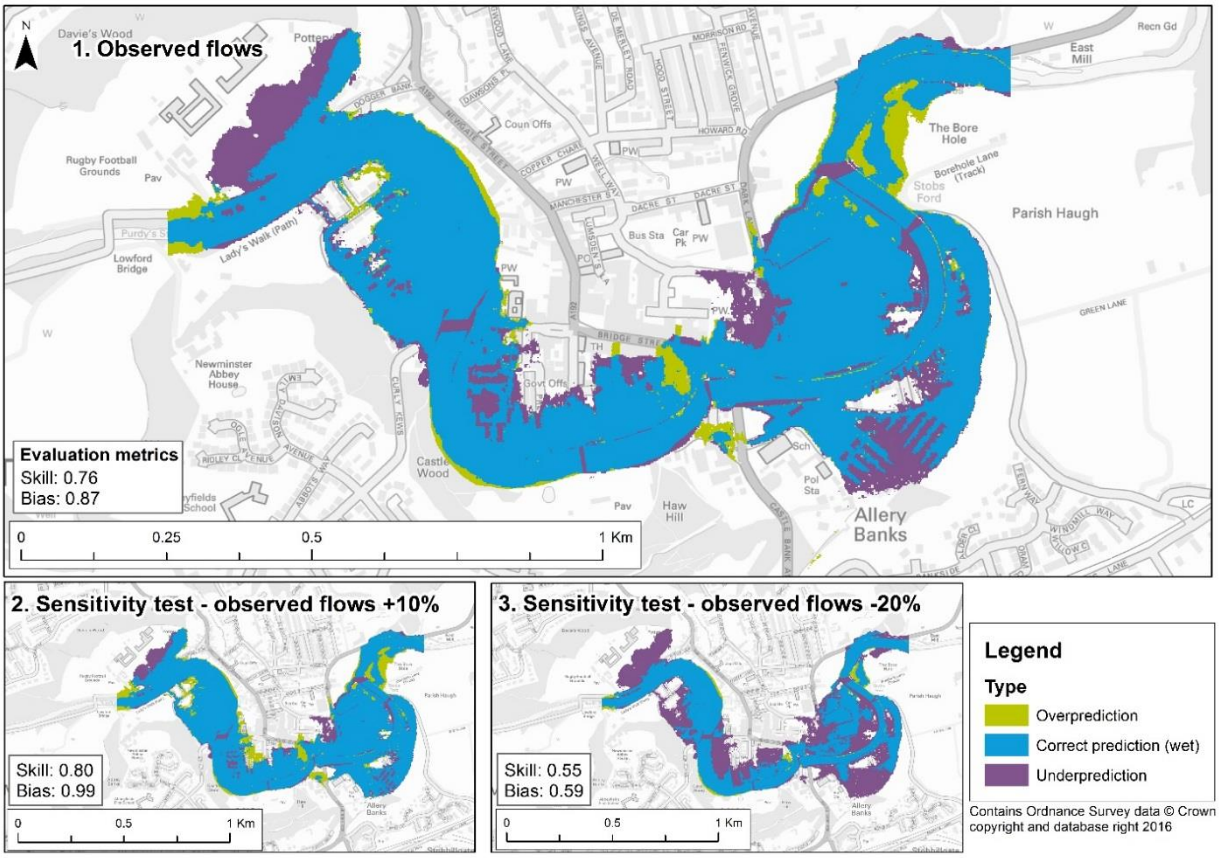


Figure 4.4 Model performance in predicting flooded extent at Morpeth (17:00 on 6 September 2008)

Table 4.4 Model performance metrics for Morpeth event

Flood Warning Area	Correct wet (%)	Over-prediction (%)	Under-prediction (%)	Skill	Bias
Modelled outline (all)	**75.83**	**6.15**	**18.03**	**0.76**	**0.87**
Modelled outline (within area covered by Flood Warning Areas only)	**76.44**	**6.08**	**17.48**	**0.76**	**0.88**
121FWF101	76.39	6.13	17.48	0.76	0.88
121FWF115	82.06	0.19	17.75	0.82	0.82
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

As shown above, the model predicts correctly in most areas. There is a slight bias towards underprediction shown in both Figure 4.4 and Table 4.4, with flood extents in the north-west (Morpeth Middle School) and south-south-eEast of the model domain (Allery Banks/Middle Greens) underpredicted by the model. However, surface water flooding is known to have occurred in these areas during the 2008 event, contributing to the observed flood extent; this hydraulic model only simulates fluvial flooding.

Model performance – temporal

Seven observed depth maps were available for 6 September 2008, at one-hourly intervals from 11:00 to 17:00.

The hydrograph (observed levels at Oldgate Bridge in Morpeth town centre) in Figure 4.5 shows the times of each depth map observations in the context of the event.

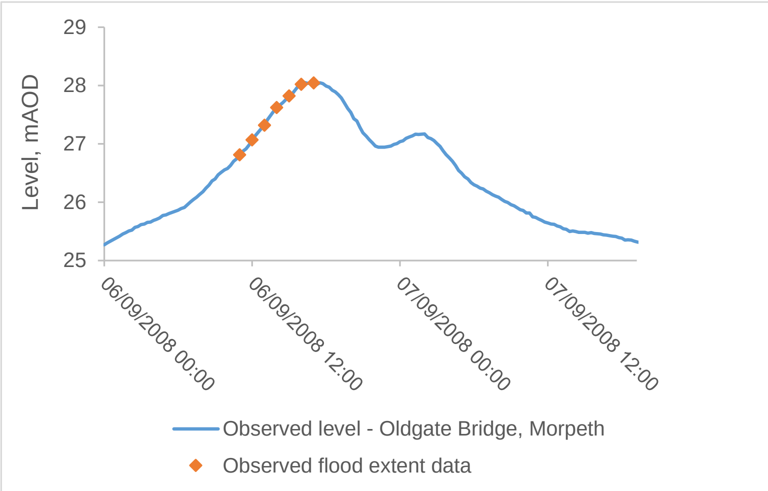
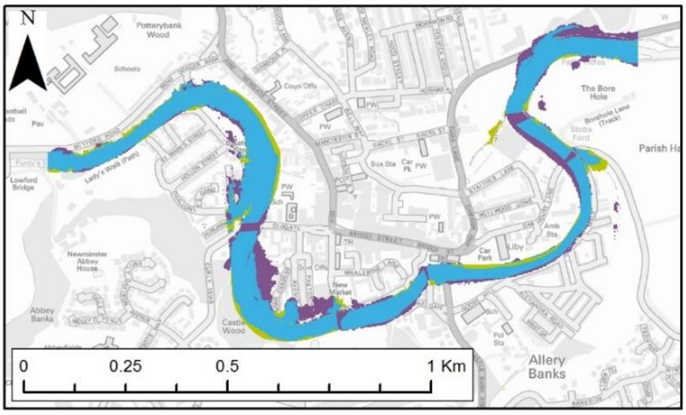
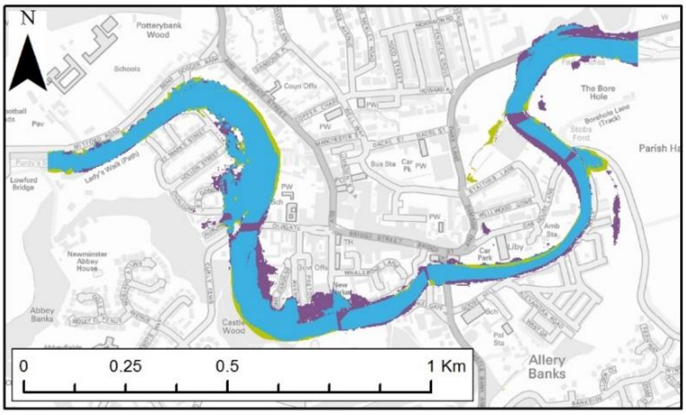


Figure 4.5 Available data for evaluation of model's temporal performance for Morpeth flood event

Table 4.5 Temporal evaluation of model performance at Morpeth on 6 September 2008

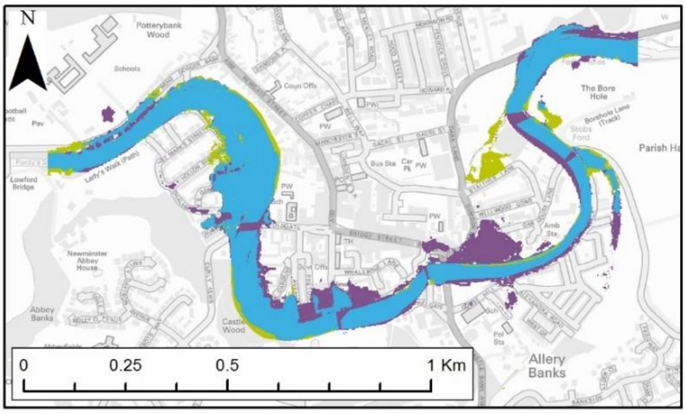
11:00			
		Correct wet (%)	70.78
		Overprediction (%)	8.47
		Underprediction (%)	20.75
	–	Skill	0.71
	–	Bias	0.87

12:00



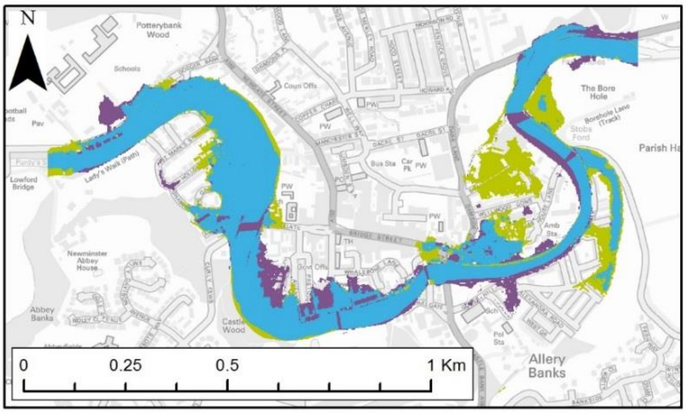
	Correct wet (%)	71.92
	Overprediction (%)	7.37
	Underprediction (%)	20.71
–	Skill	0.72
–	Bias	0.86

13:00

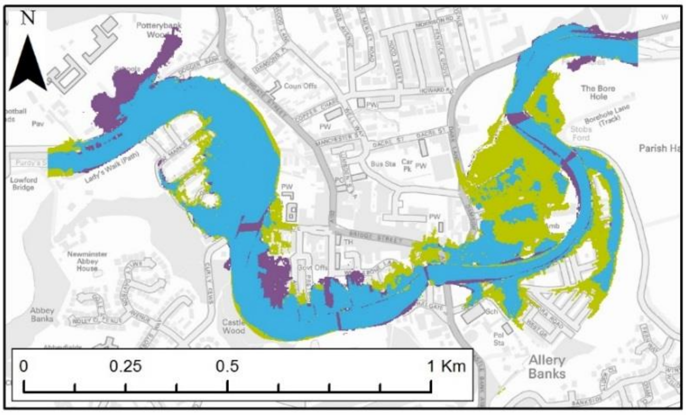


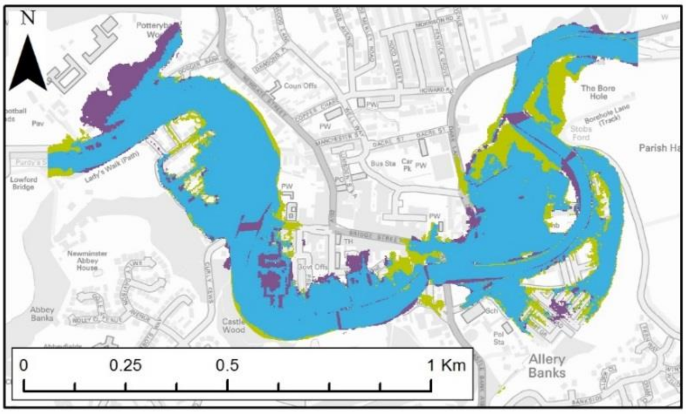
	Correct wet (%)	66.13
	Overprediction (%)	9.63
	Underprediction (%)	24.23
–	Skill	0.66
–	Bias	0.84

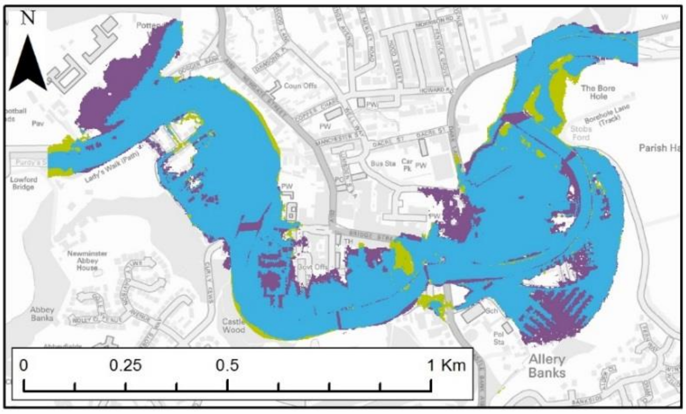
14:00



	Correct wet (%)	64.49
	Overprediction (%)	19.78
	Underprediction (%)	15.73
–	Skill	0.64
–	Bias	1.05

15:00			
		Correct wet (%)	60.81
		Overprediction (%)	27.41
		Underprediction (%)	11.77
	–	Skill	0.61
	–	Bias	1.22

16:00			
		Correct wet (%)	74.21
		Overprediction (%)	13.97
		Underprediction (%)	11.81
	–	Skill	0.74
	–	Bias	1.03

17:00			
		Correct wet (%)	75.48
		Overprediction (%)	18.61
		Underprediction (%)	5.91
	–	Skill	0.75
	–	Bias	0.87

Interpretation

As shown in Table 4.5, performance varies with each time slice, although the model still predicts correctly in most areas.

There is a slight bias towards underprediction between 11:00 and 13:00 and also at 17:00. In contrast there is a tendency towards overprediction between 14:00 and 16:00.

This variation may be associated with uncertainties in the timing and magnitude of flooding from the 3 burns (Cotting, Church and Postern). Some areas were affected by flooding from both the River Wansbeck and the burns, and it is difficult to distinguish the different sources of flooding in the modelled and observed outlines. For example, in the area around Staithes Lane where Cotting Burn discharges to the Wansbeck, flooding occurs from overtopping of the Wanbeck left bank and also Cotting Burn right bank.

Variation in model skill may also be associated with uncertainty in the observed outlines. Areas where the model is shown to overpredict and underpredict at different time intervals (such as the Allery Banks/Middle Greens district) correspond to areas of greater uncertainty in the observed flood extents. As part of the dynamic flood reconstruction study undertaken by Newcastle University (Parkin 2010), point observed water levels were interpolated to create the observed outline. Allery Banks and Middle Greens are areas where fewer point observations of water levels were available and the outline will therefore be less certain in these areas.

There is also some underprediction around the Leisure Centre in Morpeth, particularly between 12:00 and 14:00. A wall here is known to have collapsed during the September 2008 event and this breach was not modelled in this PoC.

4.1.5 Property counts (Test B)

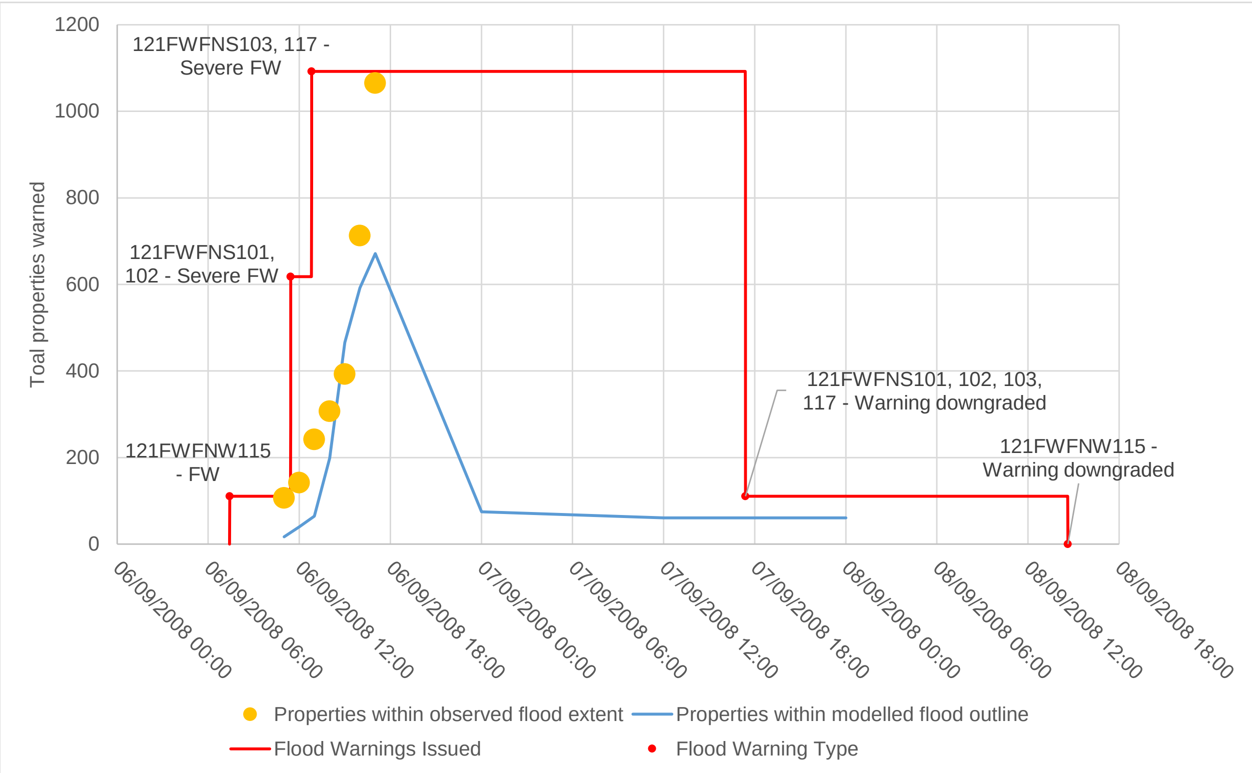


Figure 4.6 Properties within flood extent for Morpeth event

Notes: Properties are mapped below.

Table 4.6 Maximum number of flooded properties for Morpeth event

Flood Warning Area	Properties warned[1]	Observed[2]	Predicted[3]
All	**–**	**1,065**	**671**
121FWF101	–	1,060	667
121FWF115	–	5	4
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

Over the onset of the event (11:00 to 16:00 on 6 September 2008), there is a relatively good agreement between the number of properties within the observed and modelled flood outlines.

At the peak of the event, however, there is a large disparity with significantly fewer properties located within the modelled flood outline. The maps in Figure 4.7 show that many of these properties fall within the Allery Banks/Middle Green area. However, surface water flooding and surcharging of drains during the event contributed to the observed flood extent in this area.

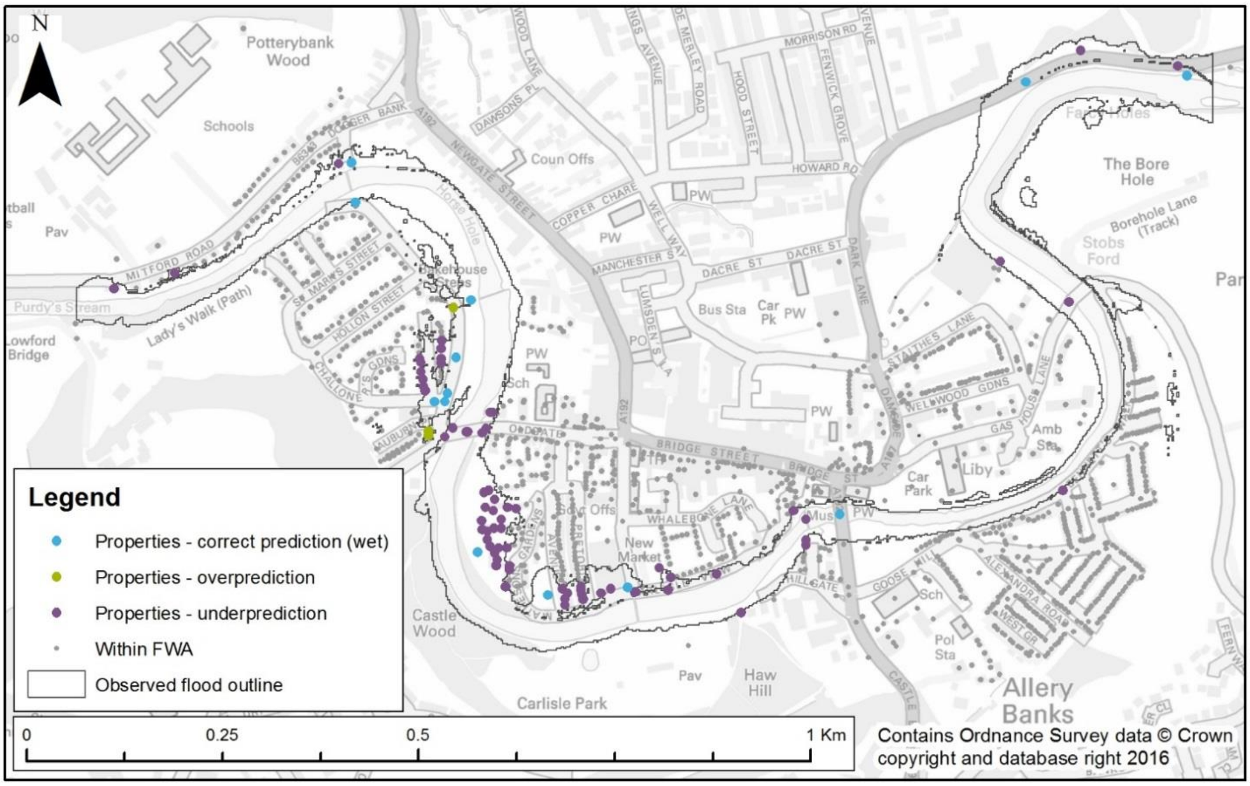
Representation of buildings in the model may also contribute to apparent underprediction in built-up areas. In this model, buildings are represented by raised footprints according to surveyed threshold levels or by 0.3m where survey was not available. So properties may not be shown as flooded if water has not risen above the threshold level, but may still be affected by flooding of the street and require a warning.

If this PoC were to be implemented operationally, careful consideration of building representation would be required.

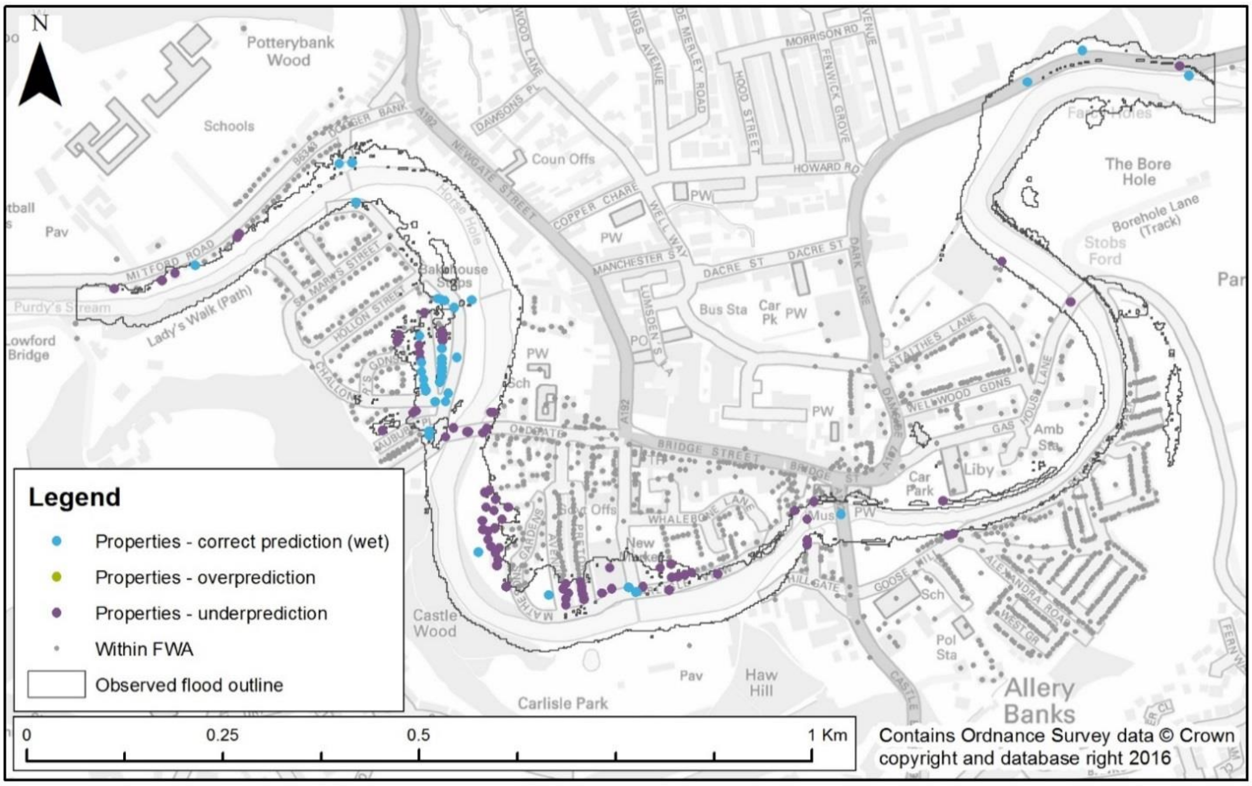
Properties mapped by model prediction

The maps presented in Figure 4.7 show property points (from the NRD) colour-coded according to whether the model overpredicts, underpredicts or correctly predicts the observed flood outline.

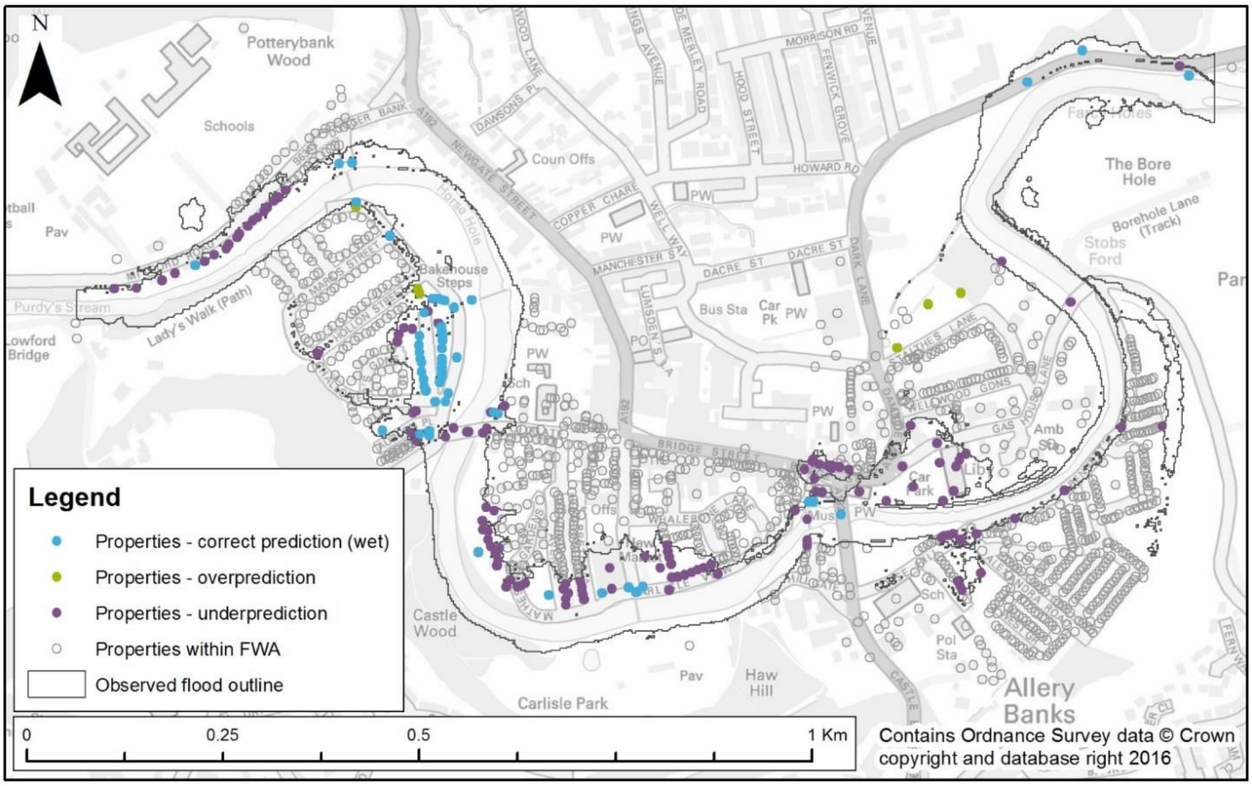
11:00


N
Legend
Properties - correct prediction (wet)
Properties - overprediction
Properties - underprediction
Within FWA
Observed flood outline
0
0.25
0.5
1 Km
Contains Ordnance Survey data © Crown copyright and database right 2016

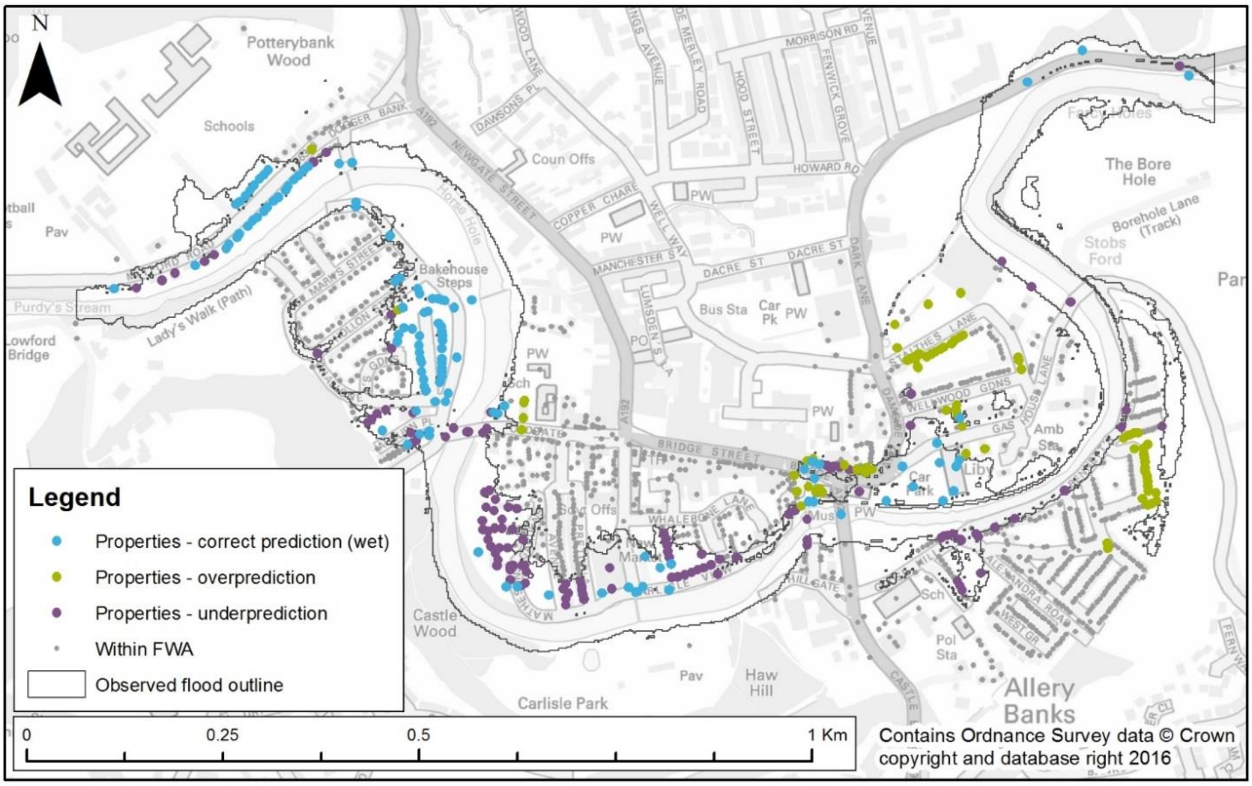
12:00


N
Legend
Properties - correct prediction (wet)
Properties - overprediction
Properties - underprediction
Within FWA
Observed flood outline
0
0.25
0.5
1 Km
Contains Ordnance Survey data © Crown copyright and database right 2016

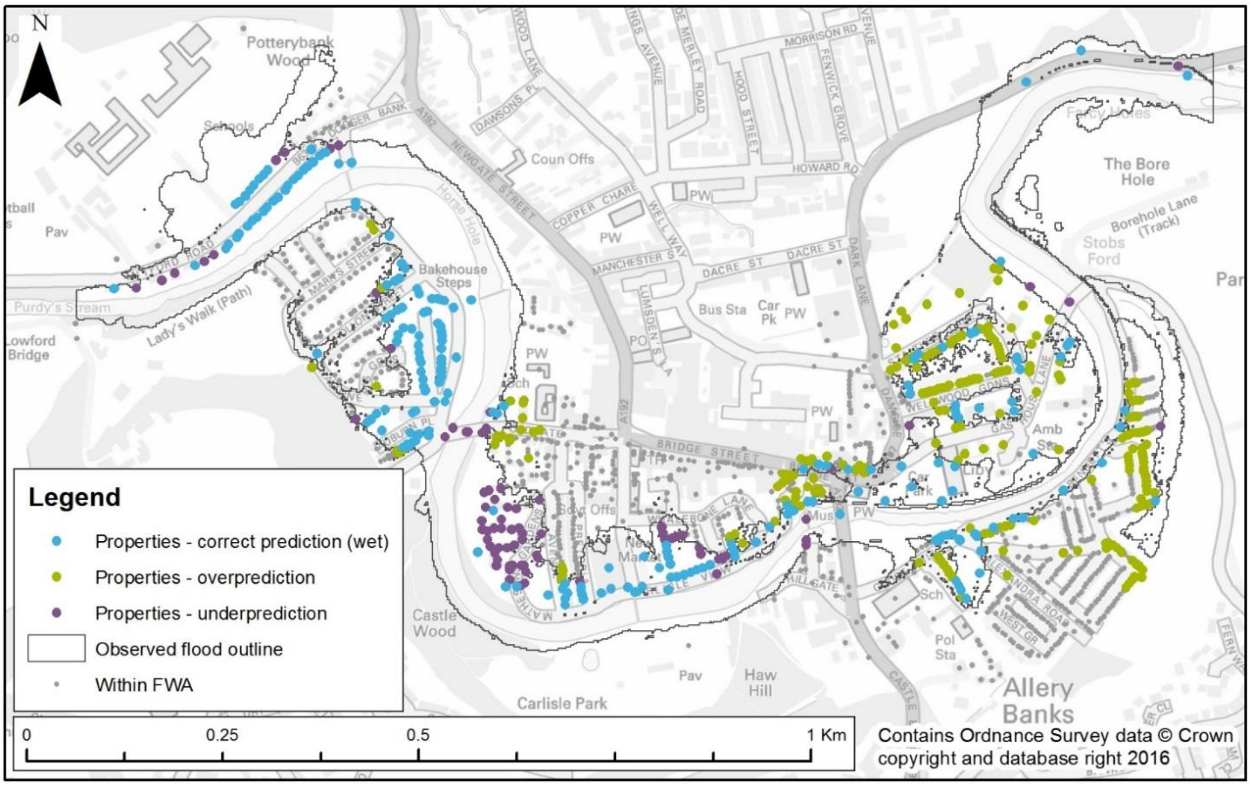
13:00


N
Potterybank Wood
Schools
Pav
Purdy's Stream
Lady's Walk (Path)
Lowford Bridge
Bakehouse Steps
Coun Offs
PW
Bus Sta
Car Pk
The Bore Hole
Borehole Lane (Track)
Stobs Ford
Castle Wood
Pav
Haw Hill
Carlisle Park
Allery Banks
Legend
Properties - correct prediction (wet)
Properties - overprediction
Properties - underprediction
Properties within FWA
Observed flood outline
0
0.25
0.5
1 Km
Contains Ordnance Survey data © Crown copyright and database right 2016

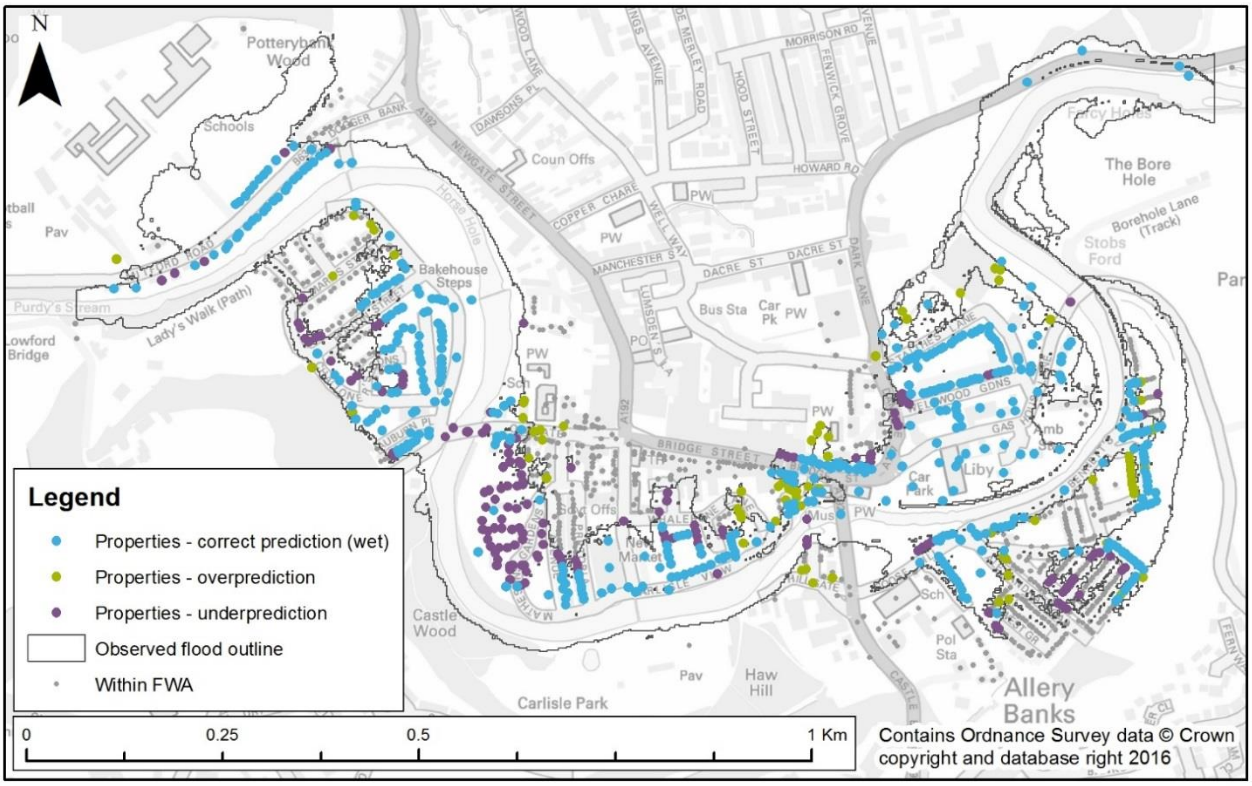
14:00


N
Potterybank Wood
Schools
Pav
Purdy's Stream
Lady's Walk (Path)
Lowford Bridge
Bakehouse Steps
Coun Offs
PW
Bus Sta
Car Pk
The Bore Hole
Borehole Lane (Track)
Stobs Ford
Castle Wood
Pav
Haw Hill
Carlisle Park
Allery Banks
Legend
Properties - correct prediction (wet)
Properties - overprediction
Properties - underprediction
Within FWA
Observed flood outline
0
0.25
0.5
1 Km
Contains Ordnance Survey data © Crown copyright and database right 2016

15:00


Legend
Properties - correct prediction (wet)
Properties - overprediction
Properties - underprediction
Observed flood outline
Within FWA
0
0.25
0.5
1 Km
Contains Ordnance Survey data © Crown copyright and database right 2016

16:00


Legend
Properties - correct prediction (wet)
Properties - overprediction
Properties - underprediction
Observed flood outline
Within FWA
0
0.25
0.5
1 Km
Contains Ordnance Survey data © Crown copyright and database right 2016

17:00

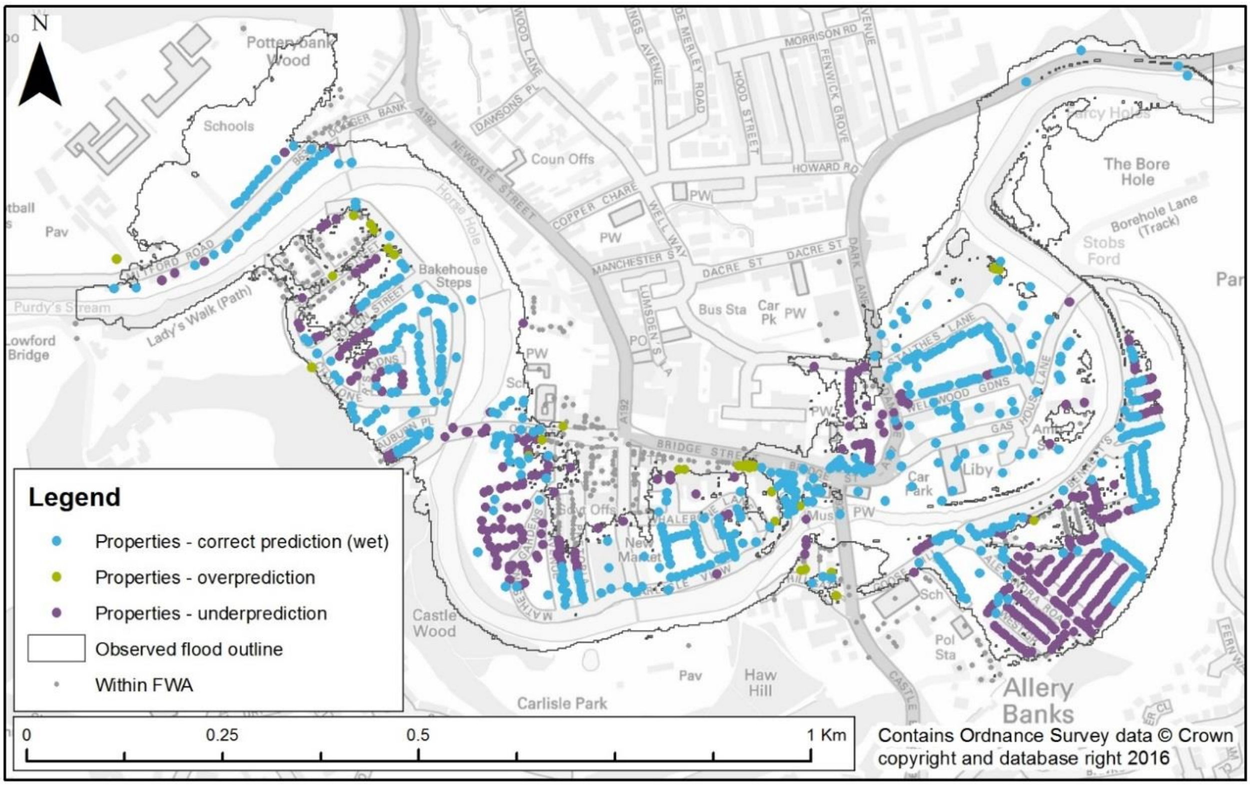


Figure 4.7 Model performance in predicting extent of flooding at Morpeth between 11:00 and 17:00 on 6 September 2008

4.1.6 Depth analysis (Test C)

Flooded depths

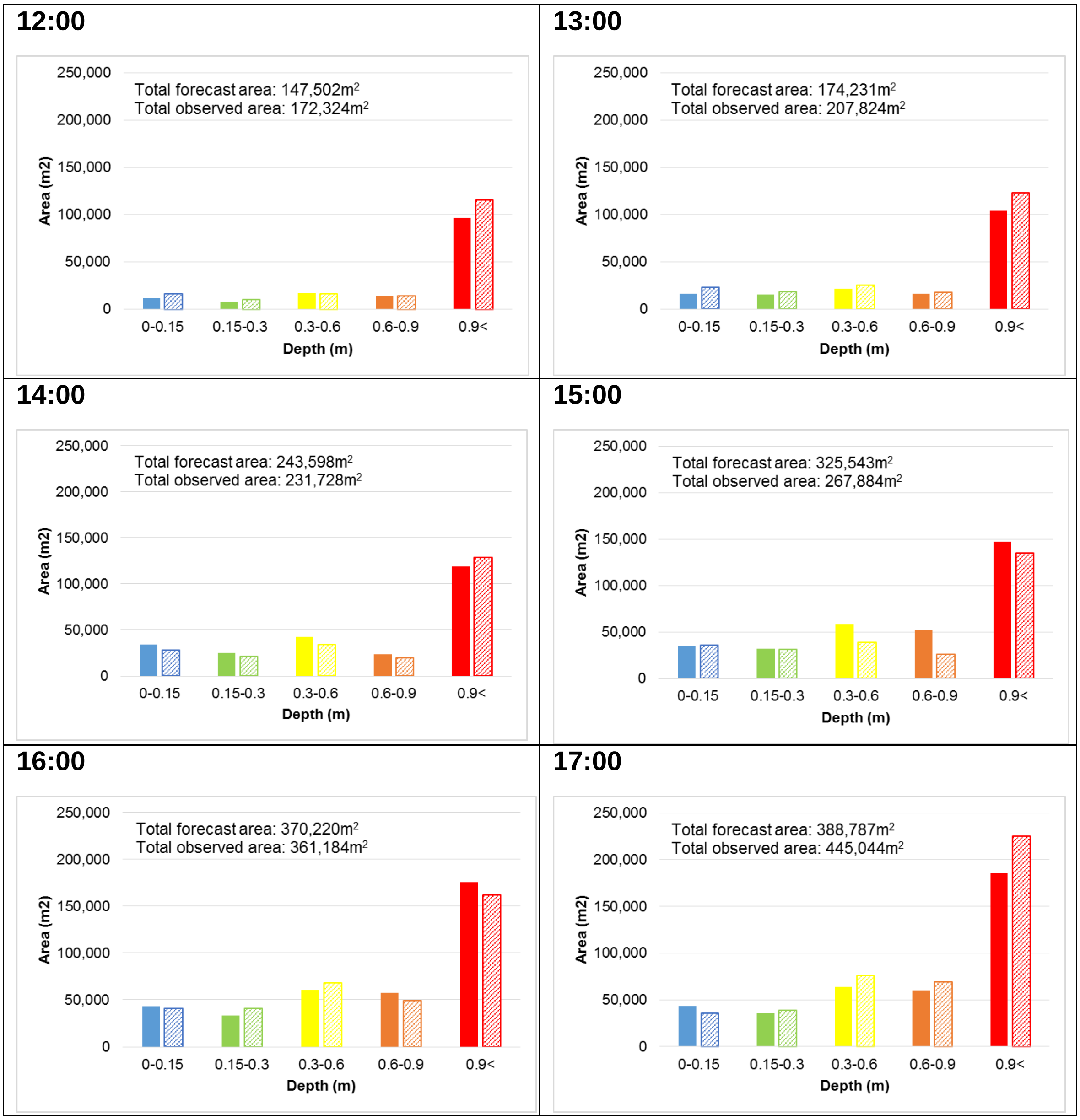


Figure 4.8 Modelled and observed flooded depths at Morpeth between 11:00 and 17:00 on 6 September 2008

Notes: Solid bars show modelled depths (from the PoC option).
Dashed bars show observed depths (based on data supplied by Newcastle University).

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

Interpretation

- There is a substantial area deeper than 0.9m in both modelled and observed cases.
- At most time steps, the modelled area is smaller than the observed area at all depths. This can be explained by the surface water influence.
- In addition, there are fewer wrack marks available in areas where surface water is believed to have contributed to flooding, particularly in the Allery Banks district. There may therefore be some uncertainty in flood depths in this area.
- Between 14:00 and 16:00, the modelled area is often greater than the observed area. This could be a consequence of model schematisation. For example, the model allows water to flow over the entire building footprint when it reaches the threshold level whereas, in reality, flow paths may be more constrained due to the internal building configuration.

4.1.7 G2G simulation

Table 4.7 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	Due to the long model run times, a sample of 3 ensemble members was tested – those that gave the 5th percentile, median and 95th percentile. Ensemble members were ranked by peak flow at the grid square corresponding to the main river model inflow on the River Wansbeck (the G2G cell centroid is at NGR 417500,585500).	

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 4.9. 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.

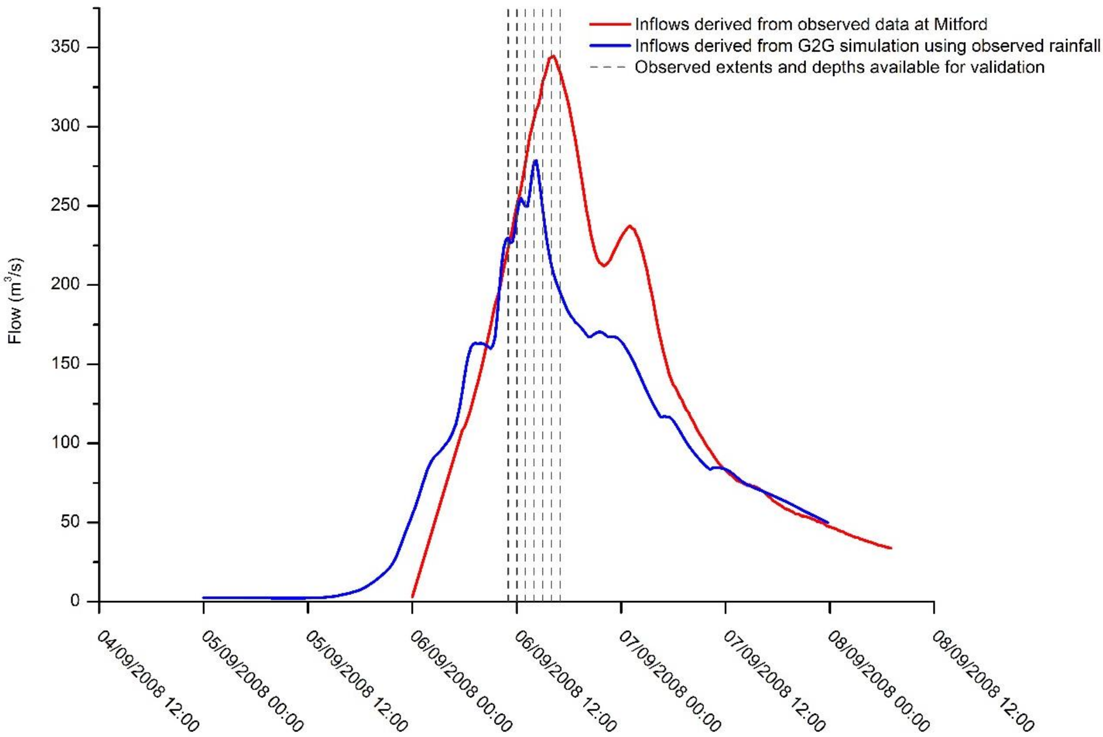


Figure 4.9 Hydrograph for the River Wansbeck

Flood extent – maximum

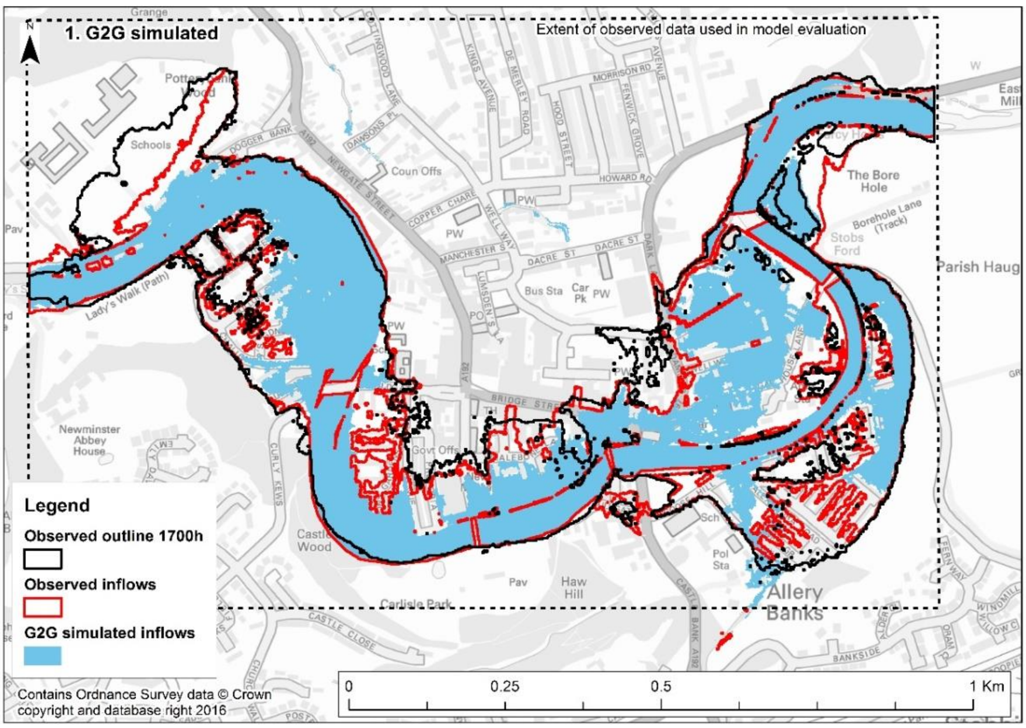


Figure 4.10 Observed and G2G simulated maximum flood extent for Morpeth event

The hydrograph (Figure 4.9) 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. The volume under the G2G simulated hydrograph is also substantially lower. Consquently, the modelled flood extent from G2G simulated flows is significantly underestimated compared with that modelled from observed flows. Both modelled extents underestimate the flood impacts compared with the observed event outline. This is consistent with reports that surface water contributed to flooding in the September 2008 event.

G2G ensemble members

The observed peak was recorded at 17:00 on 6 September 2008. However, for the selected forecast origin, all the tested G2G ensemble members forecast an earlier peak. The flood extents indicated in the map in Figure 4.12 show the maximum extent from each model run, irrespective of where it occurs during the event.

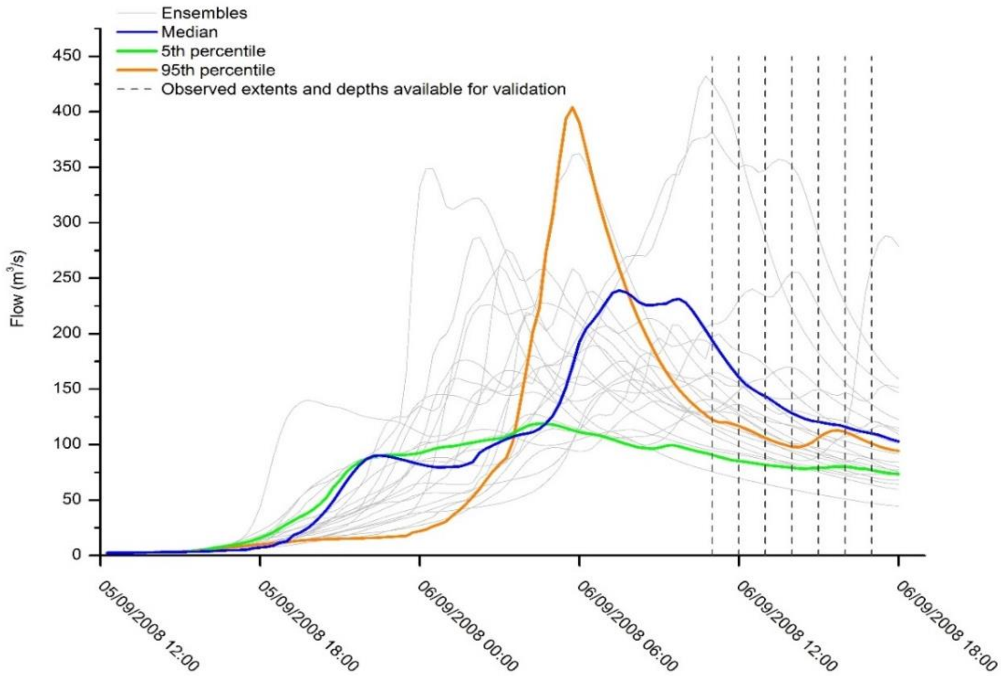


Figure 4.11 G2G ensemble members: inflows to hydraulic model for Morpeth event

Flood extent – maximum observed and maximum G2G

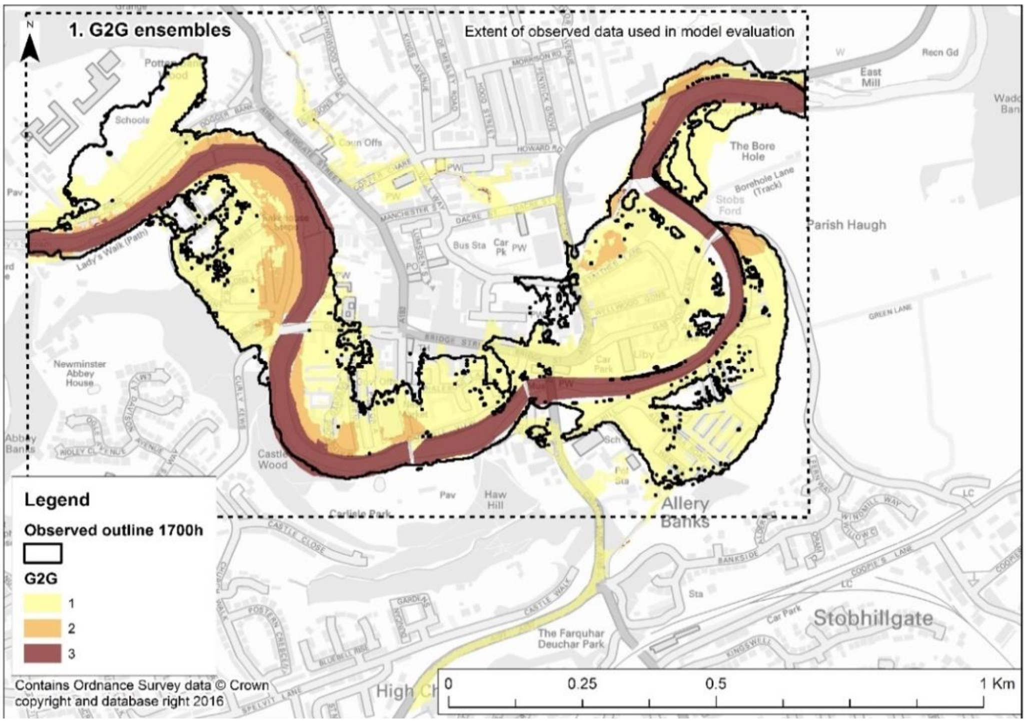


Figure 4.12 Maximum observed and maximum G2G simulation of flood extent for Morpeth event

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

For comparison, the number of properties in the observed flood extent is 1,065. Table 4.8 shows the number of properties in the modelled flood outlines. In this case, the model underpredicts flood extent in some areas. The final row of the table shows the number of properties within the observed outline that appear in none of the ensemble members.

Table 4.8 Number of NRD property points within the flood outlines for Morpeth event

Flood outlines	**Number of properties[1]**	**Cumulative property count[2]**	**Notes**
3 × ensemble member overlap	5	5	Area shown as flooded in all tested ensemble members
2 × ensemble member overlap	36	41	–
1 × ensemble member	922	963	–
Within observed outline but not forecast	266	–	Area not shown as flooded in any tested ensemble member

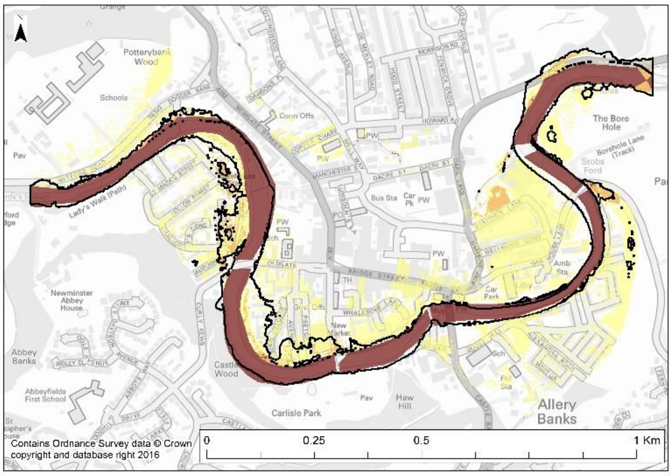
Notes: [1] This column shows the number of properties within each separate zone of the modelled outlines, ordered from the area where all ensembles coincide, to properties that appear in one ensemble member only.
[2] This column lists the cumulative number of properties within the modelled outlines, 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.

Flood extent and property counts – time slices

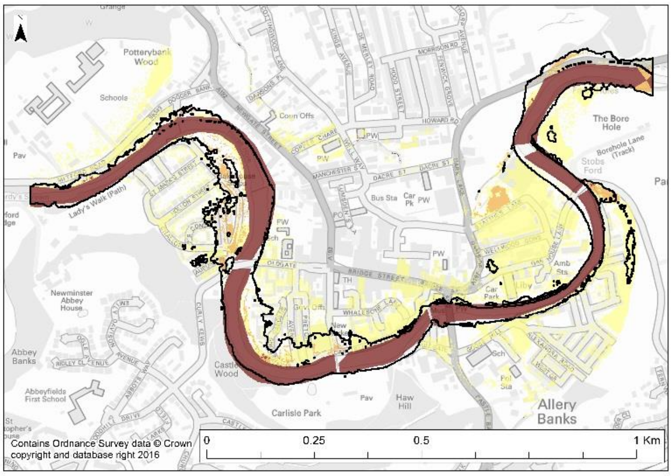
The numbers of properties in each separate zone of the modelled flood outlines are listed in Table 4.9, with the cumulative number of properties shown in brackets.

This section presents maps of modelled and observed flood extent at hourly intervals throughout the event. All are on the recession of the G2G simulation and hence their similarity to each other.

Table 4.9 Temporal evolution of observed and G2G modelled flood extent and property counts, 6 September 2008

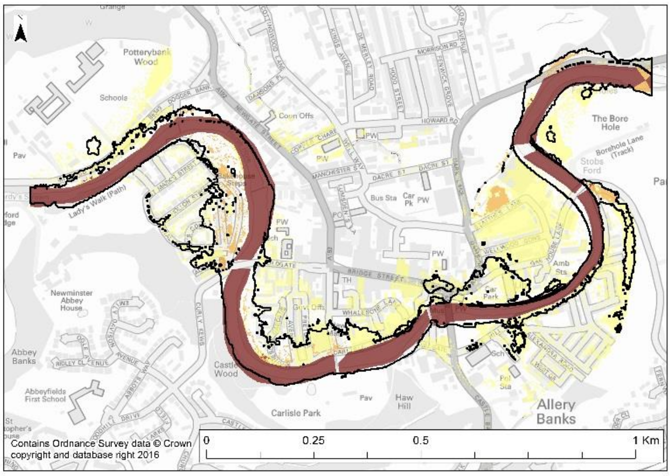
<table>
<tr><td colspan="4">11:00</td></tr>
<tr><td rowspan="6">
</td><td colspan="2">Flood outlines</td><td>Number of properties (cumulative)</td></tr>
<tr><td>—</td><td>Observed</td><td>109</td></tr>
<tr><td></td><td>3 × ensemble overlap</td><td>5 (5)</td></tr>
<tr><td></td><td>2 × ensemble overlap</td><td>18 (23)</td></tr>
<tr><td></td><td>1 × ensemble</td><td>525 (548)</td></tr>
<tr><td></td><td>Within observed outline but not forecast</td><td>57</td></tr>
</table>

12:00



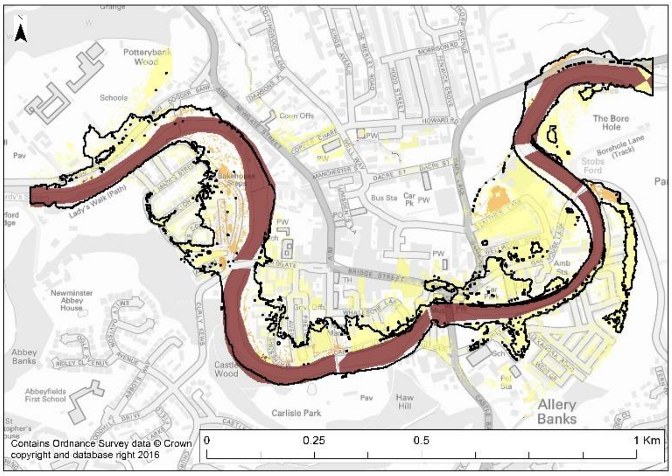
Flood outlines		Number of properties (cumulative)
—	Observed	144
	3 × ensemble overlap	5 (5)
	2 × ensemble overlap	15 (20)
	1 × ensemble overlap	497 (517)
	Within observed outline but not forecast	69

13:00



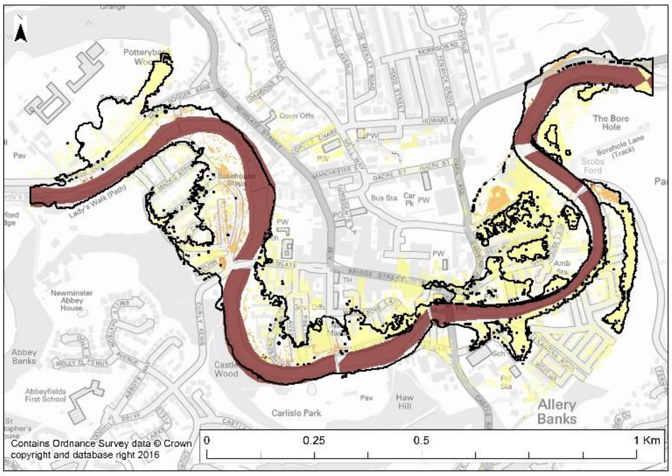
Flood outlines		Number of properties
—	Observed	254
	3 × ensemble overlap	5 (5)
	2 × ensemble overlap	14 (19)
	1 × ensemble overlap	474 (493)
	Within observed outline but not forecast	129

14:00



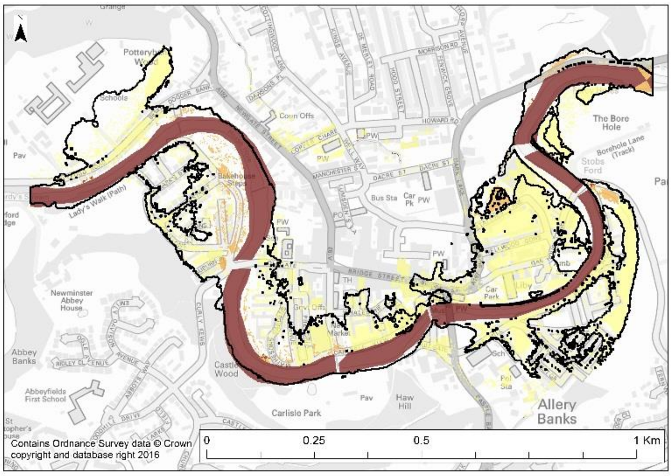
Flood outlines		Number of properties
—	Observed	318
	3 × ensemble overlap	5 (5)
	2 × ensemble overlap	12 (17)
	1 × ensemble	468 (485)
	Within observed outline but not forecast	174

15:00



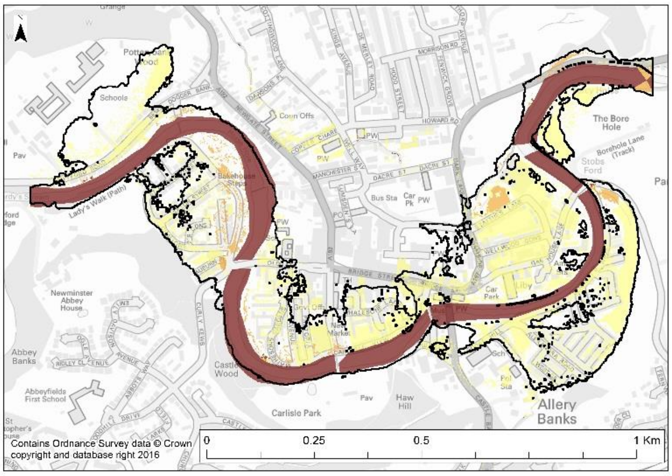
Flood outlines		Number of properties
—	Observed	5 (5)
	3 × ensemble overlap	10 (15)
	2 × ensemble overlap	459 (474)
	1 × ensemble overlap	184
	Within observed outline but not forecast	397

16:00



Flood outlines		Number of properties
—	Observed	730
	3 × ensemble overlap	5 (5)
	2 × ensemble overlap	8 (13)
	1 × ensemble overlap	444 (457)
	Within observed outline but not forecast	419

17:00



Flood outlines		Number of properties
—	Observed	1,065
	3 × ensemble overlap	5 (5)
	2 × ensemble overlap	8 (8)
	1 × ensemble	419 (427)
	Within observed outline but not forecast	739

4.2 Case study 2: Cockermouth, November 2009

4.2.1 Location

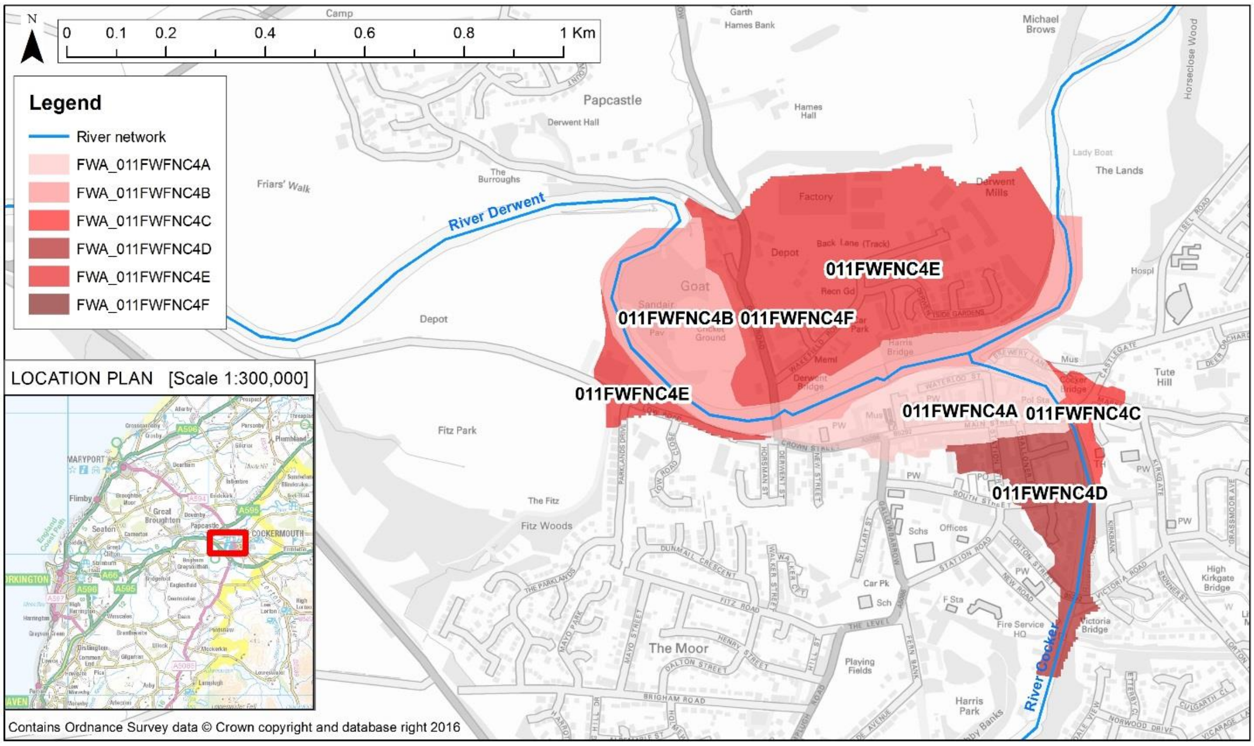


Figure 4.13 Location map for Cockermouth case study

Table 4.10 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

4.2.2 Model outputs

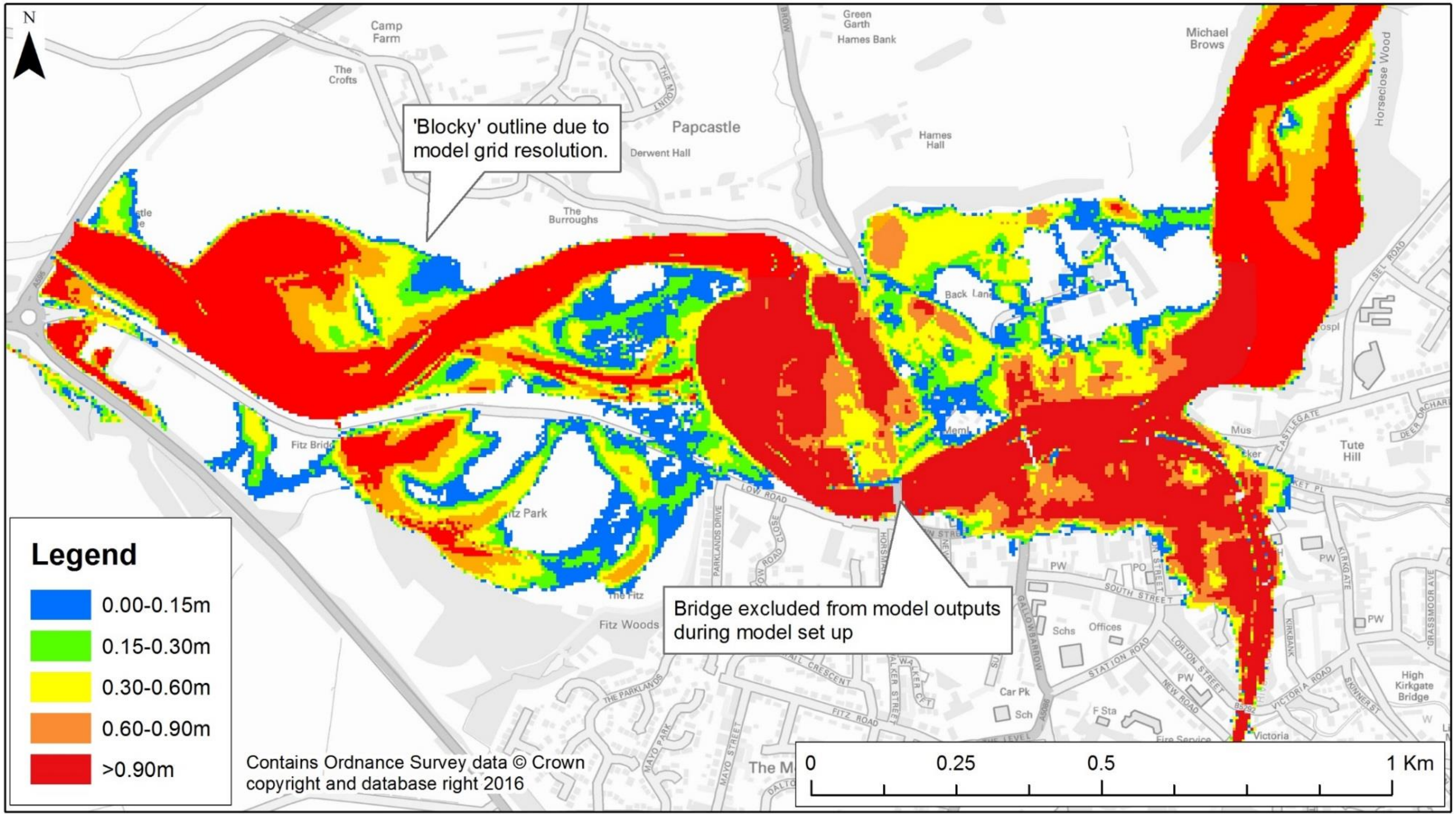


Figure 4.14 Model outputs for Cockermouth event

4.2.3 Extent flooded (Test A1)

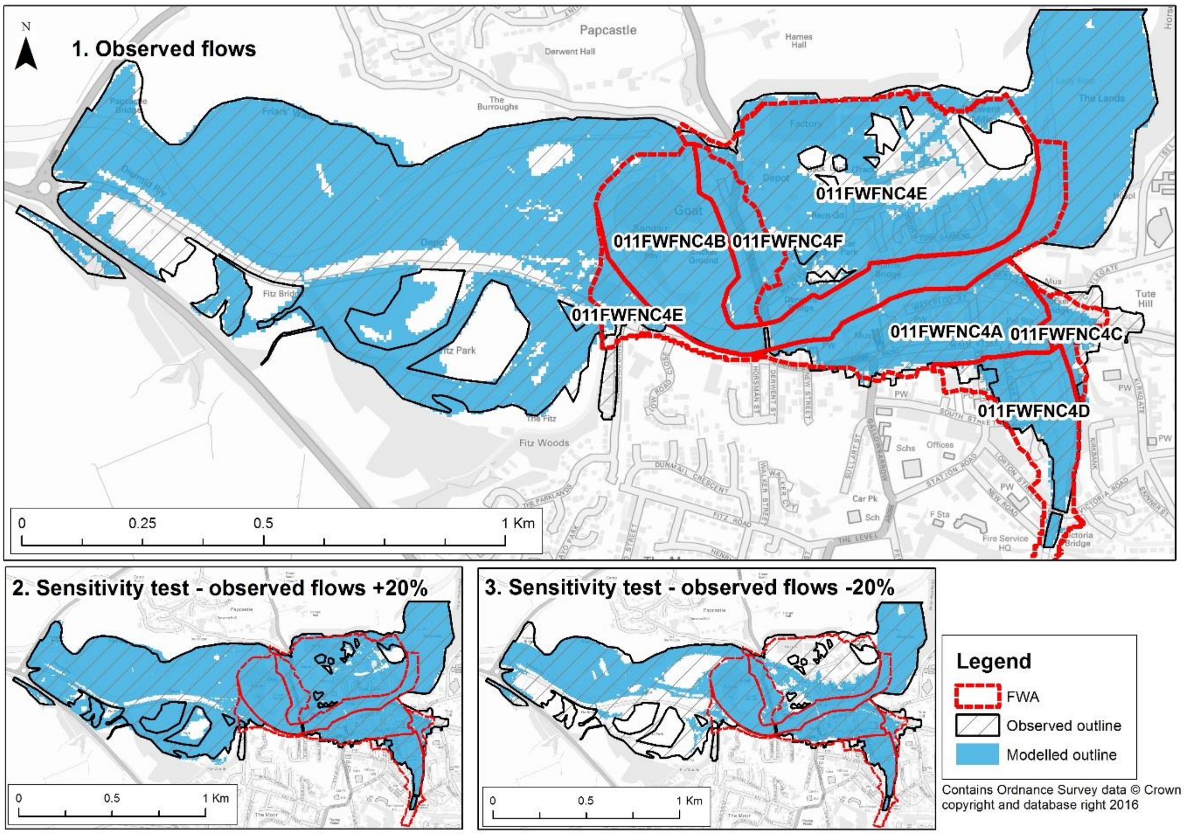


Figure 4.15 Maximum modelled extent compared with maximum available observed extent

Table 4.11 Comparison of modelled and observed area flooded for each Flood Warning Area for Cockermouth event

Flood Warning Area (FWA)	Area (m^2)	Area flooded			
		Modelled		Observed	
		m^2	% of FWA	m^2	% of FWA
All	**560,039**	**462,456**	**82.58**	**508,774**	**90.85**
011FWFNC4A	73,728	67,975	92.20	70,731	95.94
011FWFNC4B	134,289	132,534	98.69	133,541	99.44
011FWFNC4C	13,362	10,081	75.44	12,788	95.70
011FWFNC4D	57,177	37,706	65.95	37,810	66.13
011FWFNC4E	252,013	185,024	73.42	224,436	89.06
011FWFNC4F	29,469	29,135	98.87	29,469	100.00

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

Overall, the model performs well, accurately replicating the observed flood extent.

The modelled flood outline is particularly sensitive to variations in flow (see sensitivity tests). Differences between outlines are particularly marked in the north-east and sout-west areas of the model domain. Accurately quantifying flow inputs to the system is therefore a requirement for accurate prediction of flood extent.

4.2.4 Model performance (Test A2)

Model performance

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.

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

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

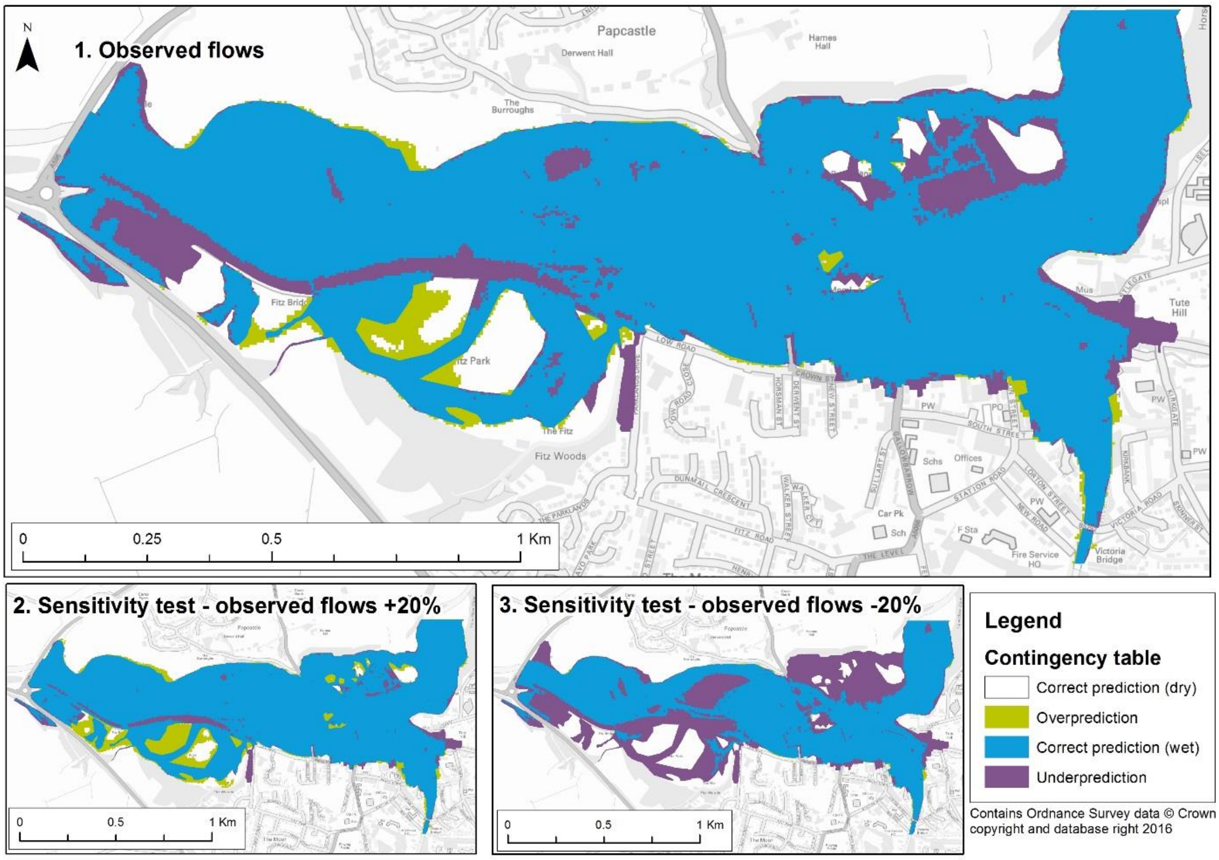


Figure 4.16 Model performance in predicting flooded extent at Cockermouth

Table 4.12 Model performance metrics for Cockermouth event

Flood Warning Area	Correct wet (%)	Over-prediction (%)	Under-prediction (%)	Skill	Bias
Modelled outline (all)	**83.33**	**3.45**	**13.21**	**0.83**	**0.90**
Modelled outline (within area covered by Flood Warning Areas only)	**88.44**	**1.29**	**10.28**	**0.88**	**0.91**
011FWFNC4A	95.40	0.36	4.24	0.95	0.96
011FWFNC4B	98.80	0.22	0.98	0.99	0.99
011FWFNC4C	71.70	3.98	24.31	0.21	0.79
011FWFNC4D	87.09	6.33	6.58	0.87	1.00
011FWFNC4E	80.03	1.32	18.65	0.80	0.82
011FWFNC4F	98.87	0.00	1.13	0.99	0.99

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

As shown above, the model predicts correctly in most areas. However, the metrics show an overall, slight bias towards underprediction, particularly in the north-east of the model domain (near Derwentside Gardens). There are also some small areas of overprediction such as in the south-west of the model domain (Fitz Park area).

These discrepancies may be partly associated with uncertanties in the observed outline, which was digitised manually from an aerial photograph. For example, it is difficult to determine from an aerial photograph whether water has entered a property, and so buildings in the Derwentside Gardens area have been included in the observed outline even though they may not have been flooded internally.

Diffferences between the modelled and observed outlines may also be associated with how surface roughness has been discretised in the model. For example, a generic 'floodplain' classification with a Manning's n of 0.05 has been applied in some areas of the 2D domain. In the vicinity of Derwentside Gardens, some areas which appear to be paved have been assigned this classification when other manmade areas have been assigned a Manning's n of 0.02. This may have the effect of causing variability in the modelled flood extent in these areas.

4.2.5 Property counts (Test B)

Properties within flood extent

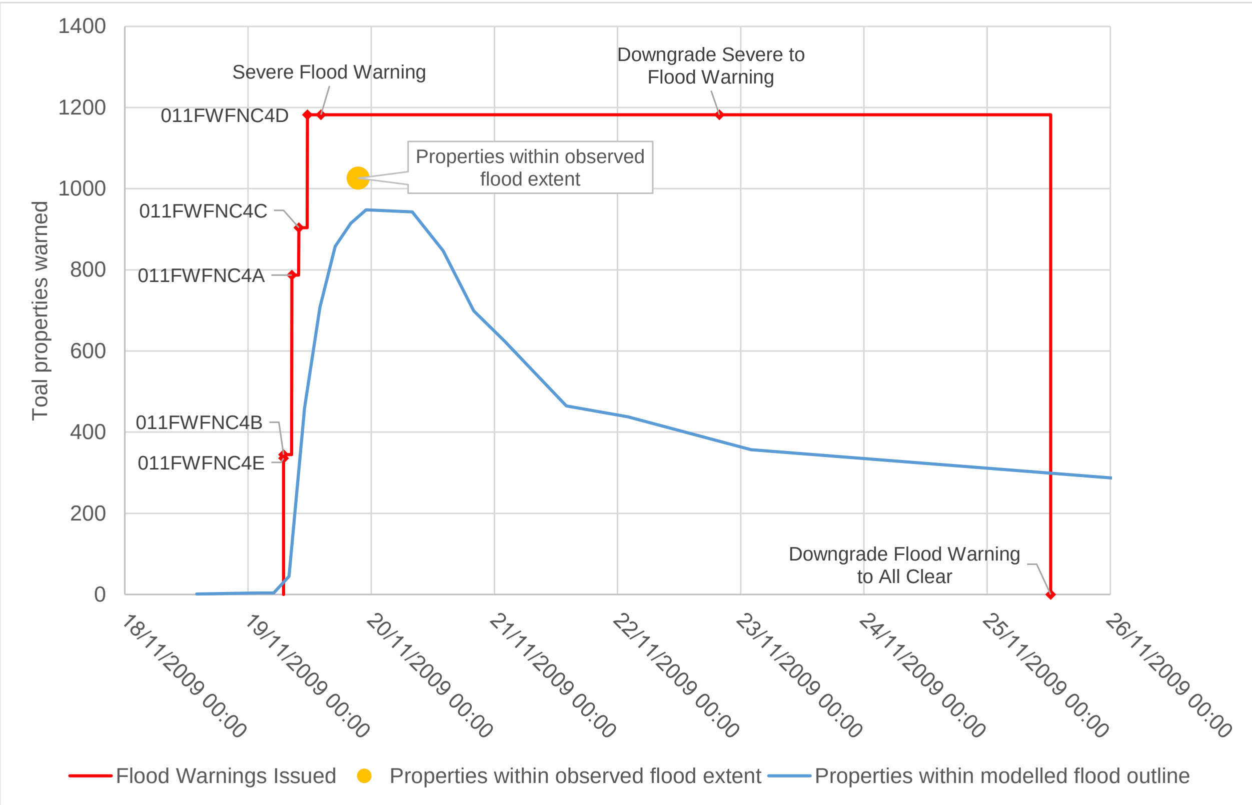


Figure 4.17 Properties within flood extent for Cockermouth event

Table 4.13 Maximum number of flooded properties for Cockermouth event

Flood Warning Area	Properties warned[1]	Observed[2]	Predicted[3]
All	**1,180**	**1,036**	**1,001**
011FWFNC4A	442	415	412
011FWFNC4B	9	7	7
011FWFNC4C	117	116	89
011FWFNC4D	278	189	205
011FWFNC4E	336	309	288
011FWFNC4F	119	119	119

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 PoC provides detailed time-varying information that can be used to supplement Flood Warnings (Figure 4.17). It is envisaged that the PoC provides supplementary information, as other factors such as local expertise are considered in decisions over whether to issue or downgrade Flood Warnings.

At the peak of the event, there are 25 fewer properties within the modelled flood outline (out of 1,036 properties within the observed outline). The map below shows that many of these properties fall within the Derwentside Gardens area. As discussed in Section 4.2.4, this discrepancy may partly result from uncertainties in the digitised observed outline.

Properties mapped by model prediction

The map presented in Figure 4.18 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.

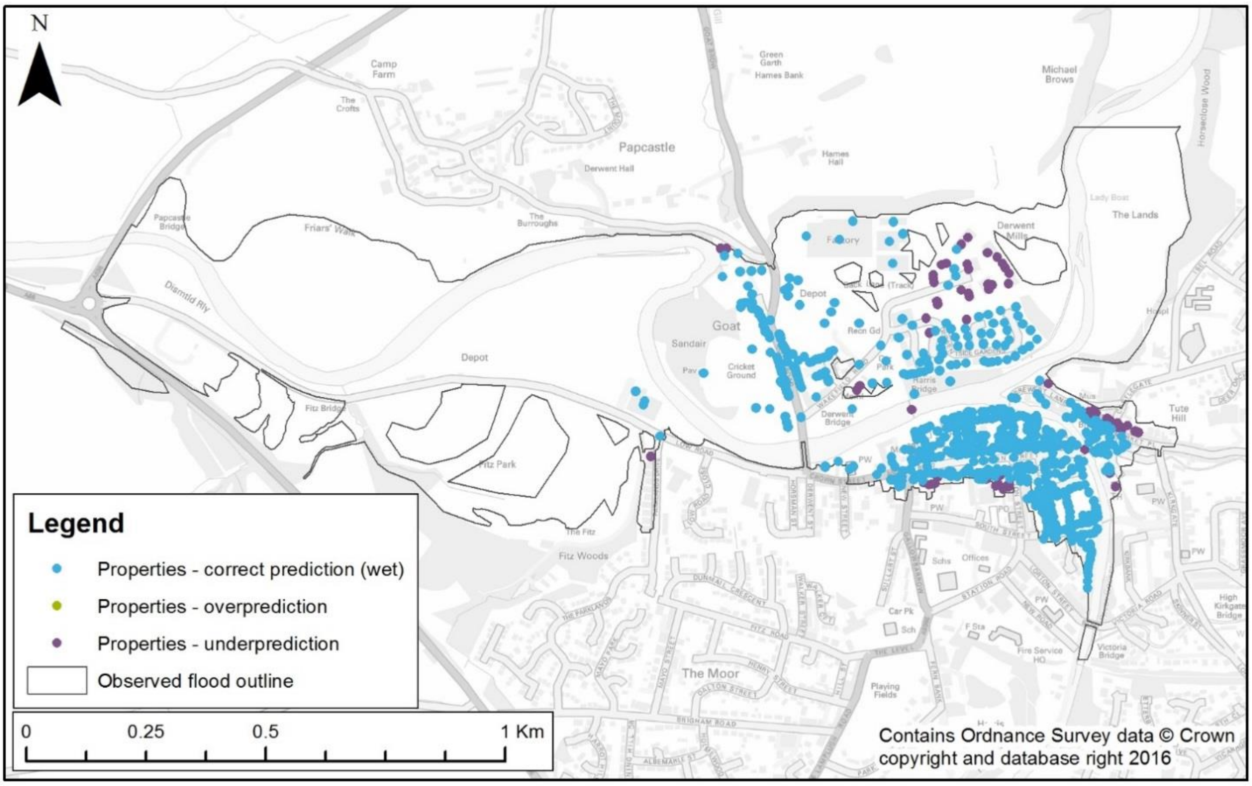


Figure 4.18 Model performance in predicting extent of flooding at Cockermouth

4.2.6 Depth analysis (Test C)

Flooded depths

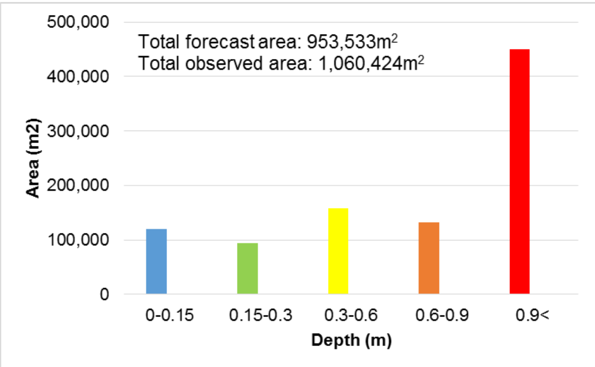


Figure 4.19 Distribution of flooded depth at the peak of the flood at 02:15 on 20 September 2009

Notes: Modelled and observed area categorised by depths.
Solid bars show modelled depths (from the PoC option).
No observed depths are available.

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

		>0.90

Interpretation

- There is a substantial area deeper than 0.9m (almost half modelled area).
- Total forecast area is smaller than observed. This may be associated with uncertainties in the observed outline digitised from aerial photography.

4.2.7 G2G simulation

Table 4.14 Details of available G2G data for Cockermouth event

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

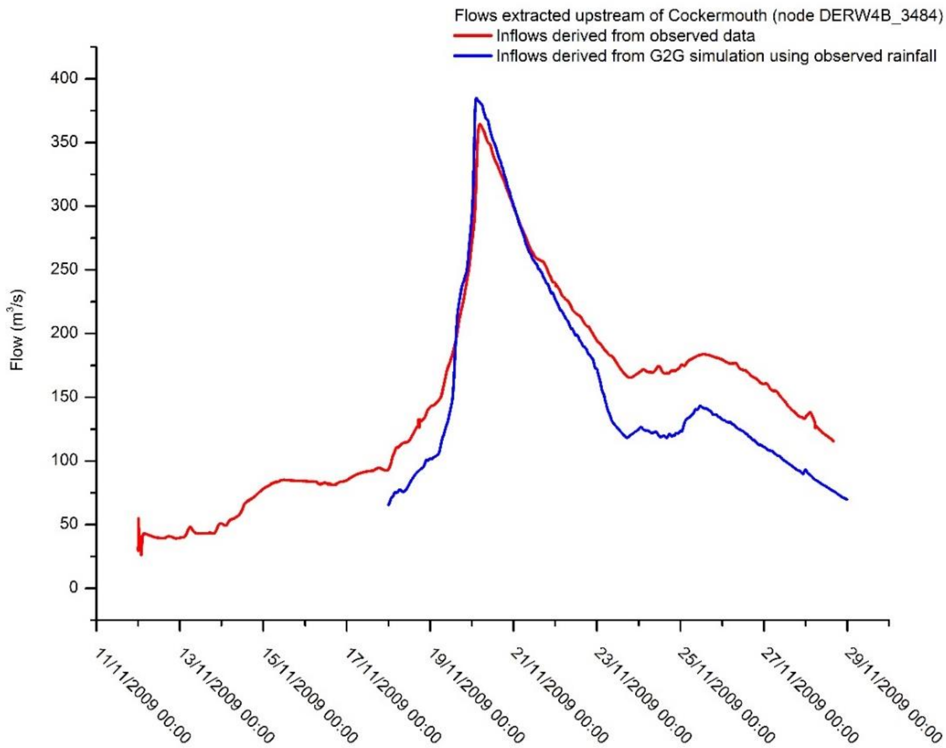


Figure 4.20 River Derwent hydrograph

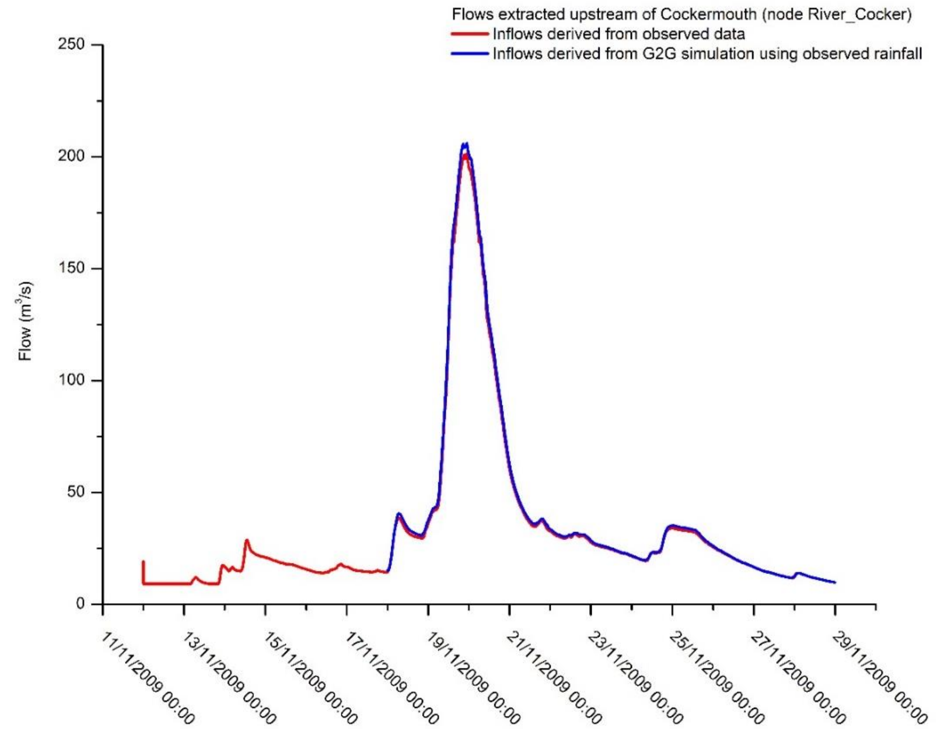


Figure 4.21 River Cocker hydrograph

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). For efficiency, the upstream 1D–2D model extent was cropped to this location when re-running the model with inflows from G2G. This reduced the number of lateral inflows required, thereby streamlining discretisation of model inflows. This location remains a significant distance upstream of the start of the 2D domain (2km) and, as shown above, a flow time series extracted directly from G2G is similar to flows routed through the ISIS reach. Cropping the model here was shown to have minimal impact on modelled flood extent and on in-channel flows and levels at Cockermouth. Model schematisation of the River Cocker remained unchanged and flows were input at the same locations.

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 on the TUFLOW domain 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

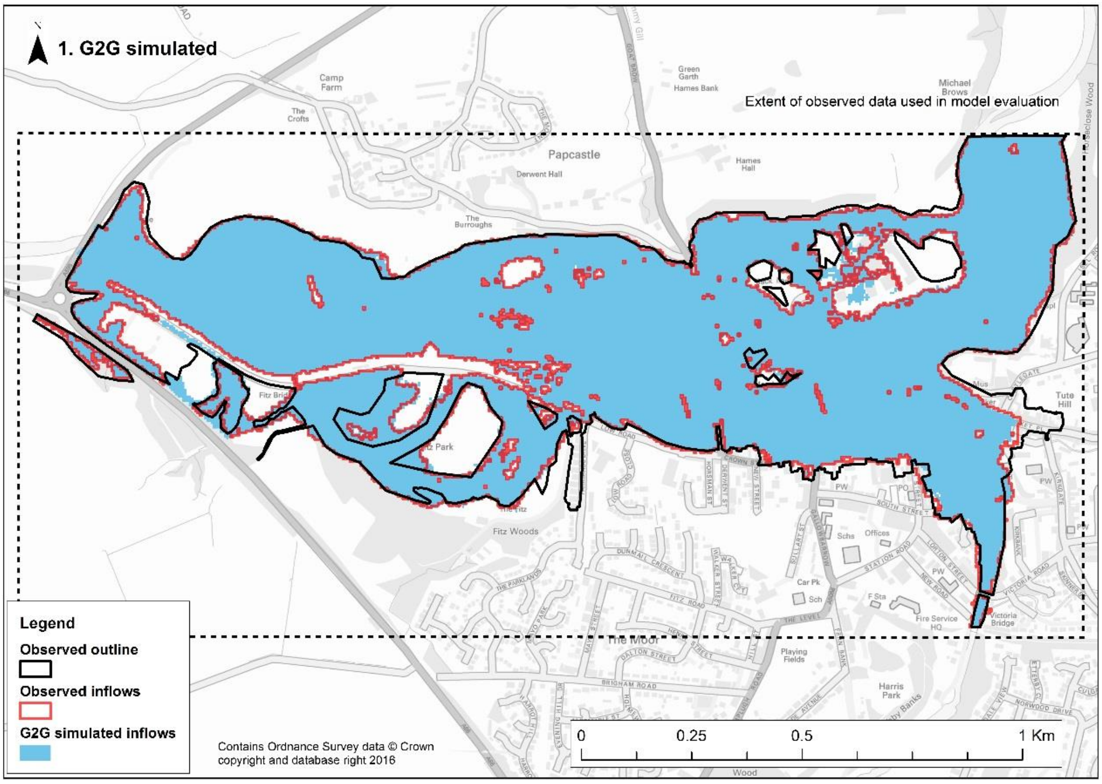


Figure 4.22 Observed and G2G simulated maximum flood extent for Cockermouth event

The hydrographs show that simulated flows from G2G (driven using observed rainfall) are very similar to observed flows at the upstream model boundary. The volume under the G2G simulated hydrograph is also comparable. Consequently, the modelled flood extent is similar. Extents modelled from both the G2G simulated and observed flows match well with the maximum observed outline in most areas.

G2G ensemble members

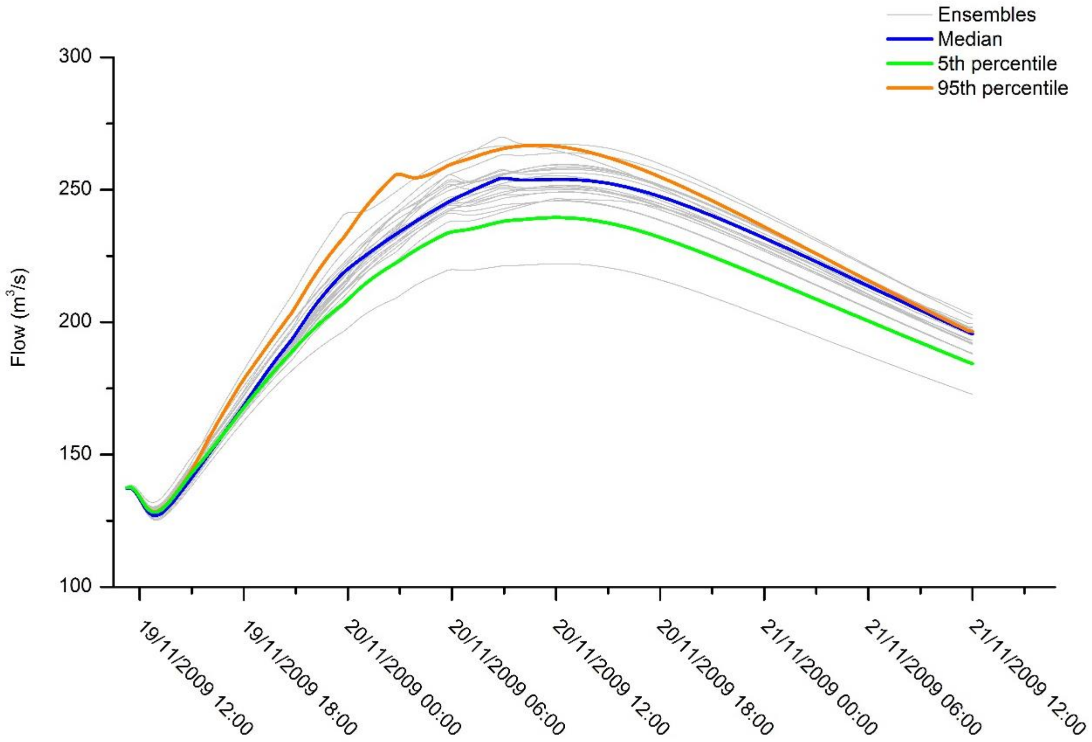


Figure 4.23 River Derwent inflows to hydraulic model

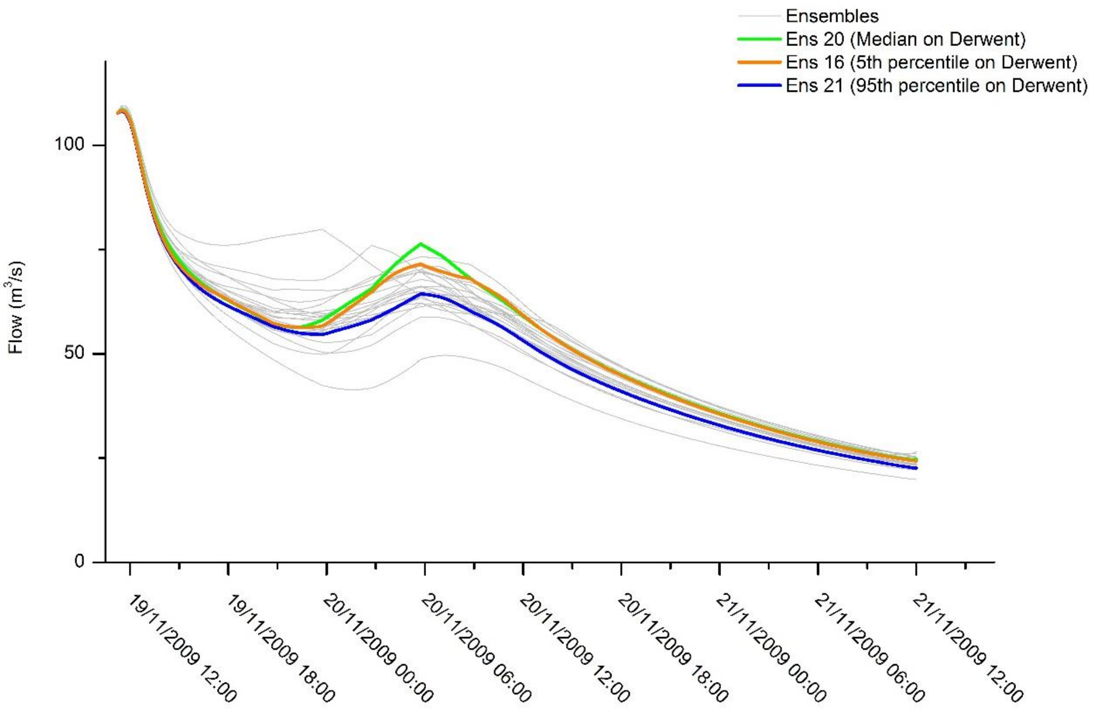


Figure 4.24 River Cocker inflows to hydraulic model

The ensemble plots above show that the initial flow for the River Cocker is greater than the peak later in the run. The hydraulic model therefore required a 10-hour 'ramp up' (or 'spin up') period prior to the start of the event in order to raise flows on the River Cocker from their initial condition to an appropriate starting state for the event. Flows on the River Derwent were constant during the 'ramp up' period.

However, 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 observed and maximum G2G

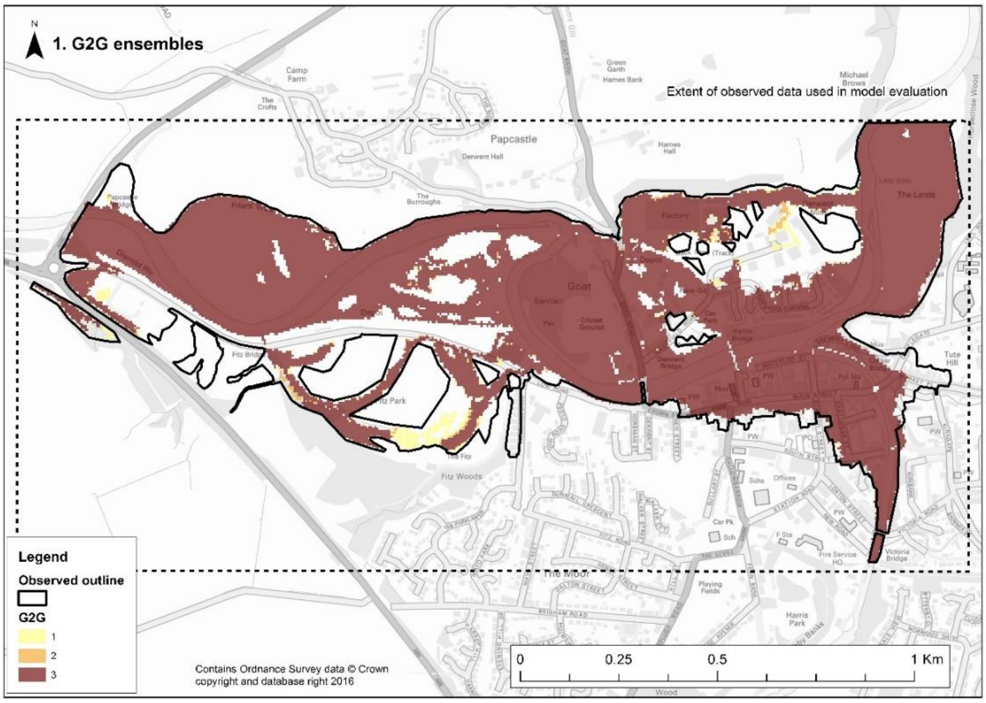


Figure 4.25 Maximum observed and maximum G2G simulation of flood extent for Cockermouth event

Property counts – maximum

For comparison, the number of properties in the observed flood extent is 1,036. Table 4.15 shows the number of properties in the modelled flood outlines.

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

Table 4.15 Number of NRD property points within the flood outlines for Cockermouth event

Flood outlines	Number of properties[1]	Cumulative property count[2]	Notes
3 × ensemble member overlap	921	921	Area shown as flooded in all tested ensemble members
2 × ensemble member overlap	0	921	–
1 × ensemble member	2	923	–
Within observed outline but not forecast	220	–	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, 921 properties are within the outlines of the largest number of ensembles, 923 properties are within the outline given by the least number of ensemble members.

4.3 Case study 3: Thames, February 2014

4.3.1 Location

The location map (Appendix 4b) shows the entire Thames reach considered by this PoC. Note that this may differ between PoCs as modelled extents are variable. Draft results were provided by an interim version (February 2014) of the hydraulic model developed for the Lower River Thames Flood Modelling Study by JBA Consulting (final version 2015).

Because some of the reach is modelled in 1D only, the analysis focuses on areas where 2D model outputs are available. The pro-forma presents detailed findings for 4 selected insets (highlighted in red on the location map). These were chosen according to the high availability of observed and modelled data, and the high concentration of flood receptors (in this study, properties within the flood outline).

Sensitivity testing results (based on increasing and decreasing model inflows by 20%) were not available within the time constraints of this project as model run times were more than 300 hours for the event. This is to be expected for a large model domain with high levels of topographic detail. Manageable run times for operational forecasting use might require this option to focus on targeted geographical areas. Model stability at a range of flows should also be considered if this option were implemented operationally.

Note about observed data

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

It should also be noted that, at the time the model results were supplied to this project, the model was in an interim stage of development. The latest available model outputs (the model was run to the peak of the event) were therefore compared with the closest available observed outline (after the peak).

Figure 4.25 shows the observed and modelled outlines used to assess the PoC, with the observed flow hydrograph at the Walton gauge (towards the downstream end of the model domain) shown in Figure 4.26 for context. However, the length of this reach and the relatively long travel times mean that Walton will not be representative of the timing of the flood peak throughout the whole model domain.

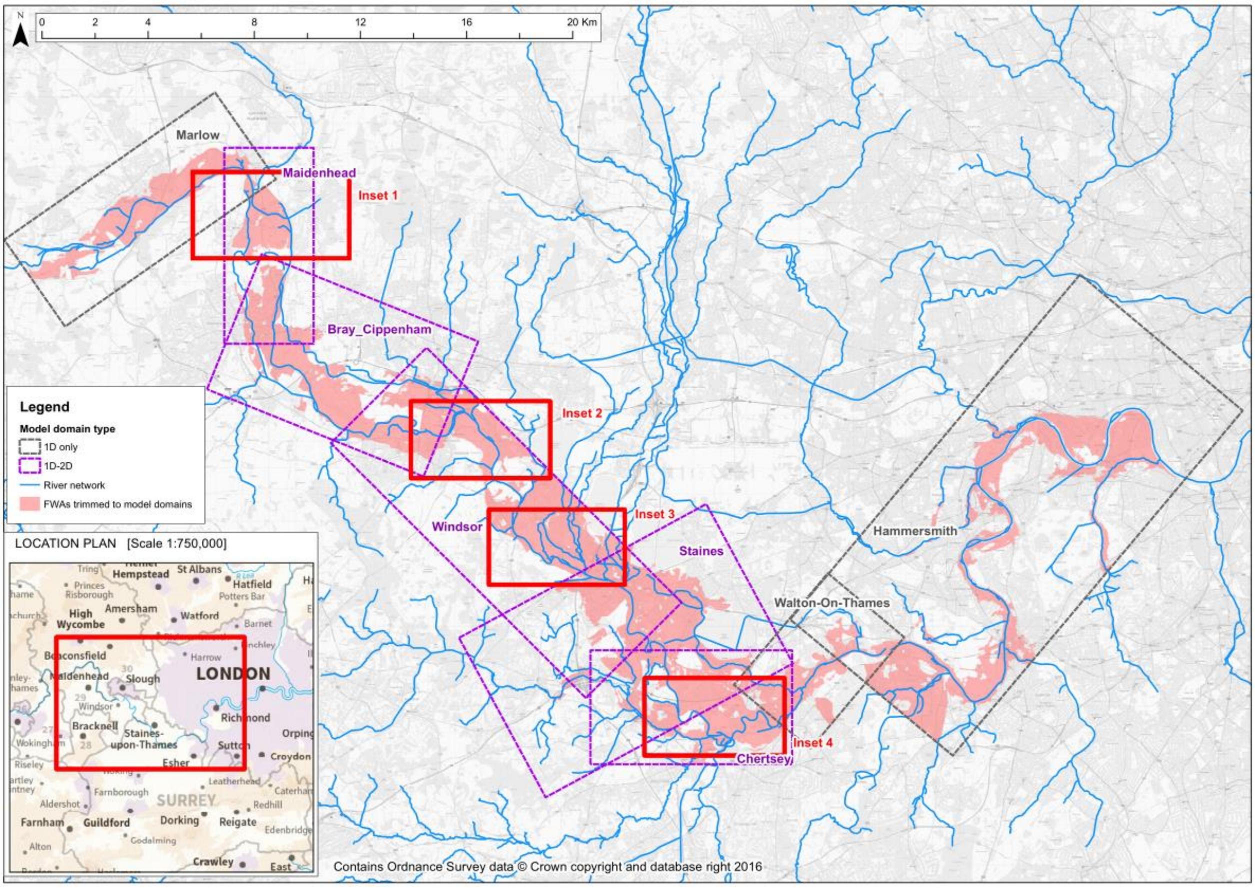


Figure 4.26 Observed and modelled outlines used to assess the PoC

Notes: See Appendix 4b for an enlarged map.

A notable amount of time elapses between the latest available model result and the observed outline. The latter was based on satellite imagery taken as the flow hydrograph started to recede, and may therefore suggest a smaller flood outline than that predicted by the model. However, in the context of a long-duration event and the slow responding nature of this catchment, comparing the available modelled and observed outlines is still informative as it can be used to assess general patterns of flooding and flood mechanisms. Later model results were not available at the time of this study.

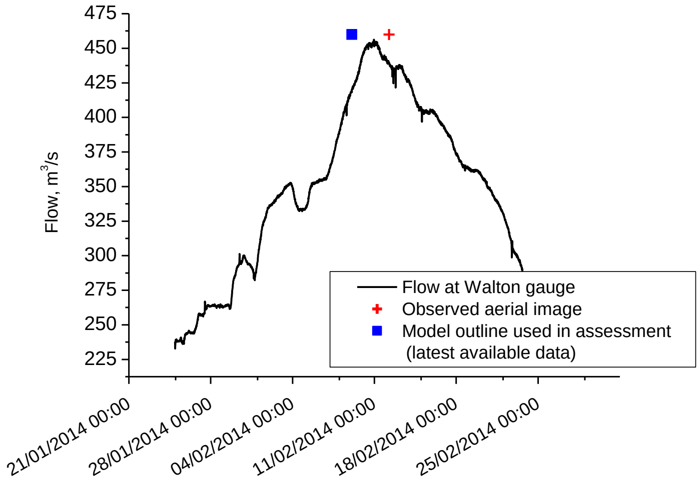


Figure 4.27 Observed flow hydrograph at the Walton gauge

Only Flood Warning Areas within the modelled extent were considered in this analysis. The number of Flood Warning Areas included may differ between PoCs as modelled extents are variable.

Table 4.16 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

Flood Warning Target Area Code	JBA code[1]	Name
		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
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

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.

4.3.2 Context for model outputs

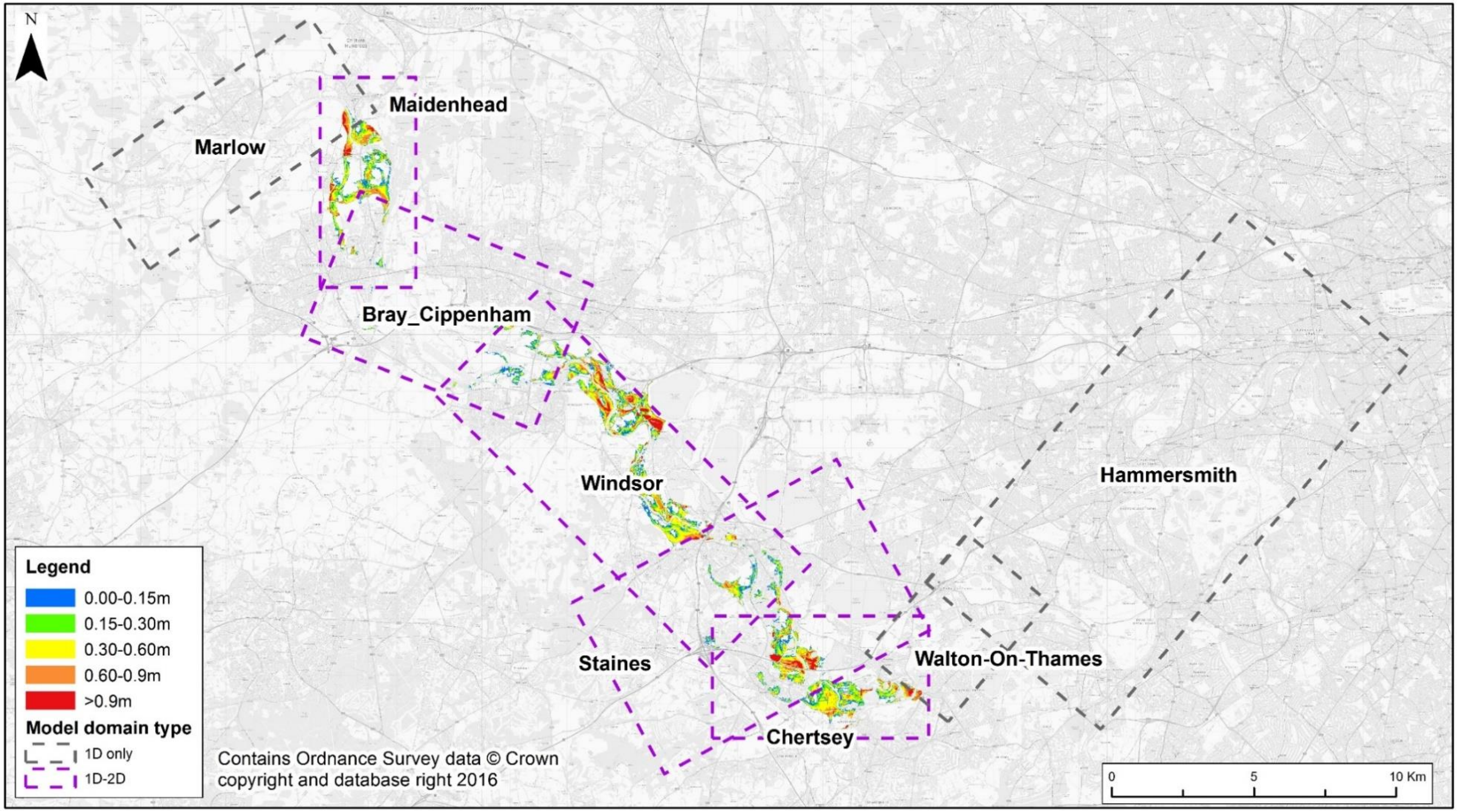


Figure 4.28 Context for model outputs for Thames case study

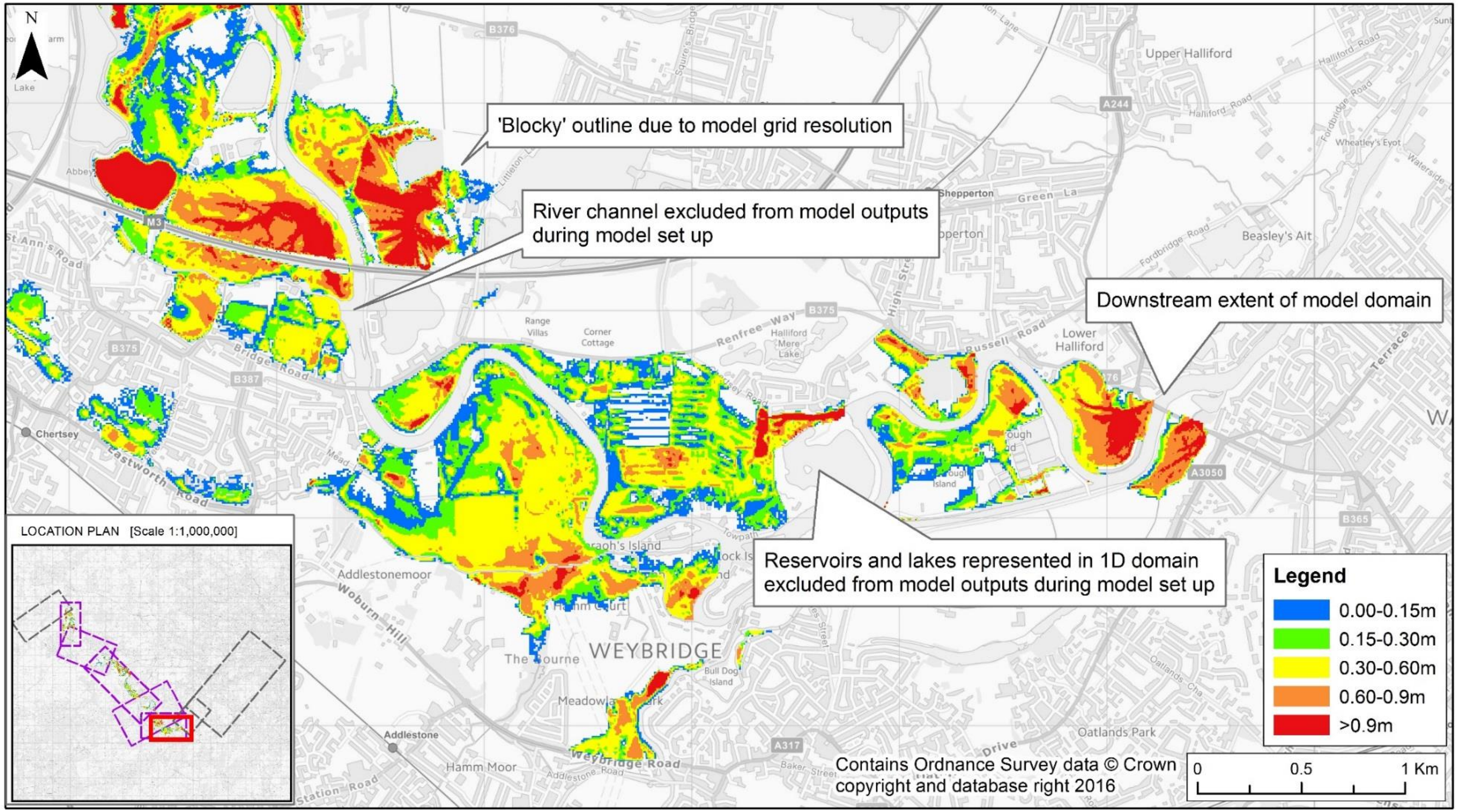


Figure 4.29 Context for model outputs in Chertsey domain

4.3.3 Extent flooded (Test A1)

See Section 4.3.1 for note about observed flood extent data.

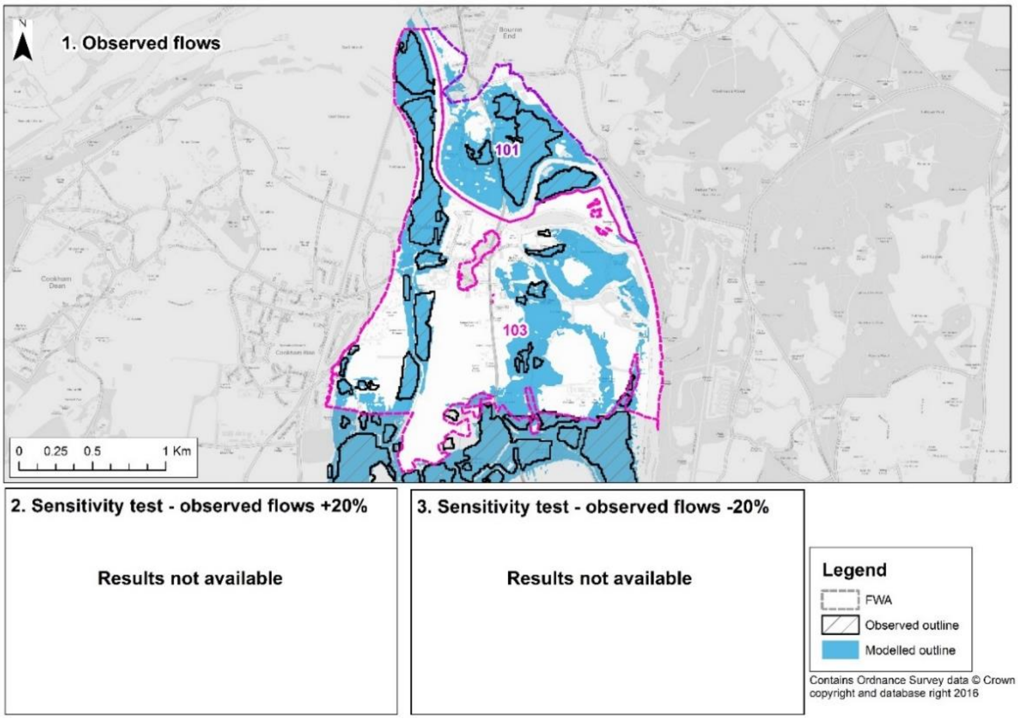


Figure 4.30 Best available maximum modelled extent compared with maximum available observed extent for Maidenhead domain (inset 1 in Figure 4.26)

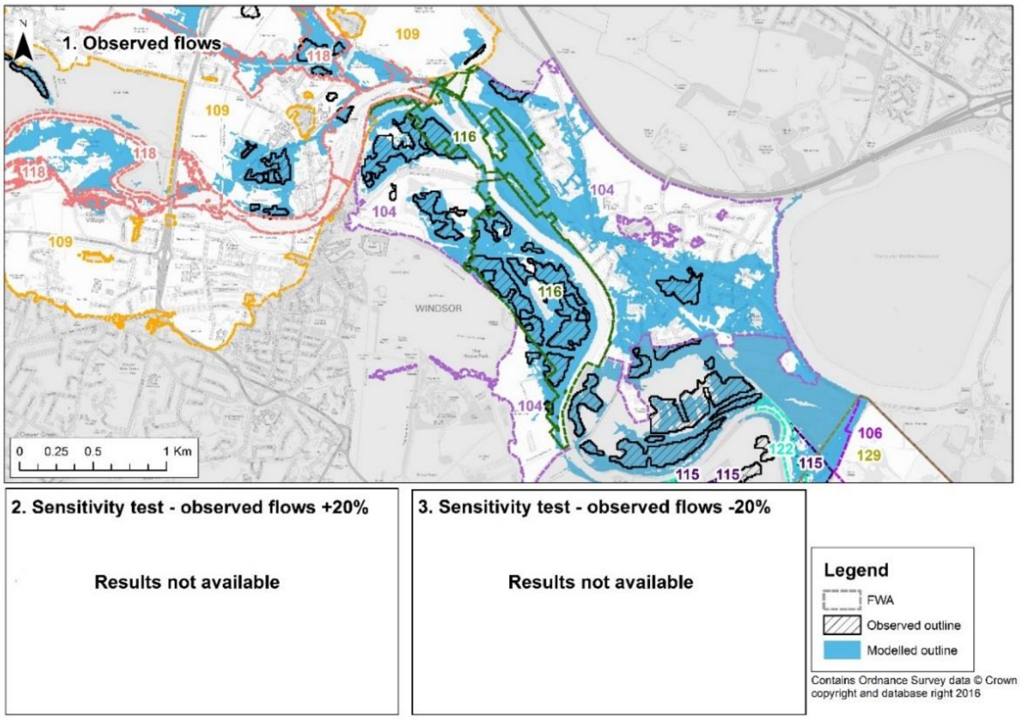


Figure 4.31 Best available maximum modelled extent compared with maximum available observed extent for Bray, Cippenham and Windsor domains domain (inset 2 in Figure 4.26)

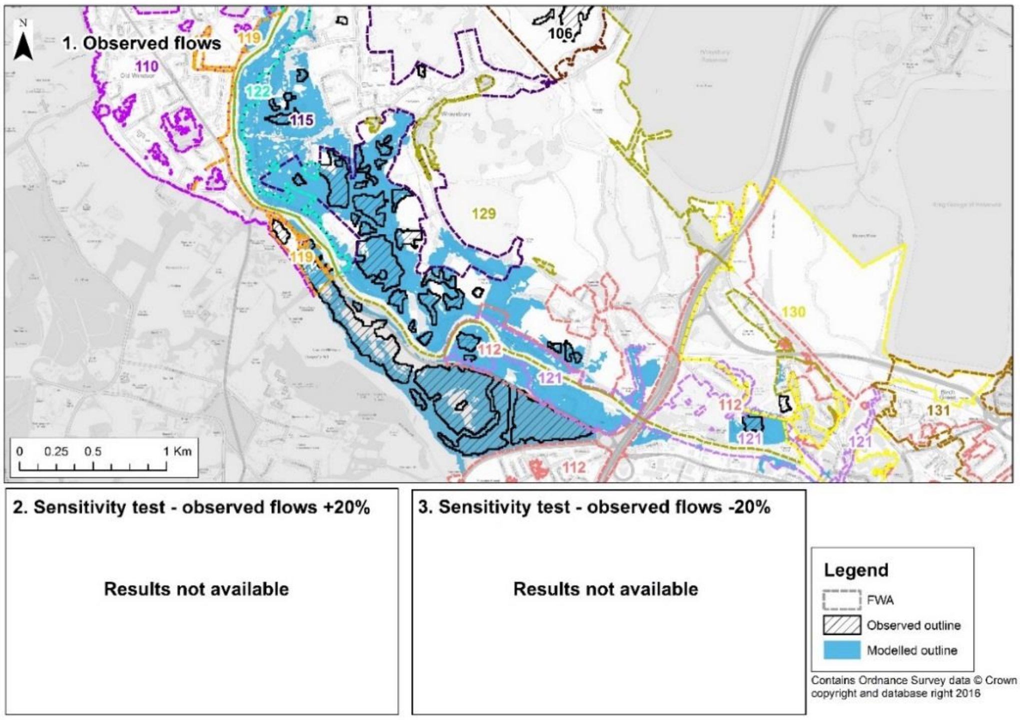


Figure 4.32 Best available maximum modelled extent compared with maximum available observed extent for Windsor and Staines domains (inset 3 in Figure 4.26)

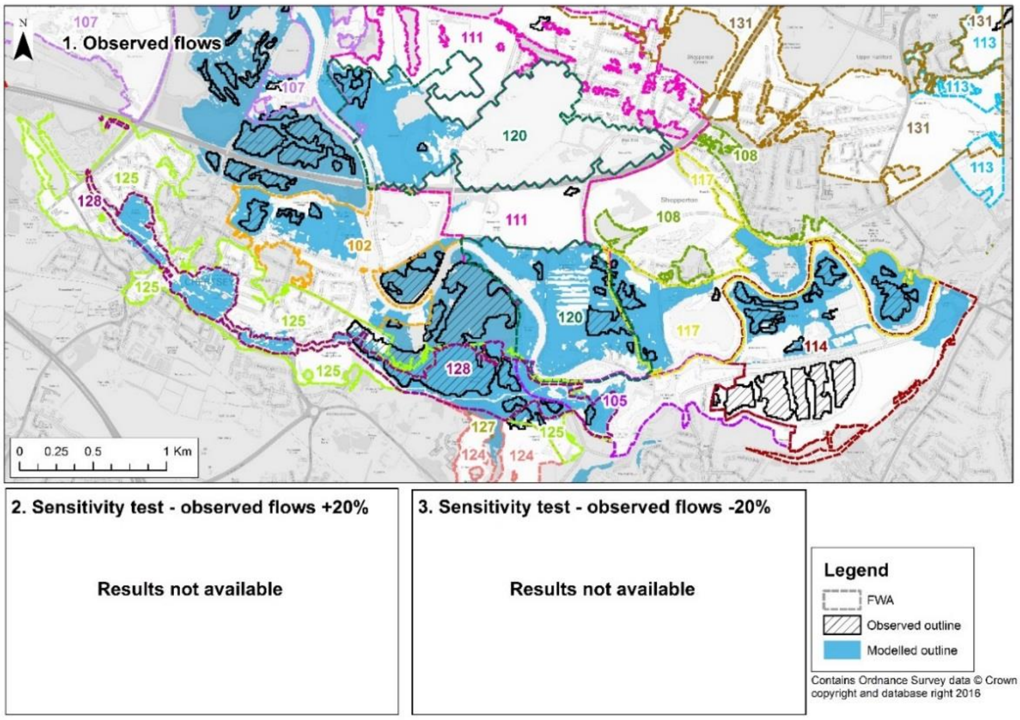


Figure 4.33 Best available maximum modelled extent compared with maximum available observed extent for Staines and Chertsey domains domain (inset 4 in Figure 4.26)

Table 4.17 Comparison of modelled and observed area flooded for each Flood Warning Area for Thames event

Flood Warning Area (FWA)	Area (m^2)	Area flooded			
		Modelled		Observed	
		m^2	% of FWA	m^2	% of FWA
All	**74,330,643**	**11,766,897**	**15.83**	**2,614,505**	**3.52**
101	832,529	538,627	64.70	210,249	25.25
102	820,307	260,339	31.74	35,416	4.32
103	3,032,280	1,088,880	35.91	366,283	12.08
104	2,951,550	1,238,300	41.95	189,845	6.43
105	476,208	103,997	21.84	5,847	1.23
106	968,939	14,202	1.47	53,590	5.53
107	2,701,220	358,048	13.26	33,634	1.25
108	711,436	2,767	0.39	0	0.00
109	17,656,100	988,326	5.60	117,901	0.67
110	1,268,770	5,527	0.44	2,212	0.17
111	1,609,120	18,470	1.15	9,376	0.58
112	10,035,800	1,004,270	10.01	87,282	0.87
113	370,183	0	0.00	2,046	0.55
114	1,318,470	307,959	23.36	265,092	20.11
115	1,684,260	465,500	27.64	34,096	2.02
116	1,065,900	776,153	72.82	256,368	24.05
117	922,556	434,125	47.06	72,331	7.84
118	1,431,340	258,886	18.09	36,224	2.53
119	212,519	57,293	26.96	49,668	23.37
120	2,020,080	854,279	42.29	94,039	4.66
121	1,272,310	395,193	31.06	31,772	2.50
122	409,355	172,570	42.16	0	0.00
124	401,553	6,241	1.55	3,702	0.92
125	1,115,270	89,190	8.00	71,077	6.37
126	527,197	65,023	12.33	0	0.00
127	20,383	559	2.74	0	0.00
128	728,015	556,702	76.47	191,544	26.31
129	8,025,600	1,609,830	20.06	383,981	4.78

Flood Warning Area (FWA)	Area (m^2)	Area flooded			
		Modelled		Observed	
		m^2	% of FWA	m^2	% of FWA
130	1,918,490	10,034	0.52	5,700	0.30
131	7,437,650	0	0.00	5,229	0.07
136	385,253	85,606	22.22	0	0.00

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 2015 modelling study by JBA Consulting calibrated the model to a number of events and it was shown to perform well. In this event, however, the model significantly overestimates observed flood extent in all the Flood Warning Areas apart from one (106). As noted in Section 4.3.1, uncertainties in the observed extent of flooding are likely to contribute to this. For example, the latest model results available to this study are from the peak of the event, while the observed outline is based on remotely sensed imagery obtained some time after the peak as the floodwater started to recede. This will contribute to the marked differences in outline.

The calibration report from the 2015 modelling study highlights the potential significance of several factors on model performance.

- Overestimation of flows from ungauged lateral inflows may be the predominant factor in model overprediction.
- The 1D–2D model does not explicitly model losses via surface water drains on the floodplain, which may also contribute to a small amount of overprediction.
- Operation of lock gates and sluices is variable throughout the duration of an event, and the modelled assumption of all lock structures being fully drawn during flood events is not always the case.
- One of two generalised hydrograph shapes based on observed records at either Windsor or ‘Maidlow’ (a combination of flows from Maidenhead and Taplow sluices) is applied to represent the main River Thames inflow. The calibration report comments on the significance of selecting the most appropriate hydrograph shape on model performance. Accurately quantifying flow inputs to the system is therefore a requirement for accurate prediction of flood extent.

An additional source of uncertainty results from the process of deriving observed outline itself, based on satellite radar. There may be inaccuracies in the digitisation of the outline, particularly in built-up or wooded areas, and therefore uncertainties in its extent which may contribute to the marked differences between modelled and observed outlines. In addition, satellite radar may pick up surface water flooding or flooding driven by other fluvial sources excluded from the model. Furthermore, there are also areas where the 2D model represents lakes that may have been excluded from observed outlines such as on Longfields Farm in the Windsor domain and at Abbeymead in the Chertsey domain.

4.3.4 Model performance (Test A2)

See Section 4.3.1 for note about observed flood extent data

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.

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

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

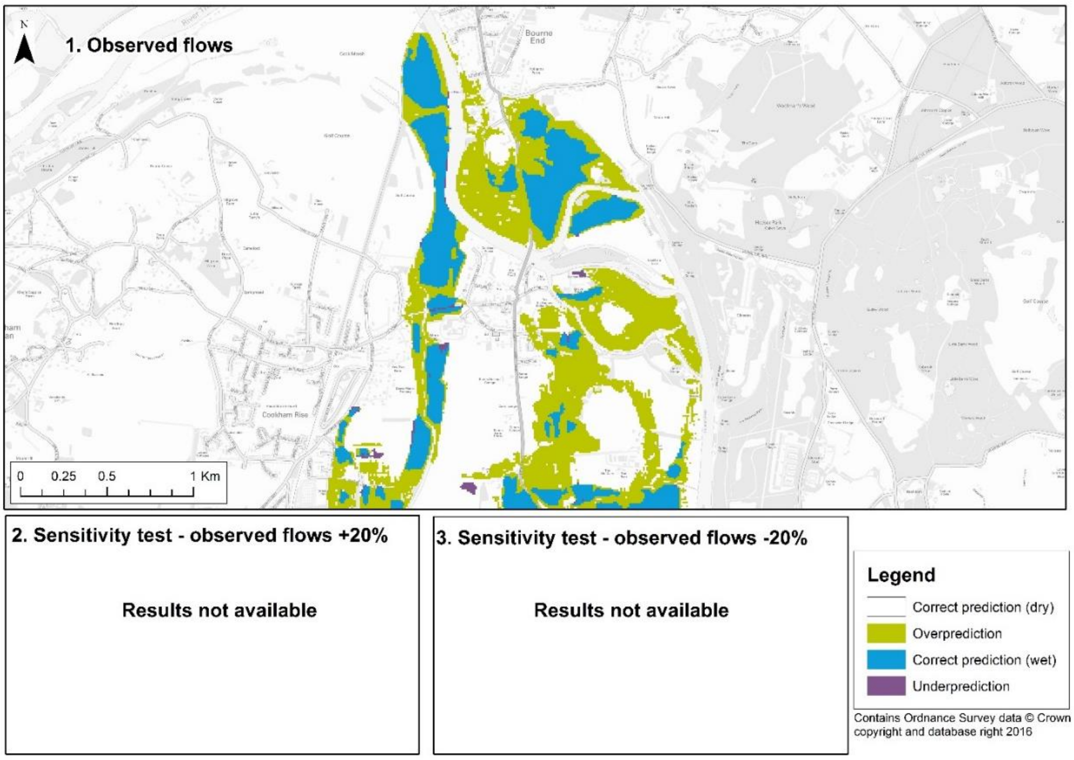


Figure 4.34 Model performance in predicting flooded extent for Maidenhead domain (inset 1 in Figure 4.26)

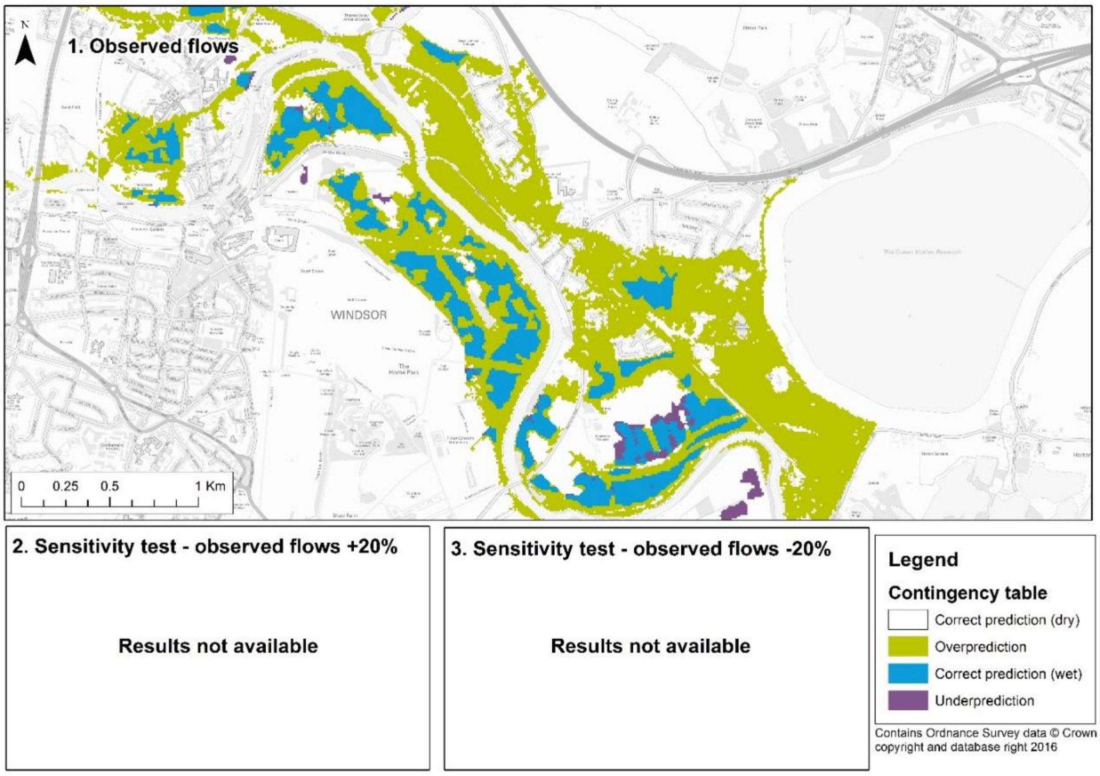


Figure 4.35 Model performance in predicting flooded extent for Bray, Cippenham and Windsor domains (inset 2 in Figure 4.26)

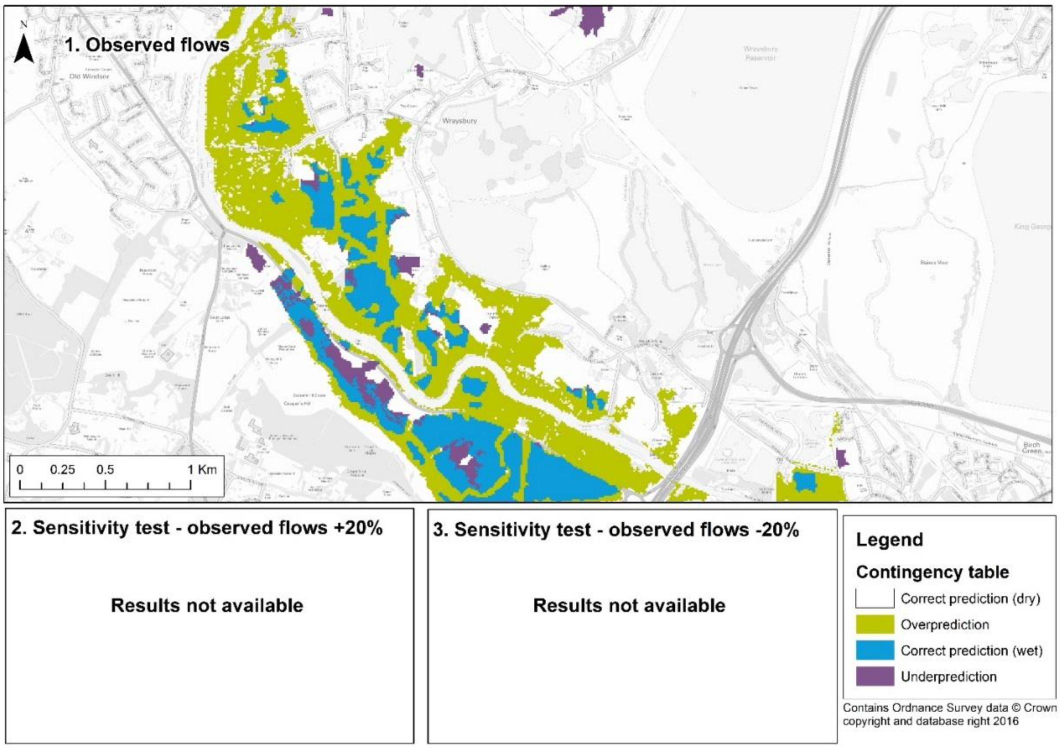


Figure 4.36 Model performance in predicting flooded extent for Windsor and Staines domains (inset 3 in Figure 4.26)

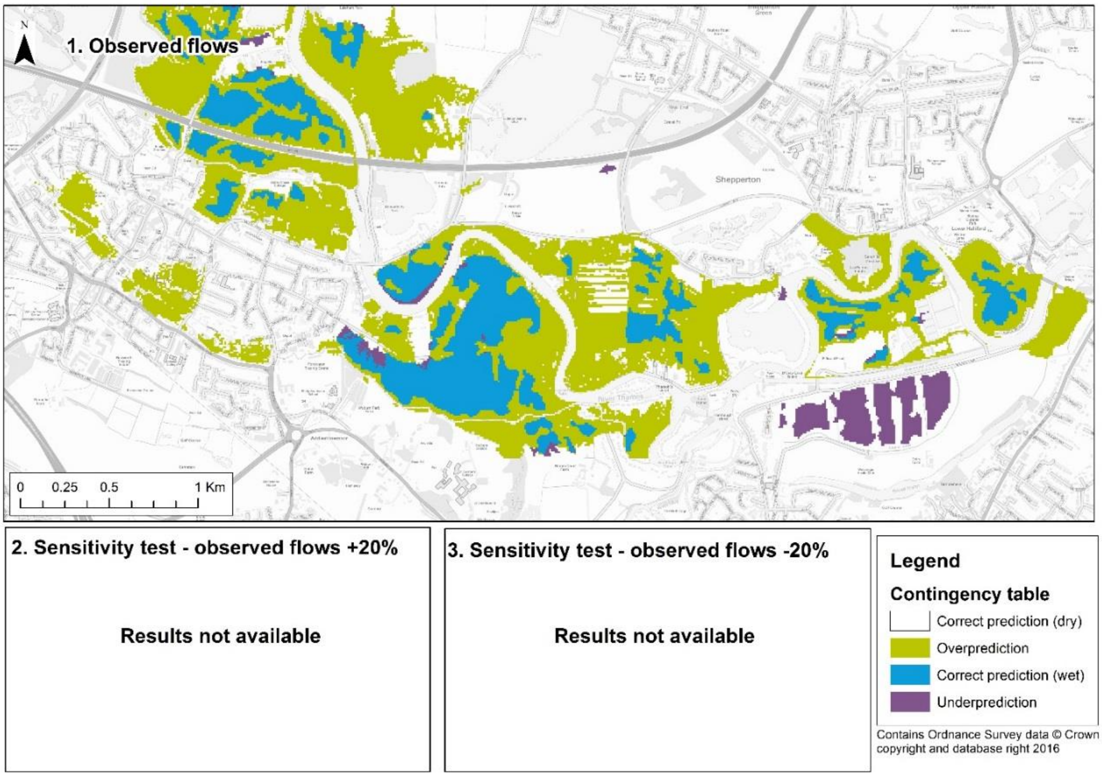


Figure 4.37 Model performance in predicting flooded extent for Staines and Chertsey domains (inset 4 in Figure 4.26)

Table 4.18 Model performance metrics for Thames event

Flood Warning Area	Correct wet (%)	Over-prediction (%)	Under-prediction (%)	Skill	Bias
Modelled outline (all)	**24.51**	**68.61**	**6.88**	**0.25**	**2.97**
Modelled outline (within area covered by Flood Warning Areas only)	**16.94**	**78.74**	**4.32**	**0.17**	**4.50**
101	38.95	60.99	0.06	0.39	2.56
102	13.40	86.42	0.18	0.13	7.35
103	30.96	67.04	2.00	0.31	2.97
104	14.24	84.81	0.94	0.14	6.52
105	4.90	94.42	0.68	0.05	17.79
106	0.00	20.95	79.05	0.00	0.27
107	5.03	90.98	3.99	0.05	10.65
108	0.00	100.00	0.00	0.00	0.00
109	8.35	88.45	3.20	0.08	8.38
110	9.32	68.76	21.92	0.09	2.50
111	3.57	65.13	31.31	0.04	1.97
112	6.17	91.51	2.32	0.06	11.51
113	0.00	0.00	100.00	0.00	0.00
114	14.36	47.10	38.54	0.14	1.16
115	5.57	92.79	1.63	0.06	13.65
116	32.93	66.99	0.07	0.33	3.03
117	16.05	83.43	0.53	0.16	6.00
118	13.43	86.08	0.49	0.13	7.15
119	29.96	39.65	30.39	0.30	1.15
120	10.84	89.01	0.15	0.11	9.08
121	7.88	91.97	0.15	0.08	12.44
122	0.00	100.00	0.00	0.00	0.00
124	14.27	57.45	28.28	0.14	1.69
125	52.51	32.36	15.13	0.53	1.25
126	0.00	100.00	0.00	0.00	0.00
127	0.00	100.00	0.00	0.00	0.00

Flood Warning Area	Correct wet (%)	Over-prediction (%)	Under-prediction (%)	Skill	Bias
128	34.29	65.62	0.09	0.34	2.91
129	16.83	77.50	5.67	0.17	4.19
130	0.00	63.77	36.23	0.00	1.76
131	0.00	0.00	100.00	0.00	0.00
136	0.00	100.00	0.00	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

As discussed earlier, difficulties in obtaining modelled and observed outlines at the same time during the event limit the representativeness of skill and bias metrics. Nonetheless, the 1D–2D model generally predicts patterns of flooding and flood mechanisms that are consistent with the available observed information.

Overall, the model generally overpredicts although there are some small, localised areas of model underprediction. An example where the model underpredicts is in Inset 4 to the south-east, between the Engine River and the Desborough Channel. This may be attributed to very small channels, such as the Engine River, not being represented explicitly in the model due to the coarse resolution of the grid and dominant driver of flood risk to properties being the larger watercourses.

The calibration report from the 2015 modelling study undertaken by JBA Consulting also highlights the significance of a number of factors on model performance including:

- overestimation of flows from lateral inflows
- design hydrograph shape
- nuances in lock gate operations
- no direct modelled representation of surface water drains in the the floodplain

As noted in Section 4.3.1, difficulties in obtaining observed flood outlines contribute to uncertainties in this assessment. There may be inaccuracies in the digitisation of the outline, particularly in built-up areas, and therefore uncertainties in its extent. Overprediction in built-up areas may also be attributed to the model not explicility modelling surface water drainage, which could have reduced flood extent during the 2014 event. There are also areas where the 2D model represents lakes which may have been excluded from observed outlines such as on Longfields Farm in the Windsor domain and at Abbeymead in the Chertsey domain, which may result in apparent overprediction.

4.3.5 Property counts (Test B)

See Section 4.3.1 for note about numbers of observed properties.

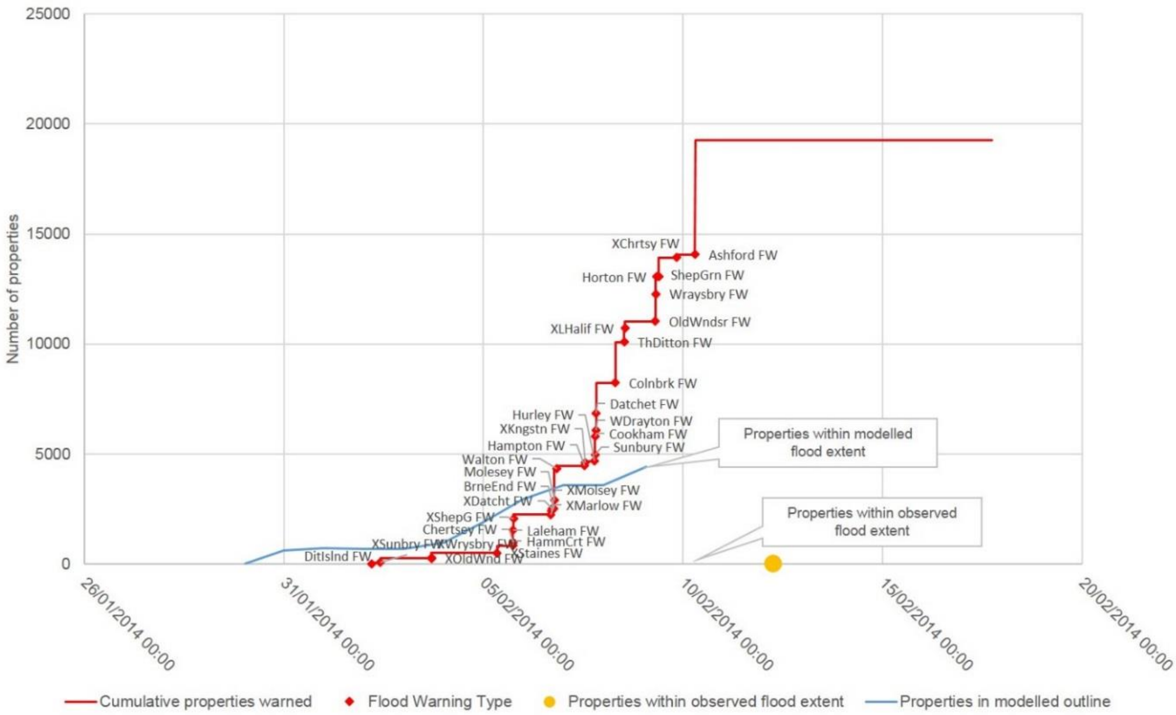


Figure 4.38 Properties within flood extent for Thames event

Table 4.19 Maximum number of flooded properties for Thames event

Flood Warning Area	Properties warned[1]	Observed[2]	Predicted[3]
All	**16,827**	**29**	**4,408**
101	247	3	103
102	1,018	0	49
103	646	5	39
104	2,703	2	1,036
105	271	0	70
106	39	0	12
107	1,232	1	306
108	469	0	0
109	14,569	1	257
110	2,203	0	2
111	1,320	1	2
112	17,571	3	701
113	133	0	0
114	77	5	17
115	1,553	0	253
116	38	0	17

Flood Warning Area	Properties warned[1]	Observed[2]	Predicted[3]
117	233	1	148
118	170	0	16
119	61	1	8
120	437	0	261
121	643	4	247
122	351	0	180
124	401	0	0
125	2,431	0	20
126	141	0	4
127	12	0	0
128	250	0	106
129	2,968	2	540
130	1,187	0	13
131	8,152	0	0
136	387	0	1

Notes: Numbers given are the best available maximum figures.
Some Flood Warning Areas overlap and, as a result, some properties are double-counted in the totals given in the first row 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.
[1] Properties warned: counts of properties within each Flood Warning Area in the model domain that received a flood warning during the event. Only Flood Warning Areas within the modelled extent were considered in this analysis. Note that the number of Flood Warning Areas included may differ between PoCs as modelled extents are variable.
[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

There are significantly more properties within the modelled flood outline than in the observed (4,408 compared with 29). However, the observed property counts are based on an intersection of property points with observed flood outlines. As noted in Section 4.3.1, obtaining accurate and comprehensive observed flood outlines for this event has proved challenging, resulting in uncertainties over observed property numbers. This is reflected in the maps shown below.

Specific causes of the discrepancy between properties within the observed and modelled outlines include:

- difficulties in selecting outlines from the same time during the event (discussed above)

- uncertainties in digitisation of the observed outline from satellite radar (mentioned in Section 4.3.4), particularly in built-up areas – this is supported by the maps below illustrating high concentrations of receptors where the model is shown to overpredict
- the possibility that overprediction in built-up areas may also be attributed to the model not explicility modelling surface water drainage

There are also a number of reasons associated with model schematisation detailed in Sections 4.3.3 and 4.3.4 which may, in part, explain the apparent overprediction.

Outputs from this PoC could be used to provide more targeted information to supplement Flood Warnings. It is envisaged that the PoC provides supplementary information, as other factors such as local expertise are considered in decision making for Flood Warnings.

Properties mapped by model prediction

The map 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. See Section 4.3.1 and discussion above for note about numbers of observed properties.

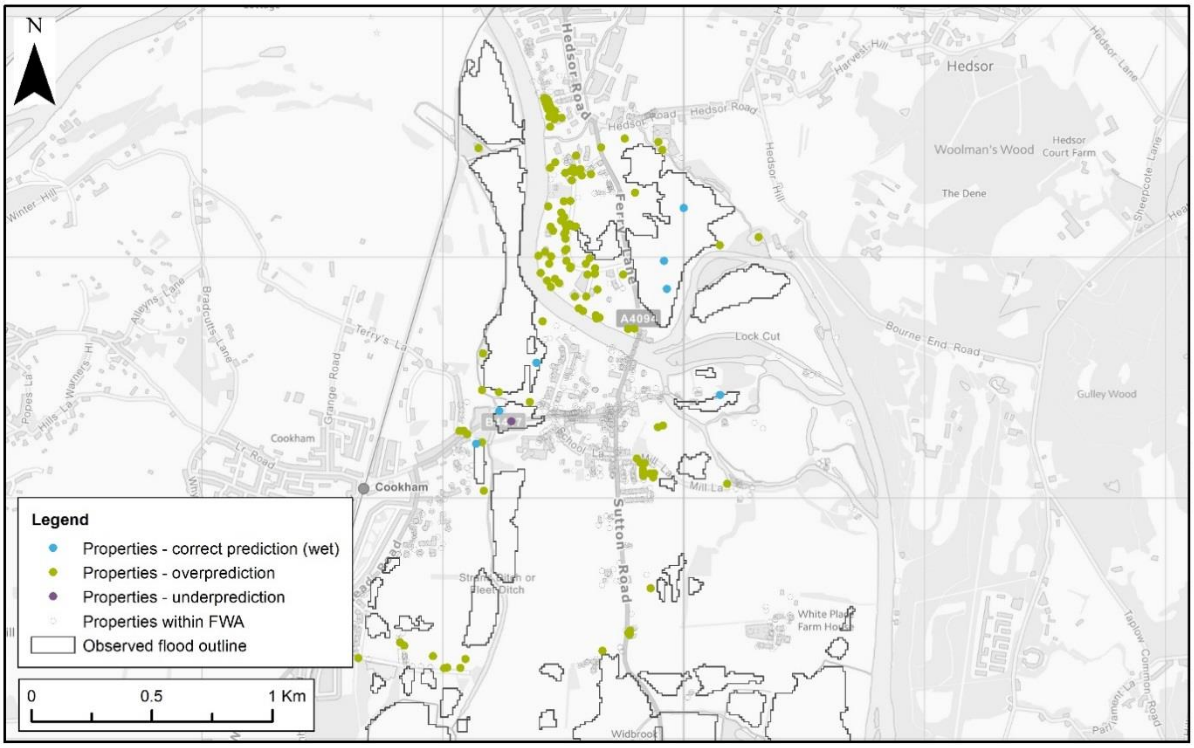


Figure 4.39 Closest modelled time step to validation data for Maidenhead domain (inset 1)

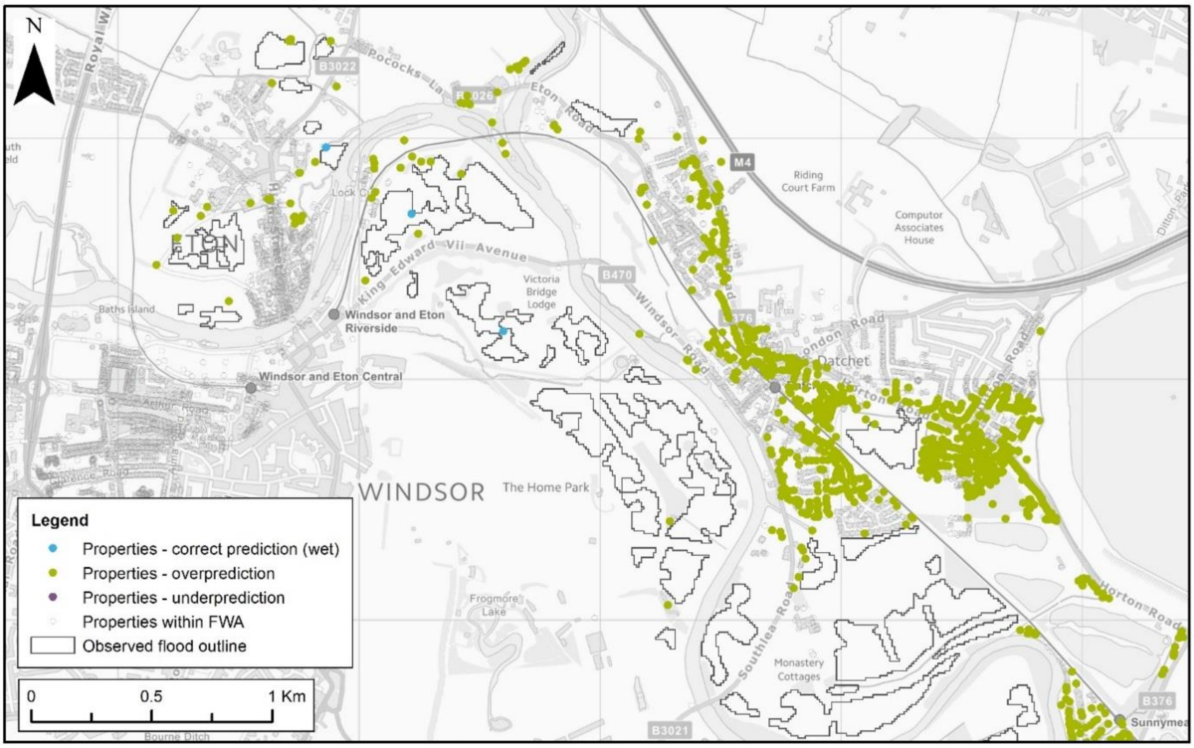


Figure 4.40 Closest modelled time step to validation data for Bray, Cippenham and Windsor domains (inset 2)

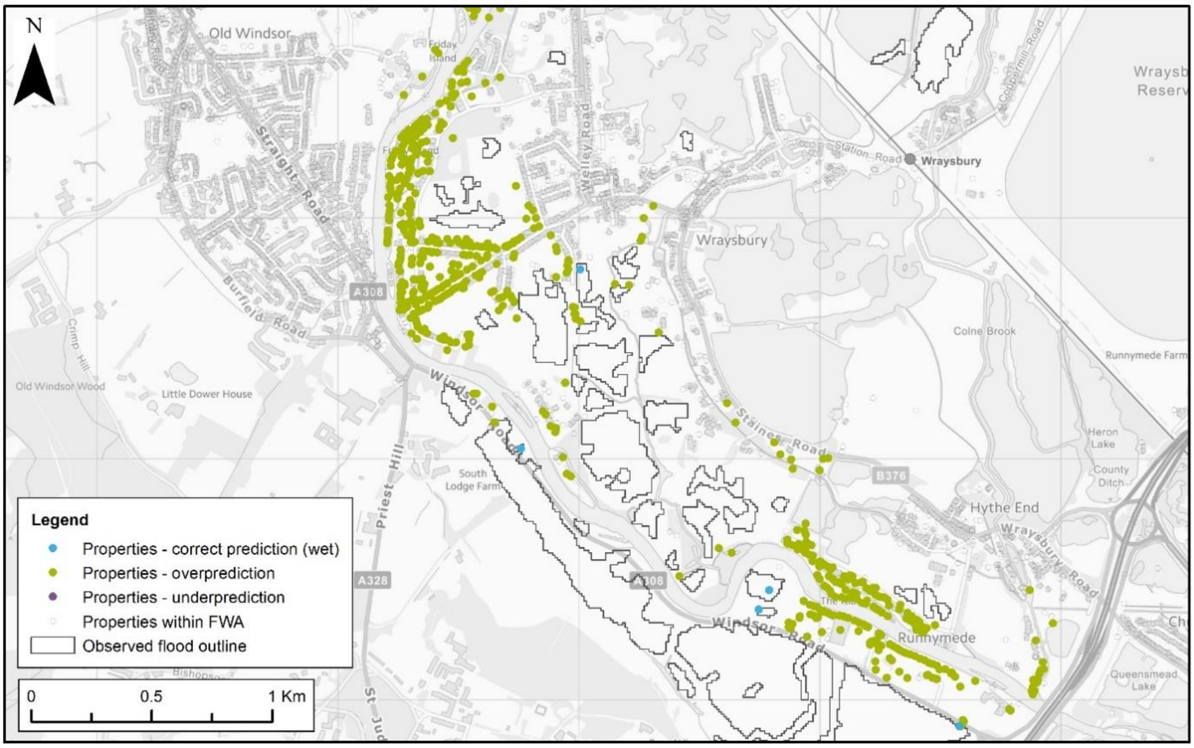


Figure 4.41 Closest modelled time step to validation data for Windsor and Staines domains (inset 3)

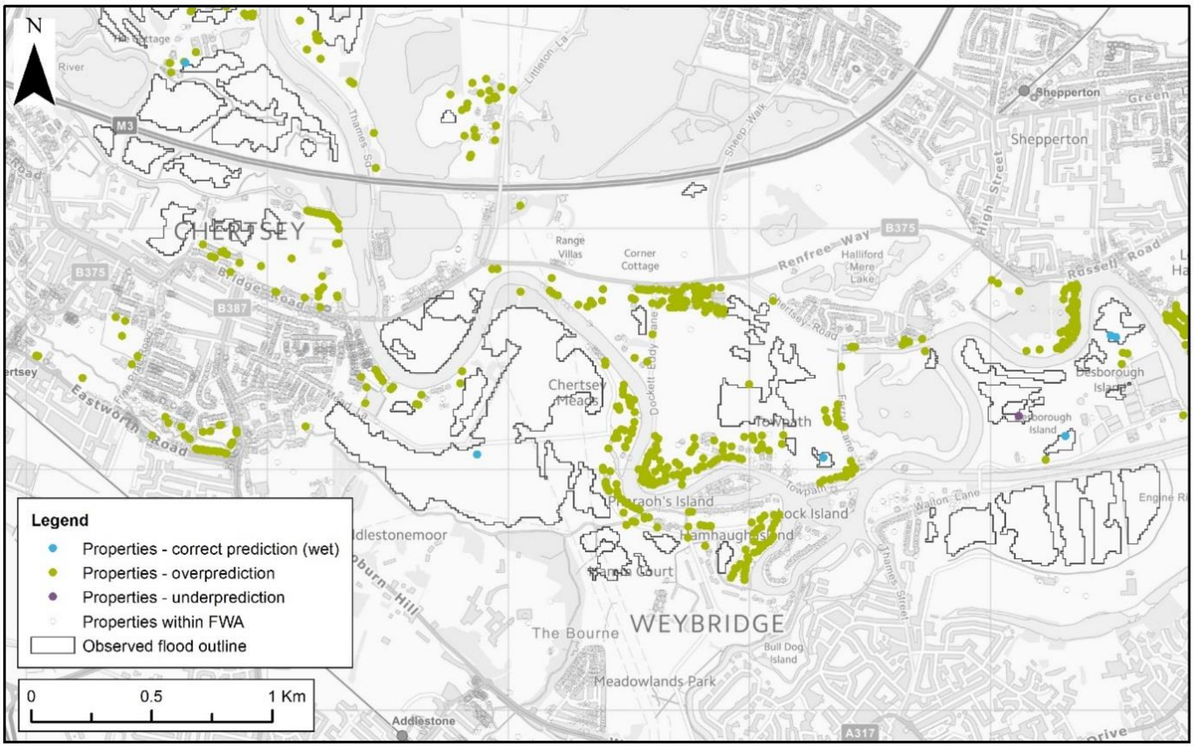


Figure 4.42 Closest modelled time step to validation data for Staines and Chertsey domains (inset 4)

4.3.6 Depth analysis (Test C)

Flooded depths

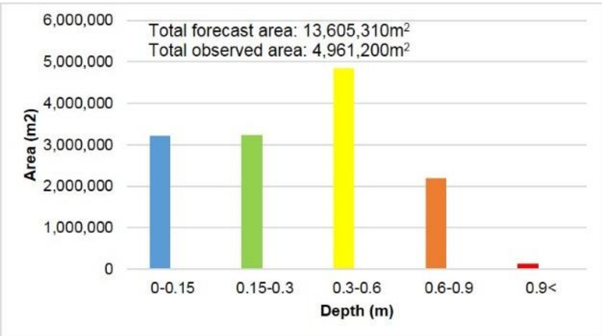


Figure 4.43 Distribution of flooded depths (02:00 on 9 February 2014)

Notes: Peak at 01:15 on 10 February 2014 at Reading
Modelled and observed area categorised by depths.
Solid bars show modelled depths (from the PoC option).
No observed depths are available.

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

Interpretation

- There is a substantial area deeper than 0.3m (over half modelled area).
- The total forecast area is much larger than observed. This may be associated with uncertainties in the observed outline. There may also be some uncertainty in modelled outputs as detailed in Sections 4.3.3 and 4.3.4, including:
  - overestimation of flows from lateral inflows
  - design hydrograph shape
  - nuances in lock gate operations
  - no direct modelled representation of surface water drains in the floodplain

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.

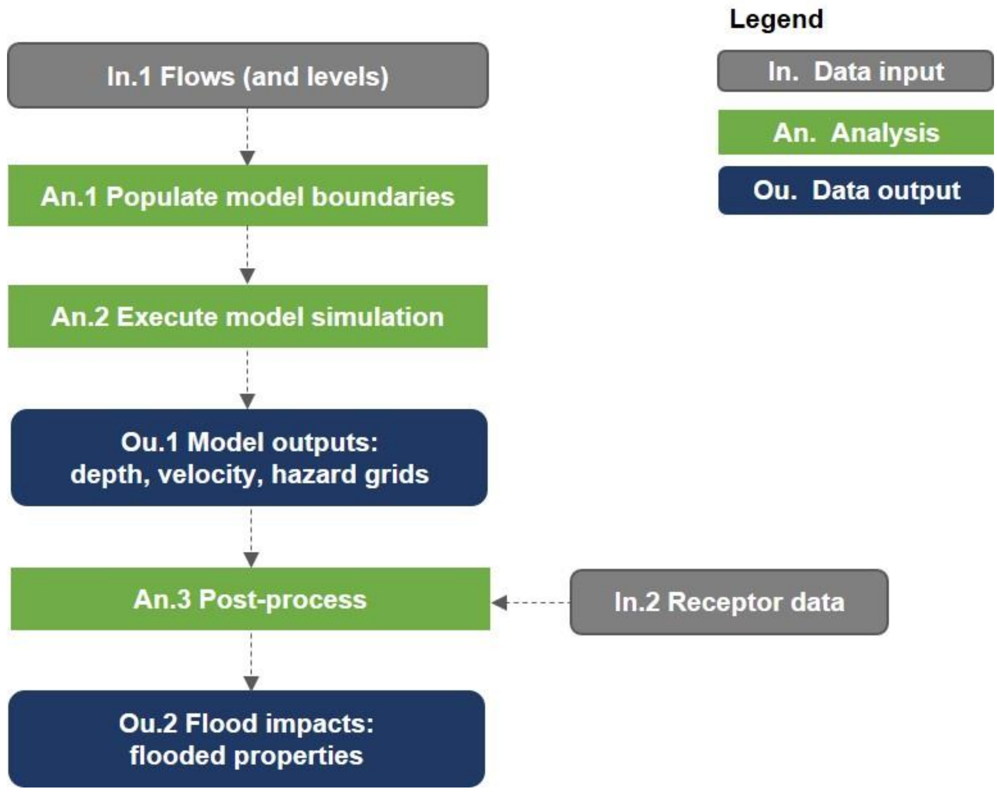


Figure 5.1 Flow chart showing PoC workflow for fully dynamic fluvial modelling

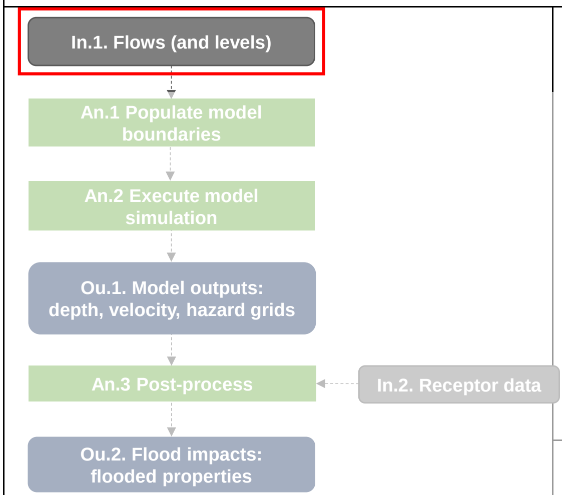
5.1 Operating the system

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

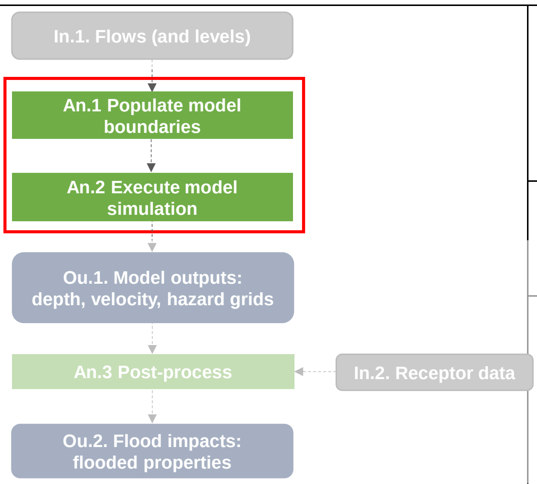
Description	Priority
Acceptable model run times for use in operational forecasting. 1D–2D real-time modelling may need to target geographical areas of high flood risk in the future.	High
Transfer of model results – output files can be large and might require the transfer of large volumes of data across networks.	High
Appropriate sources of real-time boundary conditions (flow time series)	Medium
Consideration of building representation on modelled flood impacts	Medium
Integration within forecasting systems (for example, general adapters or APIs, 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 high resolution models.	Medium

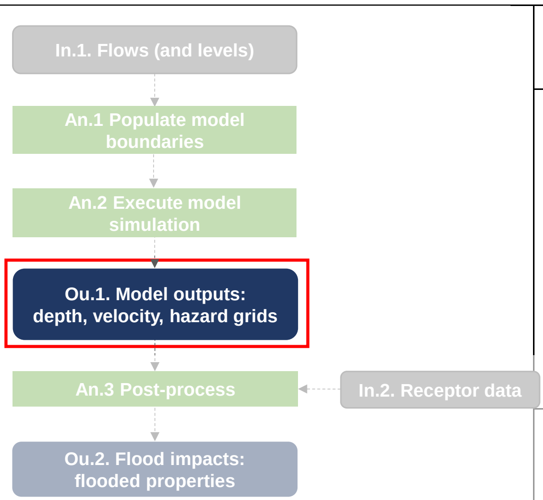
Table 5.2 Detailed considerations

In.1. Input data (observed or forecast flows and levels)



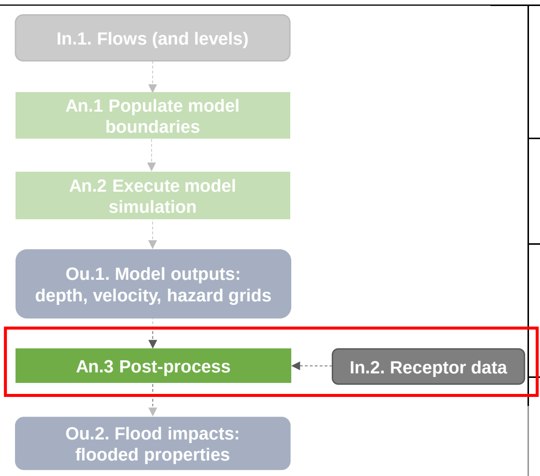
Description	Flow– time series are the main input required for this option. In some cases, level time series may also be needed (for example, tidal boundaries, to provide accurate initial conditions for reservoir levels etc.) Consideration should be given to the most appropriate source of real-time flows/levels – their accuracy has a significant impact on model accuracy.
Data overheads	Low – files tend to be plain text files and are typically small (a few MB). For example, the Cockermouth model boundary used in this study was around 1MB for 432 hours of simulation data.
Run times	Not applicable
Software	Not applicable
Hardware	Not applicable

An.1. Populate model boundaries, An.2. execute model simulation		
	**Description**	In NFFS, an adapter (a standalone executable) is used to populate the model's boundary conditions and trigger its execution. The model then runs in its native environment.
	Data overheads	Low – once a model is set up, the input data used to populate model boundaries are generally small.
	Run times	High – size of model domain, number of grid cells and computational time step will all contribute to model run times. Implementation of this PoC option might need to consider a targeted approach to only running models in areas or at times of high flood risk. Model stability issues may be encountered if forecast flows at the start of an ensemble simulation are significantly different to the initial conditions in the model. Instabilities may also occur if forecast flows are much larger than the standard suite of design AEPs.
	Software	Numerous 1D–2D modelling packages exist. The Environment Agency routinely has access to ISIS/Flood Modeller, TUFLOW and HEC-RAS.
	Hardware	Fast CPUs, large disk space and RAM required.

Ou.1 Model outputs		
	**Description**	Model outputs are typically raster grids of depth, velocity and hazard.
	Data overheads	High – file sizes can be large. Factors that will influence this include model domain size, grid resolution and frequency of outputs. Some software packages offer means of compressing data (for example, TUFLOW can output results in .xmdf format, which offers different levels of compression).
	Run times	High – bandwidth required to transmit model results across a network has the potential to be high.
	Software	GIS software is required to view model outputs. Some model output data formats may be more readily accessible than others:

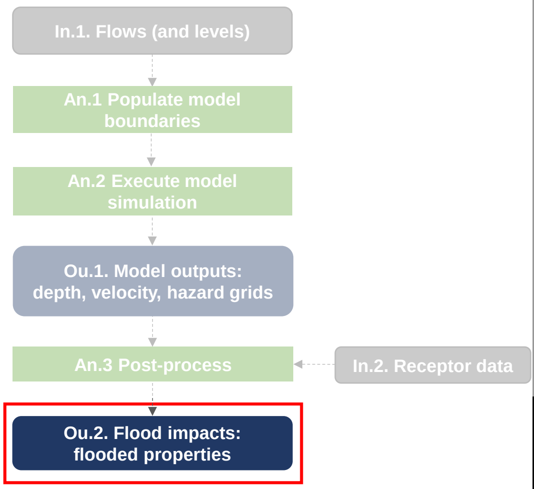
		.asc files can be read by most GIS packages (ArcGIS, MapInfo, QGIS) .xmdf files (a format used by TUFLOW) may require more specialised software WMS/WFS data feeds could be provided to Easimap2, Resilience Direct, NFFS Viewer
	Hardware	Reliable internet connections to transmit large volumes of model results to other systems

In.2 Receptor data, An.3 Post-process



Description	Post-processing grids into outlines and banded depth grids. Intersecting outlines and depth grids with receptor data (for example, properties).
Data overheads	Low – for a single time interval. Has potential to be higher for multiple time intervals.
Run times	High – model domain size and grid resolution may influence processing time. It has the potential to be higher for multiple time intervals.
Software	GIS software is required to post-process model outputs with receptor data .shp files can be read, processed and analysed by ArcGIS
Hardware	Fast CPUs, large disk space and RAM required

Ou.2 Flood impacts: flooded properties



Description	Flood outlines and property datasets, typically in GIS format
Data overheads	Low – for a single time interval. Has potential to be higher for multiple time intervals
Run times	Low – for post-processed outputs
Software	WMS/WFS data feeds could be provided to Easimap2, Resilience Direct, NFFS Viewer
Hardware	Transmitting information on flooded properties may require transfer of smaller volumes of data than model results (for example, gridded data of flood depth)

5.2 Implementation and ongoing maintenance of an operational system

Table 5.3 Summary of implementation and maintenance issues for an operational system

<table>
<tr><td colspan="4">Overview</td></tr>
<tr><td colspan="4">This option reuses existing models and software, which can be implemented within existing forecasting systems. Models currently held by the Environment Agency are typically designed for offline, detailed flood mapping. As a result, reusing these models in the near future will be challenging. The models tested in this study are computationally expensive and do not meet the run time constraints of forecasting in real time. However, there is nothing inherent to the software or data that mean shorter run times are unobtainable in future, for example, if models were developed specifically for use in real time with a maximum acceptable run time specified at the outset of model development.

Additional skills or training required to implement and maintain the system should be limited. However, consideration should be given to ongoing licensing costs (of model software) and the practicalities of updating an operational system with new software versions and models (relatively large volume datasets).

Consideration should also be given to the influence of building representation on assessment of flood impacts. For example, filling in dry islands ($<200m^2$) is a standard requirement of NFCDD flood maps. However, raw depth grids, such as those assessed in this PoC, would require additional post-processing to replicate this. Filling in dry islands would influence flood impact assessment.</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 could be implemented within existing forecasting systems. Some change would be required to disseminate real-time flood mapping and impact data.

Adapters for the Flood Early Warning System (FEWS, the forecasting software that underpins the NFFS) are already available for many hydraulic model software packages including ISIS/Flood Modeller, TUFLOW, MIKE11/21 and HEC-RAS.</td></tr>
<tr><td rowspan="2">Cost to implement</td><td>Low</td><td>Moderate</td><td>Significant</td></tr>
<tr><td colspan="3">This option assumes that existing 1D–2D mapping models are reused. Implementing this option would therefore involve configuring models into a forecasting system; the cost associated with this would be relatively low. However, as discussed, few 1D–2D models currently held by the Environment Agency are designed with real-time use in mind. The cost of developing models specifically for flood forecasting should be considered in future implementation.</td></tr>
<tr><td>Skills required to implement</td><td colspan="3">Limited additional training or skills would be required. This option uses model software that is already used by the Environment Agency. It can be configured into existing forecasting systems.</td></tr>
</table>

Time/effort to implement	1D–2D models could be implemented in existing forecasting systems alongside existing models. The time required to implement these would not be significantly greater than configuring 1D models into NFFS.		
Ongoing maintenance			
Difficulty in accommodating change	Low	**Moderate**	Significant
	The option would need to accommodate: • updates to mapping models and new commissions • updates to model software versions For practicality, in terms of staff availability and computing resources, this may need to be undertaken at set times, which may result in difficulty in accommodating rapid change.		
Cost to maintain	Low	**Moderate**	Significant
	Many modelling software packages require ongoing licensing. The cost required to update both the models themselves and new software versions should be considered.		
Skills required to maintain	Limited additional training or skills would be required. This option uses model software that is already used by the Environment Agency. It can be configured into existing forecasting systems.		
Time/effort to maintain	Further model stabilisation work may be required if a model is run for an event beyond the magnitude of events for which it has been tested. As with existing forecasting models in NFFS, third party support may be required to improve or update models.		

6 Scope for further development

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

Description	Impact	Recent examples
Increases to computer processing speed	Faster model run times	It is possible to run many hydraulic modelling software packages on graphics processing unit (GPU) accelerated hardware.
Updates to, or higher resolution geometry data, allowing improvements to accuracy of how topography is modelled	Improved model accuracy (although inclusion of higher resolution detail may increase model run times)	Some LiDAR datasets are periodically re-flown.
Improvements to accuracy of flow prediction (for example, driven by improvements to rainfall forecasts)	Model boundary conditions specified with greater accuracy, resulting in improved model performance	This project made use of G2G outputs, driven by MOGREPS data that was available at the time of the Cockermouth event (November 2009). At that time, MOGREPS had 24km resolution and produced 3-hour rainfall totals. The current MOGREPS product now has 2.2km resolution and produces 15-minute rainfall totals.

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