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delivering benefits through evidence

Real-time flood impacts mapping

Appendix 8: Simplified surface water modelling

SC120023/A8

Flood and Coastal Erosion Risk Management Research and Development Programme

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Professor Doug Wilson
Director, Research, Analysis and Evaluation

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1 Pro-forma summary

Direct rainfall modelling is conceptually straightforward and widely accepted as an appropriate method for analysing higher magnitude, lower probability storms where subsurface drainage systems are likely to be overwhelmed and/or inlet capacities exceeded.

This proof of concept (PoC) tests a two-dimensional (2D) graphics processing unit (GPU) accelerated model based on the shallow water equations. The model provides a good fit to available observations – including depth and timing – when driven by observed rainfall.

This PoC demonstrated that it can be efficiently implemented using existing updated Flood Map for Surface Water models and run-off data feeds from the Grid to Grid (G2G) forecasting model. However, run times are high for large areas (that is, 20km × 20km). Run times of approximately 1 hour for the 2m grid resolution and 6km × 6km model domains used in the updated Flood Map for Surface Water are currently at the limit of feasibility for real-time modelling. A key point is that both models are running at 2m grid resolution using GPU-based 2D hydraulic models based on the shallow water equations. Although it was not tested here, optimal model run times and model outputs will need to be tested for an operational implementation of this PoC (for example, model run times would be expected to be at least 8 times quicker if using a grid resolution of 4m).

Future implementation should also consider setting ‘thresholds’ for forecast rainfall or run-off which, when exceeded, would trigger hydraulic model runs. A criterion for operationally launching the 2D hydraulic models in real time across areas of interest would also need to be developed. In addition, the overheads associated with post-processing the high resolution model outputs into an event-specific flood footprint can be significant and this would need to be considered beforehand.

There is a large variability in the flooding generated across forecast ensemble members due to the convective storms that generated flooding across Newcastle on 28 June 2012 and Canvey Island on 20 July 2014. This type of storm is harder to predict with high certainty, and therefore a greater spread of the ensemble members is produced. On the other hand, the recent winter storms of 2015 to 2016 should exhibit less spread across ensemble members (higher predictability). Nonetheless, in areas of ‘high likelihood’ flooding such as low-lying areas and topographic depressions where flood water ponds and accumulates, it provides a good fit to observations. The PoC demonstrates how uncertainty forecast ensembles can be cascaded to maps of predicted flood extent.

The value of real-time surface water flood modelling is currently being assessed alongside the prototype Surface Water Flooding Hazard Impact Model developed by the Natural Hazards Partnership for the joint Environment Agency/Met Office Flood Forecasting Centre.

2 Proof of concept overview

2.1 About this option

Name in Technical Options Report (Appendix 2): Simplified surface water modelling

Number in Technical Options Report: Option 6

This PoC runs a fast surface water inundation model in real time, driven by G2G run-off outputs. The option produces equivalent outputs to Option 4 – a pre-computed simulation library, based on the updated Flood Map for Surface Water and linked to G2G run-off outputs. However, the primary advantage of real-time modelling is that it avoids having to relate a limited set of pre-computed flood outlines/depths (3–9 scenarios), based on design rainfall, to the temporally and spatially varying G2G run-off estimates. The Natural Hazards Partnership Surface Water Flooding Hazard Impact Model (NHP SWF HIM) programme is currently testing Option 4 and an approach to the problem of selecting appropriate flood mapping. The relative benefits of using pre-computed versus real-time mapping for surface water flood warning will be evaluated as part of the NHP SWF HIM testing process.

In this PoC, the modelling approach used is based on the direct rainfall concept. Net or ‘effective’ run-off volumes are applied to each grid cell in the hydraulic model. These are routed across the Digital Terrain Model (DTM) surface, identifying flooding pathways and areas where ponding will occur. The approach has been successfully implemented to produce surface water flood maps at all spatial scales. It is widely accepted as an appropriate method for analysing higher magnitude, lower probability storms where subsurface drainage systems are likely to be overwhelmed and/or inlet capacities exceeded (Defra 2010).

However, direct rainfall simulations in 2D hydraulic models can be very computationally expensive, depending on the mathematical basis of the software used. If a model based on the shallow water equations is used (as in this PoC), it is highly likely that high performance hardware will be required to achieve acceptable run times, for example, through the use of parallel central processing units (CPUs) or GPUs. The use of high performance computing (HPC) and/or GPUs is well established for flood modelling and facilitated by many industry-standard software packages.

Operationally, it would be necessary to determine when (and where) to trigger a real-time model run in order to manage demands on computing resources. This could be based on setting rainfall or run-off thresholds for given locations; when these are exceeded, a real-time model is triggered. Thresholds could be determined via an analysis of updated Flood Map for Surface Water data (that is, to determine what volume of rainfall/run-off generates flooding above a given depth) or based on existing Extreme Rainfall Alert criteria (or similar). G2G outputs could then be monitored to determine when a given threshold is crossed and inundation model(s) should be launched.

Alternatively, it would be relatively straightforward to couple numerical weather prediction (NWP) models and/or radar rainfall outputs to directly drive the inundation model(s) – that is, bypassing the hydrological routing within G2G. This has the potential to be easier to implement. However, antecedent catchment conditions and within-event losses (through infiltration and subsurface drainage systems) would still require representation by other means, for example, by reusing standard assumptions used in the updated Flood Map for Surface Water.

Indirect rainfall modelling, every grid cell of the model domain receives a rainfall or run-off input. Geographical information system (GIS) post-processing is therefore required to:

- improve the usability of the outputs
- identify areas and receptors at risk of surface water flooding

For example, flood maps might show only those areas with depths above a certain value. Post-processing can also be computationally expensive, depending on the complexity of the topological rules used, and the extent and grid resolution of the underlying inundation models.

The PoC reuses models and data from updated Flood Map for Surface Water. Any future operational implementation could be achieved relatively efficiently by reusing models, data and software tools that were used to produce the updated Flood Map for Surface Water.

2.2 Functional requirements

The Technical Options Report summarised the user needs identified during the consultation exercise at the outset of this project. The user requirements were compiled into an evaluation matrix for this PoC, which is reproduced in Figure 2.1.

- 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 requires the given functionality.
- If the PoC option meets a given acceptability criteria, it is assigned a ‘Y’.

FUNCTIONAL REQUIREMENTS

FLOOD SOURCE	Fluvial	Coastal	Surface Water	Groundwater	All sources
			Y		
FLOOD HAZARD	1D water levels	2D flood extents	2D flood depths / water levels	2D velocities and / or hazard rating	
		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)		
ASSET PERFORMANCE	Breach inundation and overtopping: single asset failure	Breach inundation and overtopping: multiple asset failure	Within-event asset deterioration / failure	Worst case breach inundation	
TRANSPARENCY	Individual components can be interrogated / evaluated	Closed system, simplified model-wide confidence statements			
	Y				

Figure 2.1 Evaluation matrix: simplified surface water 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)

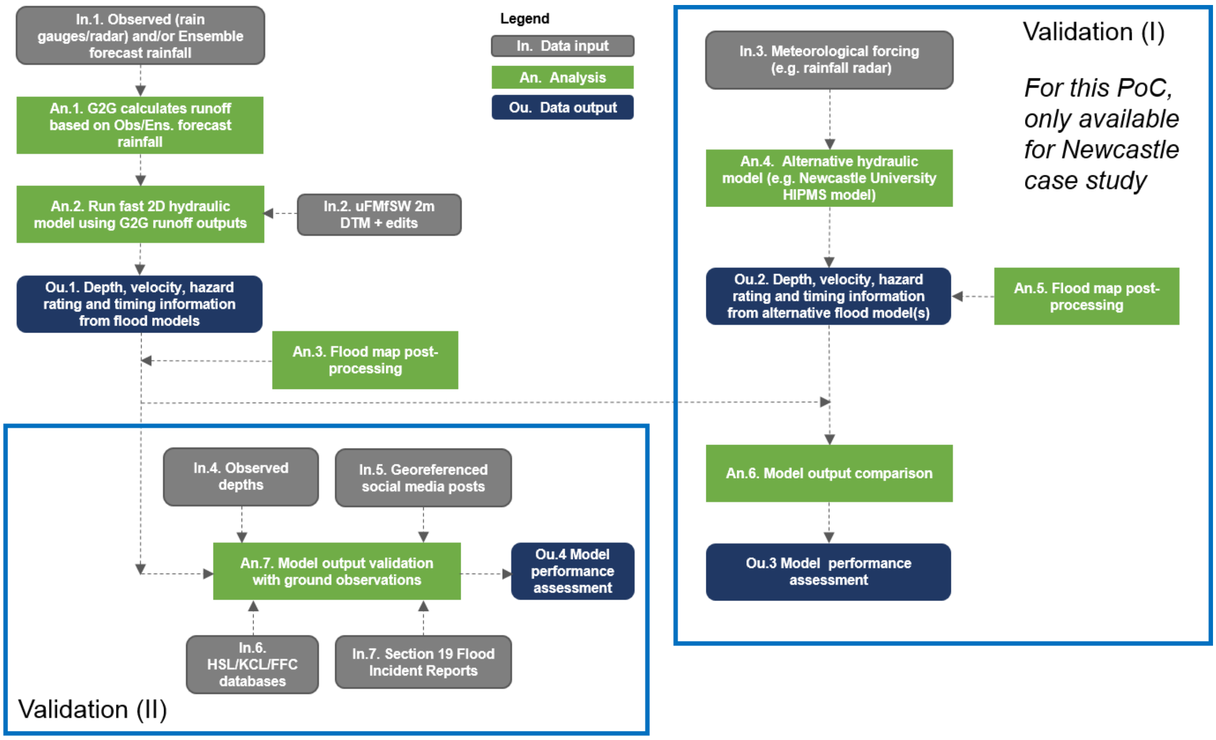


Figure 2.2 Flow chart showing PoC workflow for simplified surface water modelling

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

	Newcastle	**Canvey Island**
Event	28 June 2012 (convective storm)	20 July 2014 (convective storm)
Inputs	G2G run-off outputs linked to fast 2D hydraulic model run in 'direct rainfall' mode G2G run-off estimates, based on observed and ensemble rainfall forecasts (1 forecast origin × 12 ensemble members)	G2G run-off outputs linked to fast 2D hydraulic model run in 'direct rainfall' mode G2G run-off estimates, based on observed and ensemble rainfall forecasts (10 forecast origin × 24 ensemble members)
Evaluation data	HiPIMS 2D hydraulic model, georeferenced photos (Newcastle University) Media-based impacts database – provided by the Health and Safety Laboratory (HSL)/King's College London (KCL)/Flood Forecasting Centre (FFC) via the NHP SWF HIM programme	Media-based impacts database (HSL/KCL/FFC) via the NHP SWF HIM programme Section 19 Flood Investigation Report and supporting GIS data
Evaluation tests[1]	Adapted Tests A1 and A2, and validation analysis – see Section 3.2	
Outputs	• Flood extents • Depth • Water level • Velocity • Hazard	
Comments	G2G run-off forecasts provided as ASCII rasters at 1km^2 per 15-minute intervals for t + 32 hours lead time Reuses updated Flood Map for Surface Water 2m DTM but removes losses assumptions and accounts for antecedent catchment conditions Model outputs also require thresholding/post-processing in real time to extract flood shoreline	

Notes: [1] See Section 4.1.5 of the main report for a description of each evaluation test.
HiPIMS = High-Performance Integrated Hydrodynamic Modelling System

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.

The outcomes of the evaluation tests detailed below are presented in Section 4 of this appendix.

3.2.1 Input data

Table 3.2 Flow chart: In.1, An.1 G2G calculates surface run-off grids based on observed and/or ensemble forecast rainfall

Model files and source	G2G surface run-off grids for observed and ensemble forecast rainfall G2G surface run-off grids were provided by the Centre for Ecology and Hydrology (CEH). **Newcastle** Ensemble outputs for one forecast origin (07:15GMT 28 June 2012) and period of simulation-only using rain gauge data to define observed rainfall **Canvey Island** A G2G surface run-off forecast was produced for each of the 24-member Blended Ensemble rainfall forecasts, out to t + 32 hours. The G2G surface run-off forecasts were generated at a model time-step of 15 minutes. For the Canvey Island 2014 case study, 10 forecast origins were provided. However, the analysis here focused on the closest forecast to the onset of flooding; the emphasis of the case study is on assessing how G2G can be used to derive local flood maps rather than analysis at different lead times. CanveyIsland2014_Forecast_201407200420: 20 July 07:00 - 21 July 15:00
Required inputs	**Newcastle** G2G driven by the Short Term Ensemble Prediction System (STEPS-2) with UK4 rainfall forecasts (12 ensemble members) **Canvey Island** Gridded rain gauge data are used as the input to simulation runs. They are also used to initialise the G2G model up to the forecast origin. G2G forecasts were provided, based on STEPS-2, with Met Office Global and Regional Ensemble Prediction System (MOGREPS) UK Blended Ensembles (provided by the Met Office).
File formats	Standard ESRI ASCII file format (.asc) Naming convention (used by CEH): surfacerunoff*yyyymmddmmmm_ffff*.asc where *yyyymmddmmmm* is the time and date of the forecast

	origin (note *mmmm* is minutes past midnight) and *ffff* is the forecast lead time in minutes from 00:15 to 19:20 (t + 32 hours) It should be noted that the MOGREPS-UK based STEPS-2 Blended Ensemble rainfall forecasts have different forecast origins (01:00, 07:00, 13:00, 19:00) to the UK4 based STEPS-2 Blended Ensembles.
Data overheads	**Newcastle** Ensemble data: 163MB × 12 ensemble members Simulation data: 332MB **Canvey Island** Ensemble data: 2.10GB × 24 ensemble members Simulation data: 725MB

3.2.2 Intermediate processing

Table 3.3 Flow chart: An.2 Run fast 2D hydraulic model JFlow using G2G run-off outputs

Software	
JFlow v7.5 – licence required for commercial use	
Hardware	
Description	Runs were made on PCs with 3.20–3.60GHz CPUs and 8–32GB of RAM. JFlow is GPU-enabled and all models were run using NVIDIA GeForce GTX 690 graphics cards.
Size of model files (excluding outputs)	JFlow models are organised with Microsoft® Access databases and read in grid data (for example, DTM, run-off and roughness zone maps) via ArcSDE. All input files <10MB for Newcastle and Canvey Island case studies
Network logistics	Intermediate run files were stored on the local hard drive of each PC.
Run times	Newcastle: 30.88 hours for 24 hours of simulation data Canvey Island: 10.40 hours for 32.25 hours of simulation data Updated Flood Map for Surface Water: 0.75 hours for 6 hours of simulation data
Size of model domain	Newcastle: 400km^2; 2m grid resolution; 100,000,000 grid cells within a single model domain Canvey Island: 270km^2; 2m resolution; 67,500,000 grid cells within a single model domain Updated Flood Map for Surface Water: 36km^2; 2m resolution; 9,000,000 grid cells within a single model domain

3.2.3 Output data

Table 3.4 Flow chart: Ou.1 JFlow Observed and Ensemble Forecast outputs

Outputs			
Outputs provided	2D grids of maximum depth, velocity, water level and hazard index as .tiff 2D grids of depth, velocity, water level and hazard index as .tiff at hourly intervals		
File sizes	**Total outputs**	**Hourly dataset**	**Simulation maximums**
Newcastle	152GB	7–22GB (each observed or ensemble simulation) 51.8–351MB (each .tiff file)	7.47GB (individual grid files 103–230MB)
Canvey Island	18–31.79GB	7.87–23.6GB (each observed or ensemble simulation) 4.63–223MB (each .tiff file)	~2.169 GB observed + ensemble simulation (for example, individual grid files 101MB)

3.2.4 Post-processing

Table 3.5 Flow chart: An.3 Threshold/post-processing in real time

Software	
ArcGIS version 10.2 for use for mapping analysis and post-processing JFlow model outputs. Requires licence. A bespoke ArcGIS tool was designed by JBA to post-process JFlow outputs as per the agreed updated Flood Map for Surface Water flood map specification.	
Hardware	
Description	Runs were made on a PC with 3.60GHz CPU and 16GB of RAM. Geodatabases (.gdb) were compiled for each case study and forecast origin. Each geodatabase contains the simulation maximum depth and hazard index (.tiff) files.
Size of model files (excluding outputs)	Newcastle: 378MB (observed) + 3.41GB (forecast) Canvey Island: 234MB (observed) + 1.20–3.45GB (forecast; precise size depends on forecast origin)
Network logistics	Intermediate run files were stored on a local hard drive.
Run times	Newcastle: ~3 minutes (observed) + 0.5 hours (forecast) Canvey Island: ~3 minutes (observed) + 1 hour per forecast origin
Size of model domain	Newcastle: 400km^2; 2m grid resolution; 100,000,000 grid cells within a single model domain Canvey Island: 270km^2; 2m resolution; 67,500,000 grid cells within a single model domain

3.2.5 Alternative hydraulic model: inputs and approach

Table 3.6 Flow chart: In.3, An.4 Alternative hydraulic model (Validation I, Case Study: Newcastle)

Software	
HiPIMS is a high performance integrated hydraulic and hydrological modelling software framework for catchment systems engineering. The software framework was used to model the behavior of run-off attenuation features to assess their contribution to flood mitigation. For further information, see Newcastle University's hydrosystems modelling web page (http://spade16.ncl.ac.uk/hydrosystems/projects/hipims/).	
Hardware	
Description	First order Finite Volume 2D hydraulic model forced with rainfall radar data. Constant 12mm per hour loss rate assumed across model domain. The model provides 2 types of visual outputs: • time series of water depths and flow velocities at selected locations • snapshot maps of water depths and velocities at different times during the simulation The model uses a mask to disable the simulation on water bodies. The model is GPU-accelerated and capable of running on multiple GPU cores. NVidia Tessla K40 and NVidia Tessla K80 cards were used to generate the data for this study.
Size of model files (excluding outputs)	Information unavailable
Network logistics	Intermediate run files were stored on the local hard drive.
Run times	Newcastle event: 360 minutes (for 6 hours simulation time)
Size of model domain	Domain as requested Newcastle: 400.04km^2; 2m resolution; 100,010,000 grid cells within a single model domain

3.2.6 Alternative hydraulic model: output data

Table 3.7 Flow chart: Ou.2 Model outputs from alternative hydraulic model

Outputs		
Outputs provided	Only the 2D grids of maximum depth were used, in .img format. However, depth and velocities (in X and Y dimensions) were also supplied. The data provided contained the outputs every 10 minutes from 12:10 to 17:50 on 28 June 2012 (minimum depth 0.00000001m).	
File sizes	**Total outputs**	**Each 10-minute output**
Newcastle	19.5GB	1.01–377MB

3.2.7 Alternative hydraulic model: post-processing

Table 3.8 Flow chart: An.5 Threshold/ post-processing in real-time (Validation I, Case Study: Newcastle)

Software	
ArcGIS version 10.2 for use for mapping analysis and post-processing HiPIMS outputs. Requires licence.	
Hardware	
Description	A flood shoreline was derived from HiPIMS outputs for comparison with the fast 2D hydraulic model (JFlow). Two criteria were used to generate the flood outline: • calculate the simulation maximum depth • set up a minimum depth threshold to consider as flooded (0.1m) The output is the daily maximum depth (from 12:10 to 17:50) on 28 June 2012. Each model output is saved as raster and shapefile. Runs were made on a PC with 3.60GHz CPUs and 16GB of RAM.
Size of model files (excluding outputs)	Newcastle: 11.5GB
Network logistics	Intermediate run files were stored on a local hard drive.
Run times	Post-processing run times were minimal.
Size of model domain	Domain as requested Newcastle: 400.04 km^2; 2m resolution; 100,010,000 grid cells within a single model domain

3.2.8 Alternative hydraulic model: model output comparison

Table 3.9 Flow chart: An.6 Model output comparison

Software	
ArcGIS version 10.2 for use for mapping analysis and post-processing JFlow and HiPIMS outputs. Requires licence. A bespoke ArcGIS tool was designed by JBA to post-process outputs such as calculating contingency tables and maps.	
Hardware	
Description	Runs were made on a PC with 3.60GHz CPUs and 16 GB of RAM. A geodatabase (.gdb) was compiled for each case study as it is requirement of the ArcGIS tool used here. Each geodatabase contains the simulation maximum depth (.tiff) files.
Size of model files (excluding outputs)	25.7MB (.gdb format)
Network logistics	Intermediate run files were stored on a local hard drive.
Run times	Newcastle: <1 minute HiPIMS: not applicable
Size of model domain	Newcastle: 400.04 km^2; 2m resolution; 100,010,000 grid cells within a single model domain

3.2.9 Alternative hydraulic model: model comparison output data

Table 3.10 Flow chart: Ou.3 Model comparison outputs

Outputs	
Outputs provided	Table with total flooded area and percentage for each model Contingency table and map (.tiff) comparing both models Daily maxima have been generated
File sizes	**Total outputs**
Newcastle	8.2MB (each .tiff file)

3.2.10

3.2.11 Validation: input data

Table 3.11 Flow chart: In.4, In.5, In.6 Validation datasets

Inputs	
Files and source	**Observed depths** Nine measurements of observed depths were available for the Newcastle event only. These were based on photographs of flooding at known locations. Depths were recorded after the event by measuring the level of water against structures that were visible in the photographs (for example, bins, phone boxes and other street furniture). The data were provided by Newcastle University (Bertsch 2013). **Photographs** A total of 117 photographs of the event were provided by Newcastle University. These were filtered by known location and time, as follows. Most (81) were attributed with the name of location. Some (36) were of unknown location. Some 66 photographs were georeferenced, of which 31 had a registered time. These 31 georeferenced and time tag photos provided wide spatial coverage of the city, although they missed some potential key areas shown in other georeferenced photographs without a registered time. The times of the photographs ranged from 16:17 until 21:18 on 28 June 2012. **Other information** • HSL/KCL/FFC database: contains points (34 Newcastle, 5 Canvey Island), roads and polygons that register a flood impact. Based on mining media data for impact verification methodology. • Canvey Island: Section 19 Flood Investigation Report (Government Office for Science 2014) • Essex County Council Flood Investigation Report: Canvey Island (Essex County Council 2014) • Social media information, for example, Twitter (#CanveyIsland flooding)
Required inputs	Information collected by each of the institutions
File formats	Photographs: .jpeg, with ArcGIS shapefiles containing georeferenced information. HSL/KCL/FFC databases: shapefile (ArcGIS) and .xlsx (Excel). Section 19 Flood Investigation Reports: .pdf document and as shapefile (ArcGIS)
Data overheads	Photographs: 108MB HSL/KCL/FFC databases: 1.55KB Section 19 reports: 2MB

3.2.12 Validation with social media databases

Table 3.12 Flow chart: An.7 Models output validation with ground observation (Validation II)

Software	
ArcGIS version 10.2 for use for mapping analysis and comparing the validation datasets with JFlow outputs. Requires licence.	
Hardware	
Description	Quantitative and qualitative validations were performed to compare the JFlow model output to the validation datasets.
Size of model files (excluding outputs)	Newcastle: as defined above Canvey Island: as defined above
Network logistics	Not applicable
Run times	Not applicable
Size of model domain	As above

3.2.13 Validation: output data

Table 3.13 Flow chart: Ou.4 Model performance

Outputs	
Outputs provided	Maps and images comparing datasets for daily maxima
File sizes	**Total outputs**
Newcastle	Small in comparison to model inputs and outputs
Canvey Island	Small in comparison to model inputs and outputs

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
Newcastle	Predictions of flood extent made using the 2D hydraulic model generally match well with the diverse observed datasets, with limited bias towards overprediction or underprediction. Two different validation approaches were implemented. 1. The outputs from 2 hydraulic models (JFlow and HiPIMS) were compared. The main limitation of this comparison is that both models are only an approximation of 'reality'. However, corroborating the results shows where consistent patterns of flooding are predicted by the 2 different modelling approaches. Overall, there is limited agreement between the 2 models. Only ~18% of the area was reported as flooded by both models, across the same geographical area. HiPIMS mainly overpredicts the flood extent compared with JFlow. However, the discrepancies are mainly due to differences in the underlying data rather than the method employed by this PoC: The JFlow model used a light detection and ranging (LIDAR) DTM that had been subject to detailed, manual editing (for example, for flow routes beneath road bridges), as applied in the updated Flood Map for Surface Water. The HiPIMS DTM had not been subjected to the same level of detailed editing. The models were driven by slightly different meteorological forcing (observed rain gauges and observed radar rainfall). Rain gauges typically provide accurate measurements of rainfall, but the dataset is not spatially distributed. JFlow results were post-processed in accordance to the updated Flood Map for Surface Water specification. Similar post-processing was not carried out on the HiPIMS results. However, despite the apparent lack of agreement in area flooded, the spatial patterns of flooding are similar, that is, floodwater accumulates in areas low-lying topography. 2. The outputs from the JFlow hydraulic model were compared with observed flooded water depths, photographs, affected roads from news reports and severity at specific locations. Overall, predictions of flood

	extent and depth are good, with limited bias towards overprediction or underprediction. These validation datasets proved to be very useful in identifying the accuracy of the simulations in this case study. It was demonstrated that it is feasible to run all G2G ensemble members through a high resolution inundation model. This allows the uncertainty in the rainfall and hydrological forecasts to be cascaded through to flood hazard footprints and the affected receptors. In addition, the results from the JFlow model, driven by forecast rainfall, show that areas of highest agreement between ensemble members tend to be low-lying areas and topographic depressions where flood water will pond/accumulate. These are the areas that are most susceptible to surface water flooding. However, there are wide areas of poorer agreement (that is, only shown as flooded in 1–4 ensemble members). This is due to the high variability between ensemble members; short duration, high intensity convective storms are difficult to capture far in advance by forecast rainfall products. In general, most of the ensemble members tend to underpredict the flood extent in comparison with the JFlow simulation driven by observed rain gauges.
Canvey Island	Predictions of flood extent made using JFlow in general match well with the diverse observed datasets, with limited bias towards overprediction or underprediction. For this case study, a smaller number of datasets were available for validation. The outputs from the hydraulic model JFlow were compared against photographs, affected roads and news reports. Even though this PoC is technically feasible (as for the Newcastle case study), the simulated flood outline in Canvey Island was underestimated due to low accuracy of the observed rainfall data used to force the hydraulic model. Elsewhere within the study area, the model simulated large flooded areas. However, the validation datasets did not provide full coverage for many of those areas, as the impacts of that flood event were minor compared with those focused on Canvey Island itself. The results from the hydraulic model driven by forecast rainfall show low agreement between the ensemble members (for example, 1–4 ensemble members). This is the case even in low-lying areas and topographic depressions. This is partly due to the potential underprediction by most of the G2G ensemble members across the study area, including over Canvey Island. The results suggest that this event was difficult to correctly forecast; the short duration, high intensity convective nature of the storm would have contributed to the challenges involved in accurately predicting rainfall.

4.1 Case study 1: Newcastle, 28 June 2012

4.1.1 Location

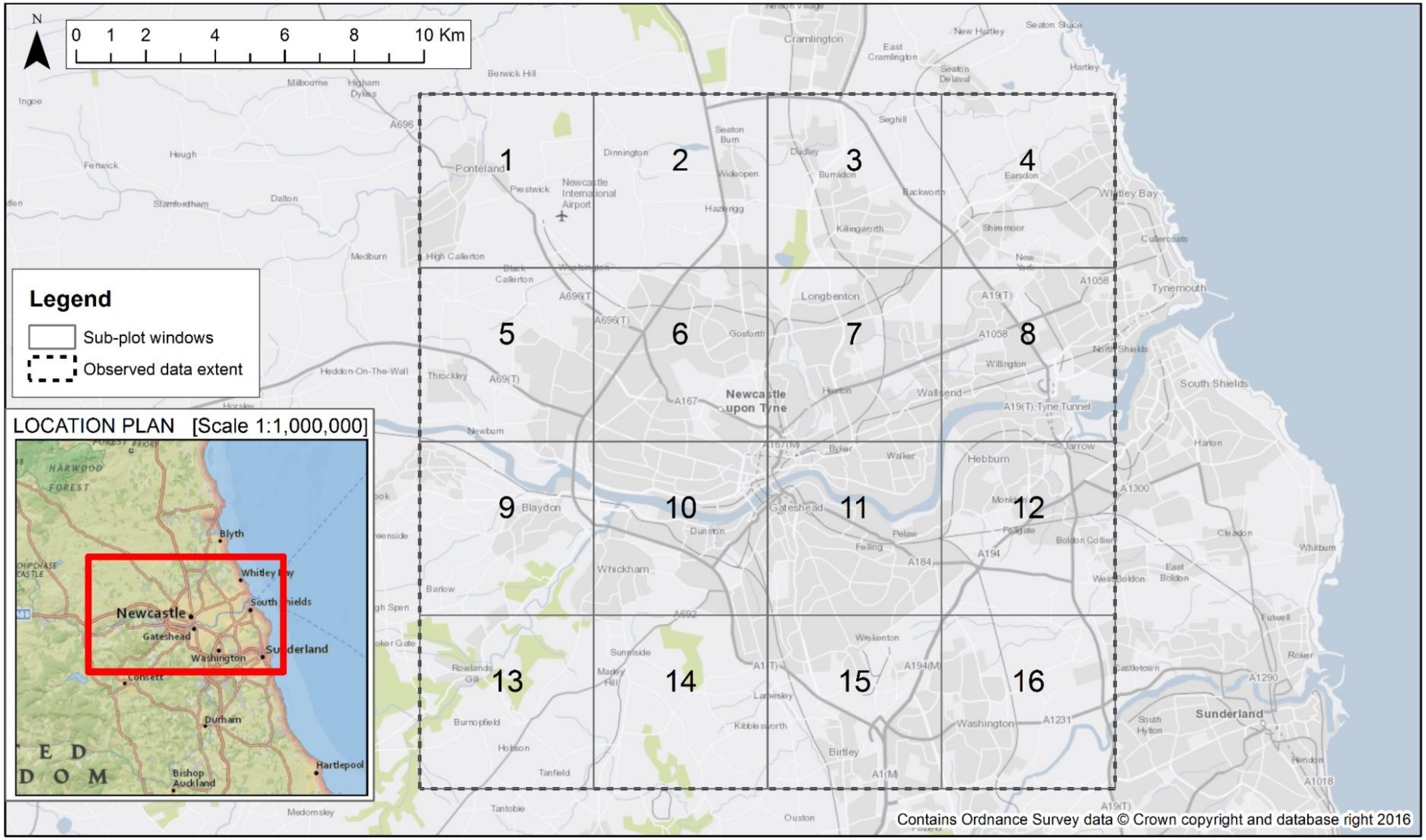


Figure 4.1 Location map for Newcastle case study

4.1.2 Extent flooded (Test A1)

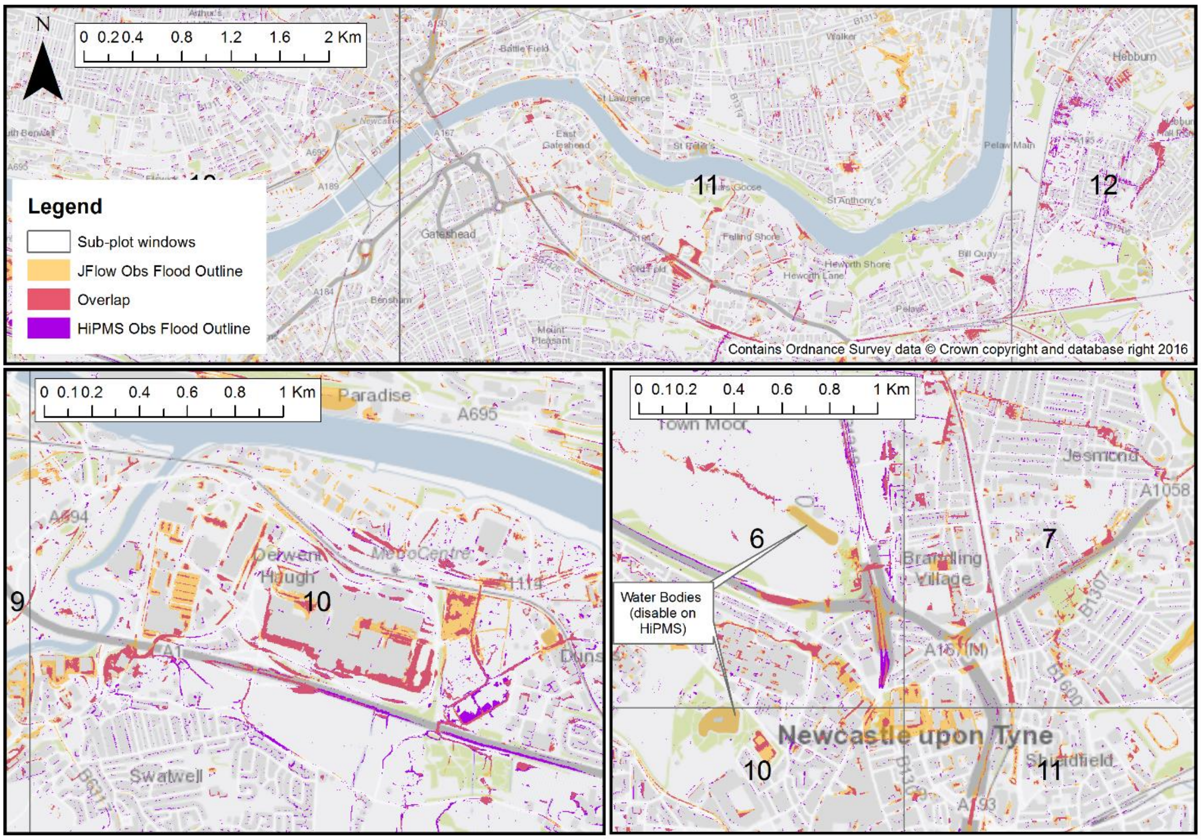


Figure 4.2 Simulation maximum of extent flooded: Newcastle

Table 4.2 Comparison of modelled areas flooded by JFlow and HiPIMS based on observed rainfall: Newcastle

Newcastle	**Area flooded – modelled**			
	JFlow		**HiPIMS**	
	km^2	**% of total area**	**km^2**	**% of total area**
All	7.72	1.93	16.87	4.22

Notes: The model results have been trimmed to the extent of study area.
The total flooded area simulated by each model is summarised.
The percentage of flooded area, within the study area, was calculated as:
P = ([Area] × 100)/Total area

Interpretation

Overall, there are large areas where both the JFlow and HiPIMS model results overlap (quantified in Section 4.1.3). This could indicate areas that are most susceptible to surface water flooding as they are inundated regardless of model configuration. Nonetheless, where the outputs of 2 different modelling approaches are in agreement, it provides higher confidence in the results.

The absolute values of flooded area are substantially different, but this is primarily due to the different post-processing strategies applied to outputs from the 2 models.

Although a similar wet–dry threshold is applied to both models, only small isolated wet areas (<96m^2) have been removed from the JFlow mapping as per the updated Flood Map for Surface Water specification. This accounts for the more ‘speckled’ appearance of the HiPIMS based flood mapping.

Furthermore, there are areas shown as flooded in either JFlow or HiPIMS, but not both (see Figure 4.2). This highlights the marked sensibility of direct rainfall models to the rainfall inputs and run-off assumptions. Other research has shown that direct rainfall modelling is very sensitive to the choice of method for modelling drainage and hydrological losses, and the values and spatial discretisation of parameters used therein. This sensitivity is evidenced in Section 6.2 of the 2012 Updated Flood Map for Surface Water Pilot Improvements Study (Halcrow and JBA Consulting 2012). However, these areas of ‘disagreement’ seem to appear around areas of ‘agreement’ between the models.

4.1.3 Model performance (Test A2)

Model performance scores are derived by comparison of modelled flood outlines. The terminology ‘correct wet’, ‘overprediction’ and ‘underprediction’ were retained for consistency with other PoCs in this project. In this case study, however, the analysis involved corroborating 2 different modelling approaches; it is acknowledge that neither model is without its own uncertainties.

Percentages were calculated as follows.

- Correct wet: proportion of HiPIMS modelled flood extent that is also predicted by JFlow (blue)
- Overprediction: proportion of HiPIMS modelled flood extent that is overpredicted in comparison with JFlow (green)
- Underprediction: proportion of HiPIMS modelled flood extent that is underpredicted in comparison with JFlow (purple)

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

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

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

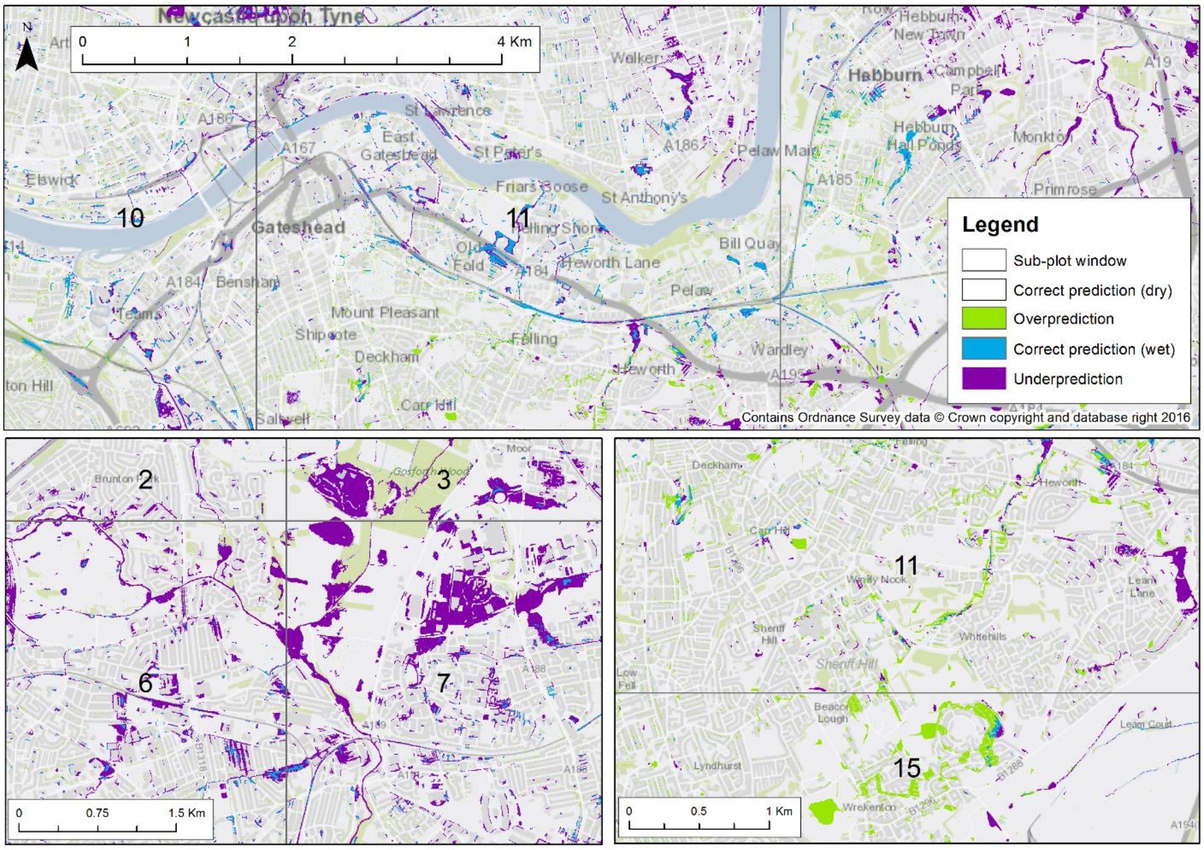


Figure 4.3 Model performance: simulation maximum: Newcastle

Table 4.3 Model performance metrics: Newcastle

Newcastle	Correct wet (%)	Overprediction (%)	Underprediction (%)	Skill	Bias
Modelled outline (all; 100%)	17.64	19.31	63.05	0.176	0.468

Notes: Metrics are reported for the full model domain.

Interpretation

As shown above, there is large disparity between both models, where only 17.64% is simulated ‘correct wet’. There is a large bias towards underprediction (bias score of 0.468), when taking JFlow as the reference model and comparing it to HiPIMS: 63.05% of the area flooded is underpredicted by JFlow and 19.31% is overpredicted.

This is consistent with the analysis in Section 4.1.2, as JFlow generally has a smaller flood area/extent than HiPIMS. As there is no independent observed flood extent available for this event, at this stage it is challenging to reach conclusions on the performance of the models.

However, patterns of flooding can most likely be linked to land use, as these determine the run-off assumptions in each case. In addition, while the topography within the 2 models is likely to be very similar – both are based on LIDAR DTMs – detailed manual DTM editing has been carried out for the JFlow modelling to remove artificial blockages such as ‘flyover’ structures. The approach was based on the updated Flood Map for

Surface Water. In the HiPIMS modelling, structures were removed on the basis of Ordnance Survey MasterMap data only.

4.1.4 Modelled depth comparison with observations

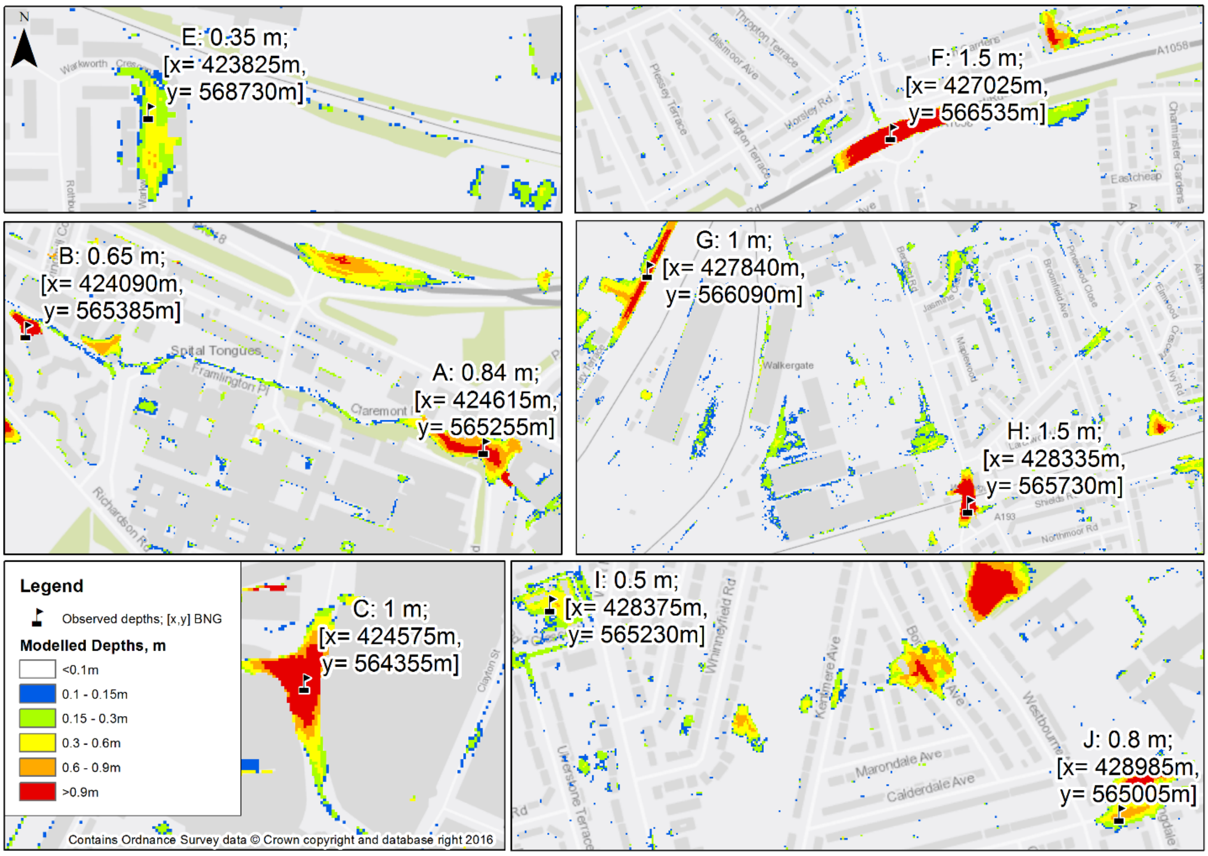


Figure 4.4 JFlow depth comparison with point observations: Newcastle

Notes: Maps provided by Newcastle University

The maps in Figure 4.4 show the depth of the modelled flooding using observed rainfall on a 2m × 2m grid. The measured point depth for the 28 June 2012 flood event is shown at 9 locations. In general, the results show good agreement between the modelled and the observed depths at these locations. All these points are located in areas where water accumulates, but include a range of depths – they are not just focused where the water is very deep (>0.9m). Points E, B and I are particularly encouraging and show that the model is not grossly overpredicting or underpredicting depths at these locations.

4.1.5 Spatial comparison with georeferenced photographs

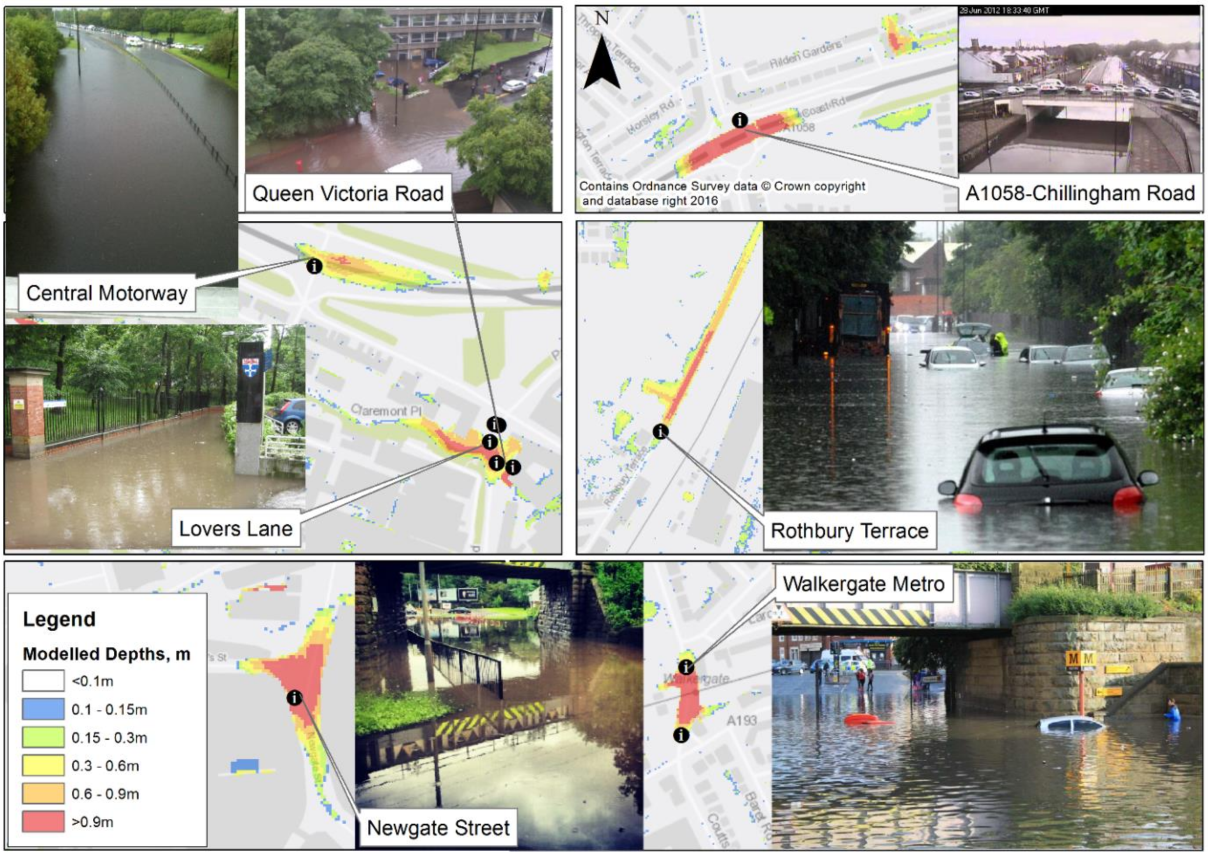


Figure 4.5 Spatial comparison with georeferenced photographs: Newcastle

Notes: Photographs provided by Newcastle University

In total, the dataset provided contained 66 georeferenced photographs. Of them, 31 also had date–time information. These 31 georeferenced and time-tagged data points have a wide spatial distribution, despite missing some areas shown as flooded in other georeferenced photographs without a registered time.

The images in Figure 4.5 show flood depths, modelled using observed rainfall, on a 2m × 2m grid (as in Section 4.1.4). At 7 sample locations, the pictures taken during the 28 June 2012 flood event are shown. Modelled flood extent and depth is generally consistent with the information provided from the photographs at these locations.

4.1.6 Spatial comparison with the HSL/KCL/FFC flood impacts database

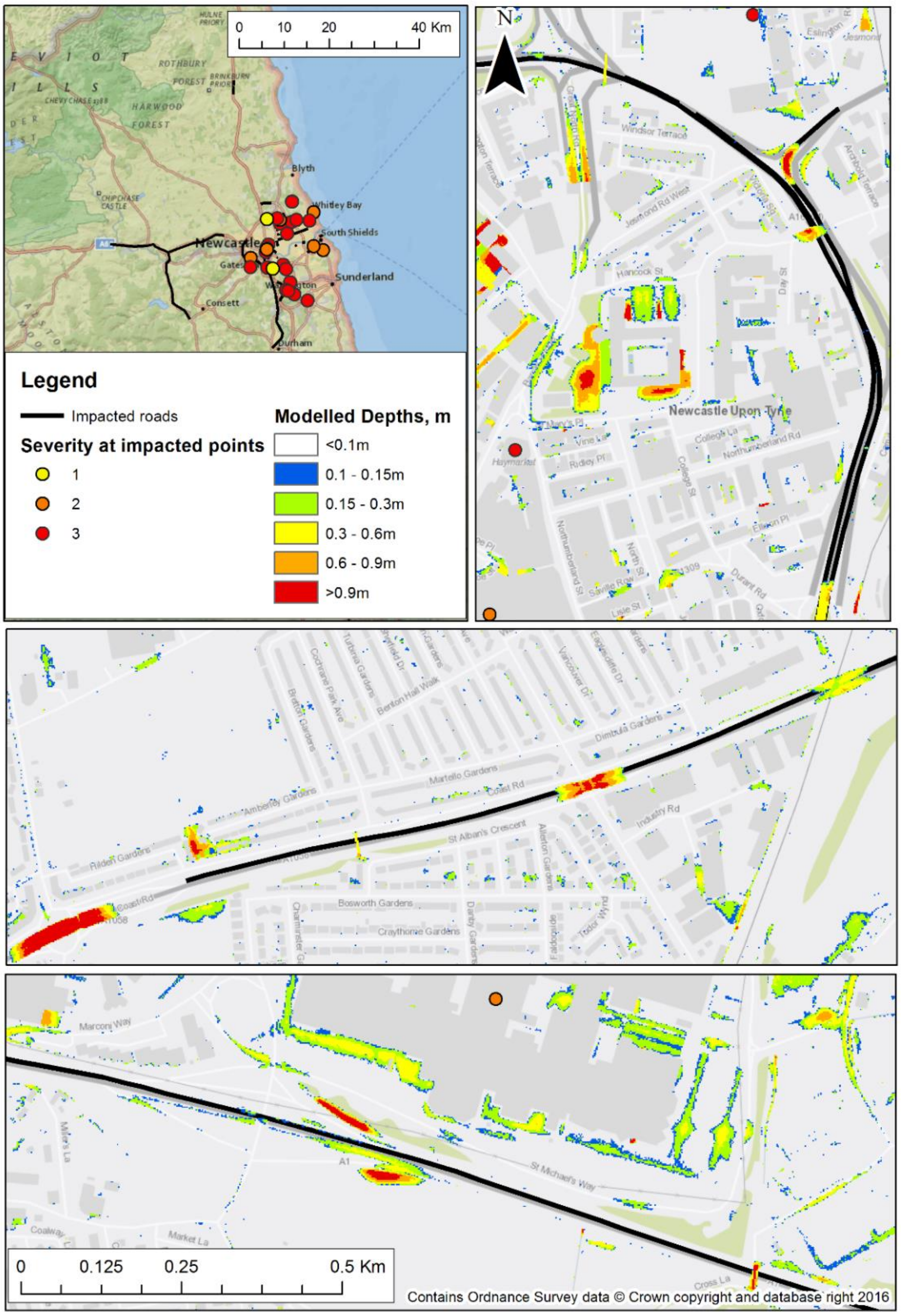


Figure 4.6 Spatial comparison with the HSL/KCL/FFC flood impacts database: Newcastle

This dataset contains 34 affected locations for the Newcastle 28 June 2012 flood event. In addition, some main roads were identified as affected by searching databases of published media reports. In total, there were 171 non-georeferenced reported incidents in north-east England (Minimal 15, Minor 70, Significant 84, Severe 2) due to disruption and damage to traffic and communities. The severity of impacts is based on scoring used by the FFC within the Flood Guidance Statement matrix. Due to the localised nature of the analysis carried out here, it was not possible to evaluate whether all the affected areas recorded in this dataset were affected on the ground during this flood event.

The model simulated flooded areas along the main roads where flooding was reported. However, the model shows that many other smaller roads were also flooded. One limitation of using the media database for validation is that some receptors were not sufficiently noteworthy to be reported by the local or national media. However, some of these smaller scale flood impacts were shown in previous validation analysis (for example, based on photographs in Section 4.1.5) and these were also accurately simulated by the hydraulic model.

4.1.7 Comparison across forecasted ensemble members

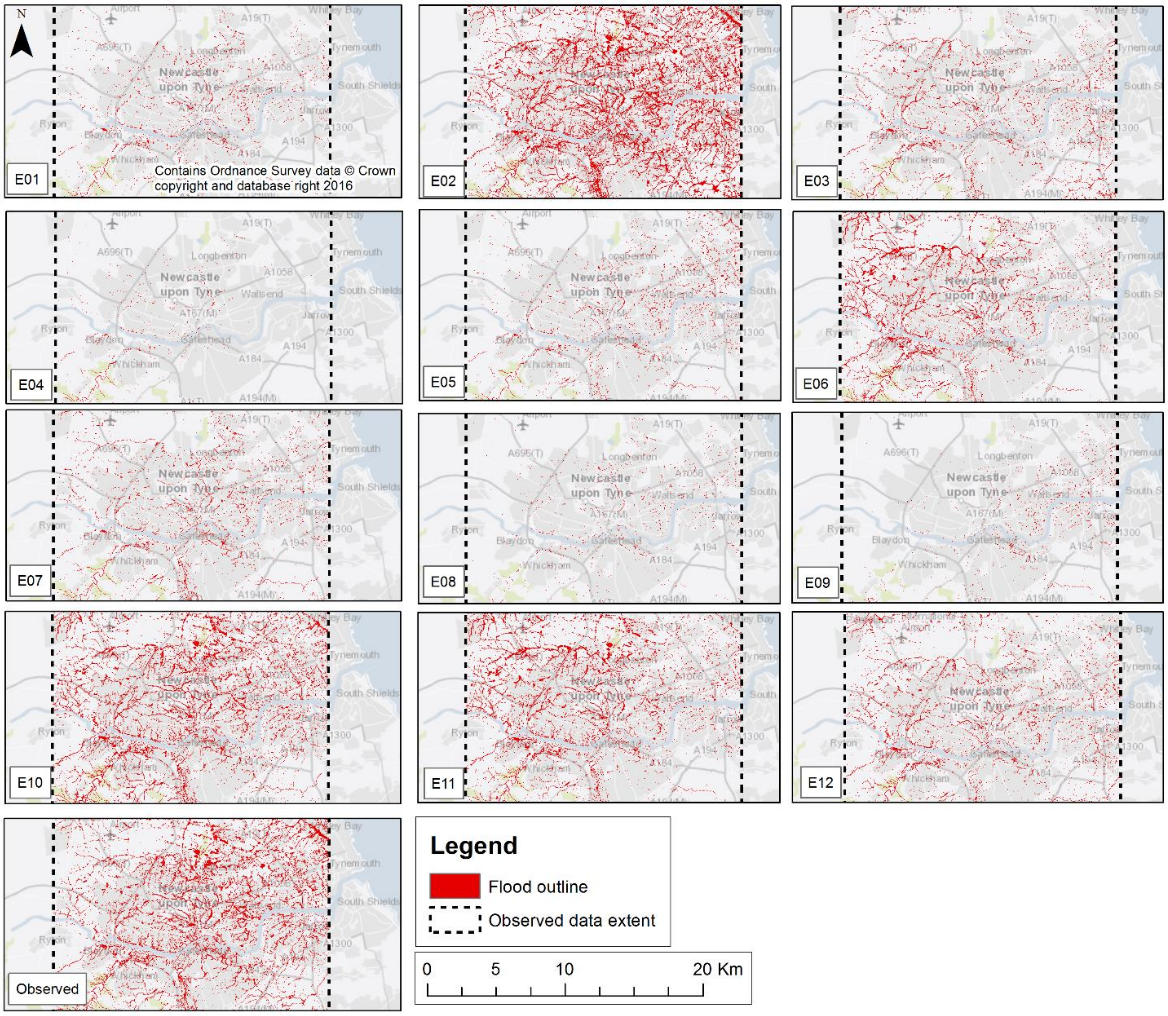


Figure 4.7 Flood outline by forecasted ensemble member: JFlow Hazard maps (Newcastle)

The maps shown in Figure 4.7 are the result of forcing the hydraulic model with probabilistic run-off forecasts from G2G (described in Section 3.2.1). The forecast data for Newcastle consist of 12 ensemble members. The maps in Figure 4.7 show a sample of simulated flood outlines by each ensemble member on the forecast for 28 June 2012. It illustrates the variability provided by the different ensemble members. This is to be expected in short duration, high intensity convective storms such as the Newcastle event. The bottom left map (labelled 'observed') in Figure 4.7 represents the flood outline when JFlow was driven by observed rainfall, based on rain gauge data. Most of the ensemble members underpredicted the flood extent in comparison with the extent based on observed rainfall; only a few ensemble members (for example, E10 in Figure 4.7) come close to capturing the flood extent accurately.

4.1.8 Ensemble-based flood likelihood maps

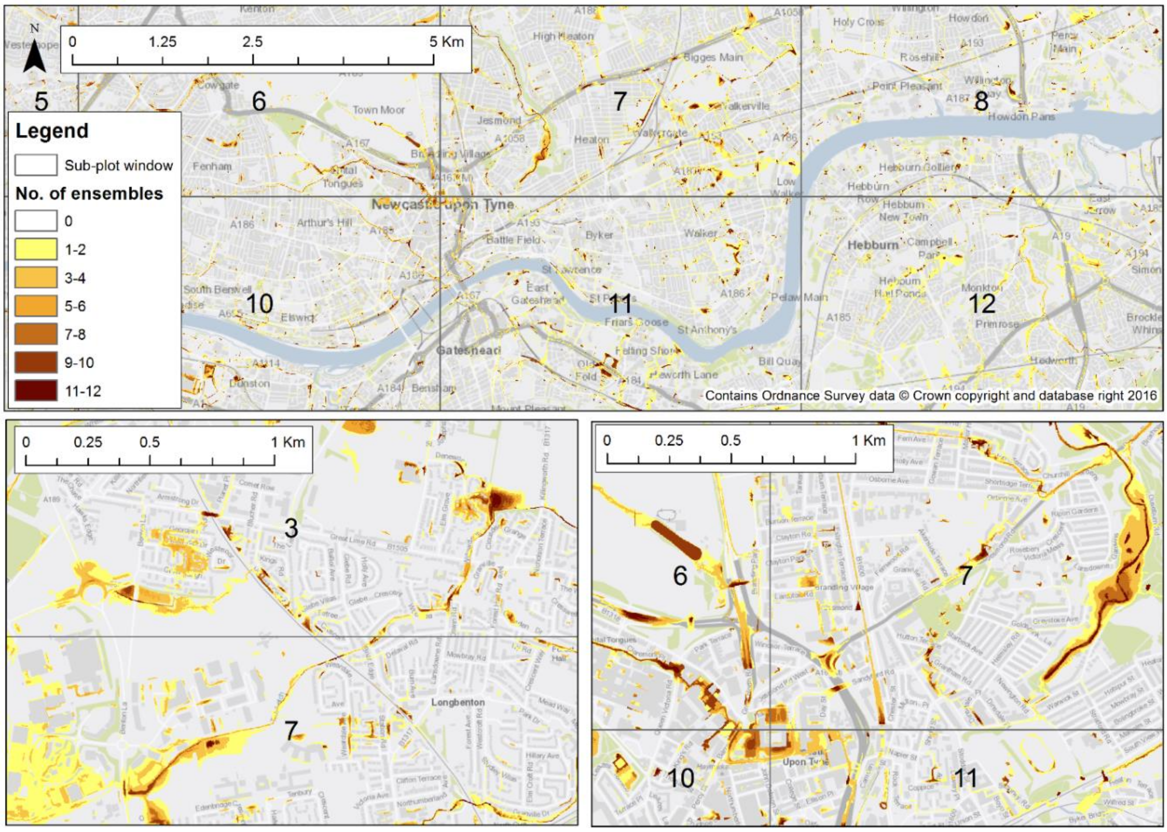


Figure 4.8 Ensemble-based flood likelihood maps: Newcastle event

Figure 4.8 shows flood outlines based on the total number of ensemble members on a 2m × 2m grid. It illustrates the variability in flood outlines provided by the different scenarios. This is a common feature in forecasting rainfall for short duration, high intensity convective storms. For longer duration, lower intensity rainfall events, associated with frontal weather systems, higher agreement across the ensemble members would be expected as it tends to be possible to predict these types of events with higher certainty.

Areas of highest agreement tend to be in low-lying areas and topographic depressions where flood water ponds and accumulates. These are the areas that are most susceptible to surface water flooding. However, large areas of the flood outline have low agreement between ensemble members (that is, shown as flooded in 1–4 ensemble members only). This illustrates the high variability of flood outlines across the ensemble members, as shown in Section 4.1.7.

Finally, in areas of high agreement across the ensemble members, there is a poor agreement with the HiPIMS simulation driven by rainfall radar. This again highlights the sensibility of direct rainfall models to the rainfall inputs and run-off assumption.

4.2 Case study 2: Canvey Island, 20 July 2014

4.2.1 Location

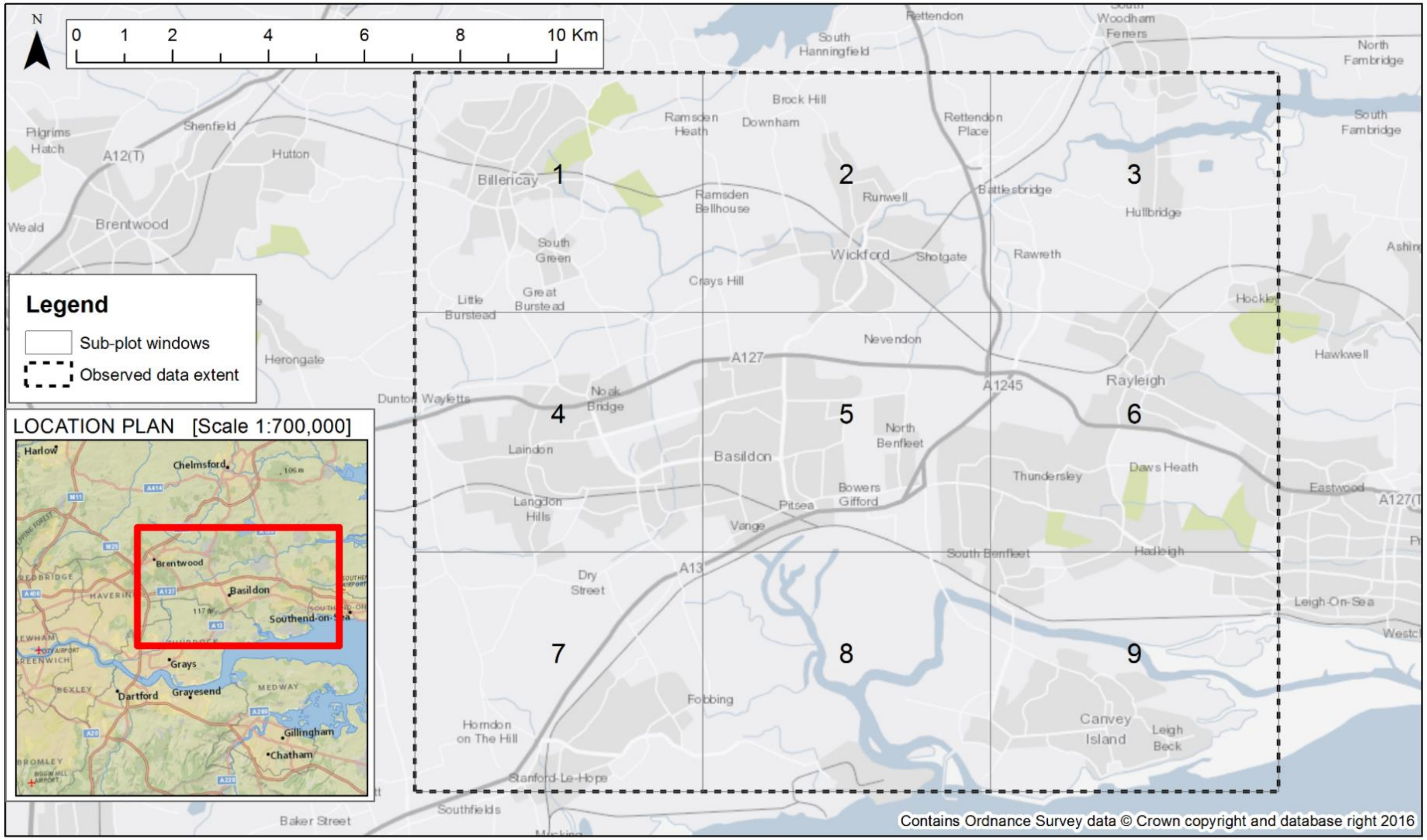


Figure 4.9 Location map for Canvey Island case study

4.2.2 Extent flooded (test A1)

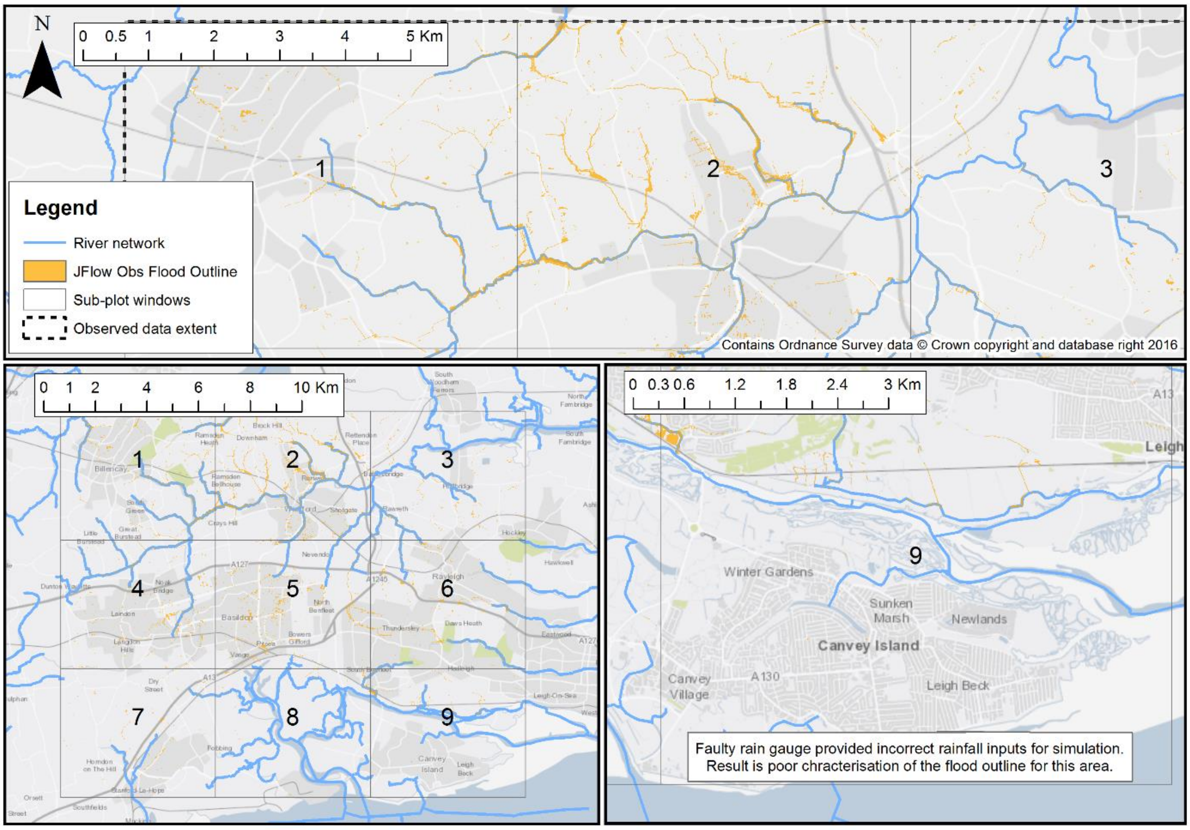


Figure 4.10 Simulation maximum of extent flooded: Canvey Island

Table 4.4 Modelled area flooded by JFlow based on observed rain gauge data: Canvey Island

Canvey Island	Area flooded – modelled (JFlow)	
	km^2	% of total area
All	2.23	0.99

Interpretation

Overall, the model simulated a small flood extent across the study area. However, a fault with a rain gauge that provided rainfall inputs for this simulation means that they (and thus the modelling of flooding) were poor. Accurately specifying rainfall inputs to the system is therefore a requirement for accurate prediction of surface water flood extent. In this example, the flood extent was largery underestimated with very little flooding shown across Canvey Island.

CEH subsequently re-ran the G2G simulations using rainfall radar. However, the run-off outputs were not available to JBA Consulting within the time constraints of this study.

4.2.3 Spatial comparison with HSL/KCL/FFC flood impacts database

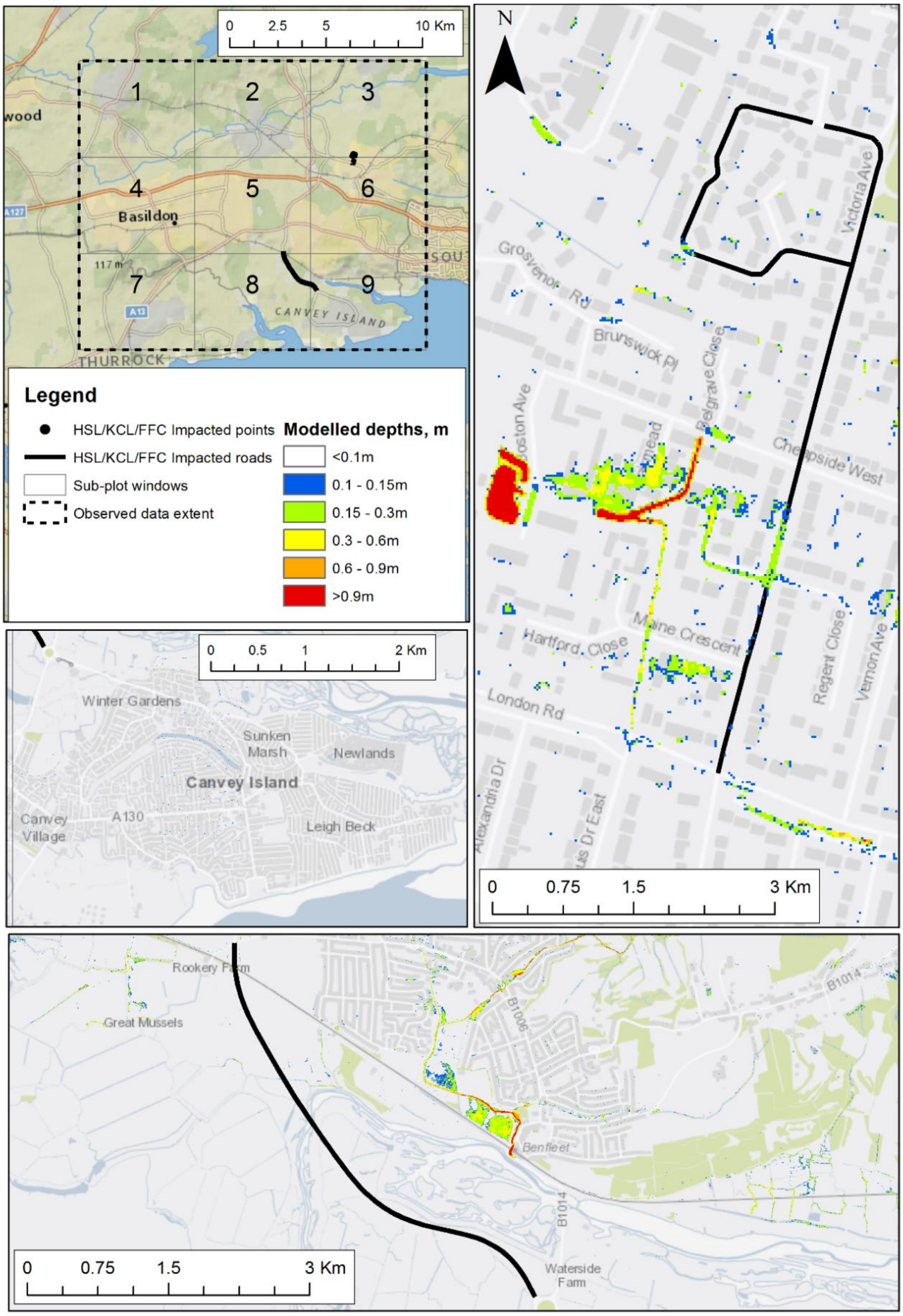


Figure 4.11 Spatial comparison with HSL/KCL/FFC dataset: Canvey Island

The HSL/KCL/FFC dataset contains 5 affected points for the Canvey Island 20 July 2014 event. However, all of them are outside the study area and model domain – as can be seen on the top left map of Figure 4.11.

Some main roads were identified as affected from searching databases of published media reports. Due to the localised analysis carried out here, however, it was not possible to evaluate whether all the affected areas identified in the database were affected during this flood event. Unfortunately, as explained in Section 4.2.2, the modelled output failed to fully capture the extent and intensity of the flood event due to a faulty rain gauge.

4.2.4 Spatial comparison with Essex County Council Section 19 Flood Investigation Report

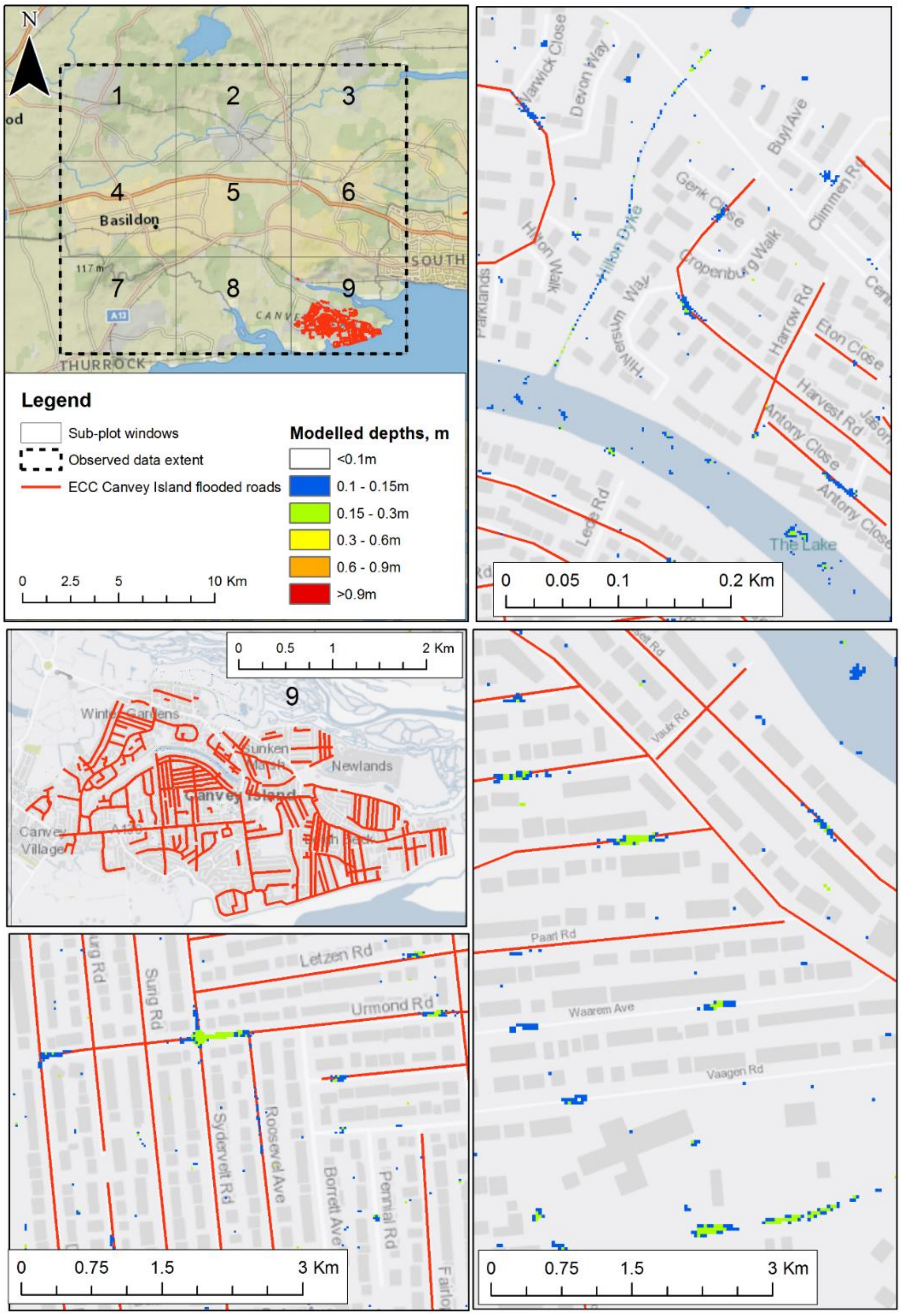


Figure 4.12 Spatial comparison with Essex County Council dataset

Essex County Council compiled a dataset of roads, partially or fully affected by flooding, exclusively for the Canvey Island area. This dataset was based on reports received from professional partners, residents and local councillors who were present during the event or spoke to eyewitnesses. Unfortunately, as explained in Section 4.2.2, the modelled output failed to fully capture the extent and intensity of the flood event due to a faulty rain gauge.

4.2.5 Information from social media

Figure 4.13 Further information from social media: Canvey Island event

Social media data can provided useful, at times georeferenced, real-time information about a given flood event. For example, it can provide information of areas with difficult access during flooding whenever there are members of the public with such an application.

Due to the limited nature of the available rainfall data, it was not possible to fully validate the model output. However, examples of social media reports are shown in Figure 4.13 for context.

4.2.6 Comparison across forecasted ensemble members

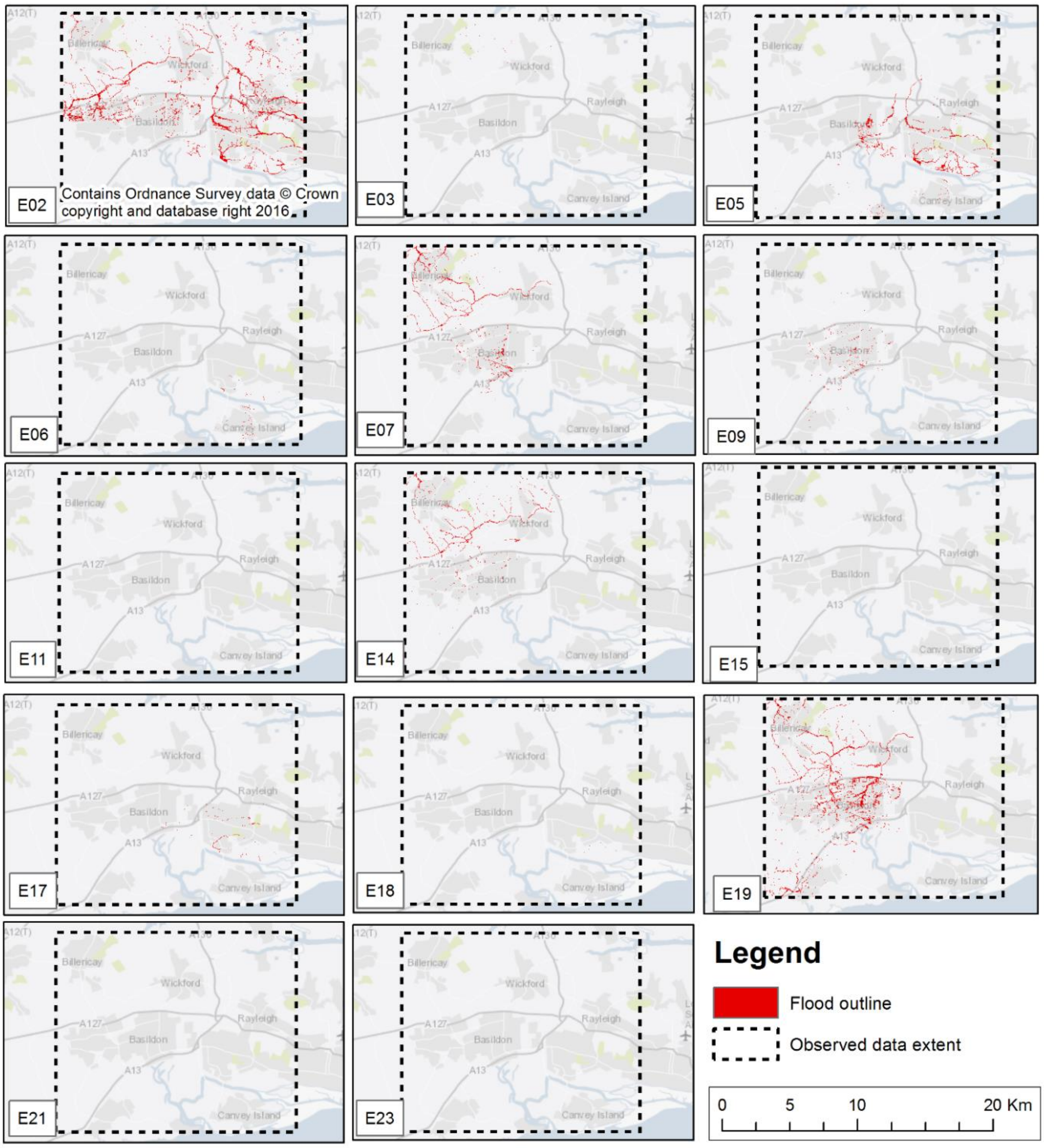


Figure 4.14 Flood outline by forecasted ensemble member: JFlow Hazard maps for Canvey Island event

The maps shown in Figure 4.14 are the result of forcing the hydraulic model JFlow with probabilistic run-off forecasts from G2G (described in Section 3.2.1). The forecast data for Canvey Island consist of 24 ensemble members. Figure 4.14 show a sample of simulated flood outlines by each ensemble member on the 20 July 2014 07:00

forecast. It illustrates the variability provided by the different scenarios. Like the Newcastle 2012 event, this is common in short duration, high intensity convective storms.

Ten out of the 24 ensemble members contained no significant surface water flooding (taken as hazard rating ≥0.575, as in the updated Flood Map for Surface Water specification). Only 5 ensemble members (E02, E05, E07, E14 and E19) simulated larger flood extents. Those ‘extreme’ members, which forecasted a larger flood extent, are potentially the most accurate scenario in this case, even if none of them captured the full flood extent in Canvey Island.

4.2.7 Ensemble-based flood likelihood maps

Figure 4.15 Ensemble-based flood likelihood maps: Canvey Island event

Figure 4.15 shows the agreement between flood outlines predicted by different ensemble members on a 2m × 2m grid. It again illustrates the variability provided by the different scenarios.

Even though there are a larger number of ensemble members in the Canvey Island simulation (24, as opposed to 12 in the Newcastle case study), the agreement is generally low. Most flooded areas have fewer than 4 members agreeing, and in many cases, only 1 or 2 are in agreement. It is suspected that this is due to the complexity of capturing convective rainfall, but also due to the limited flood extent forecasted by most of the ensemble members.

Areas of highest agreement tend to be in low-lying areas and topographic depressions where flood water will pond/accumulate. These are the areas that are most susceptible to surface water flooding.

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 **Error! Reference source not found.** details technical considerations (input ata, 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 **Error! Reference source not found.** discusses the skills, cost and effort that ight be required to implement and maintain the system.

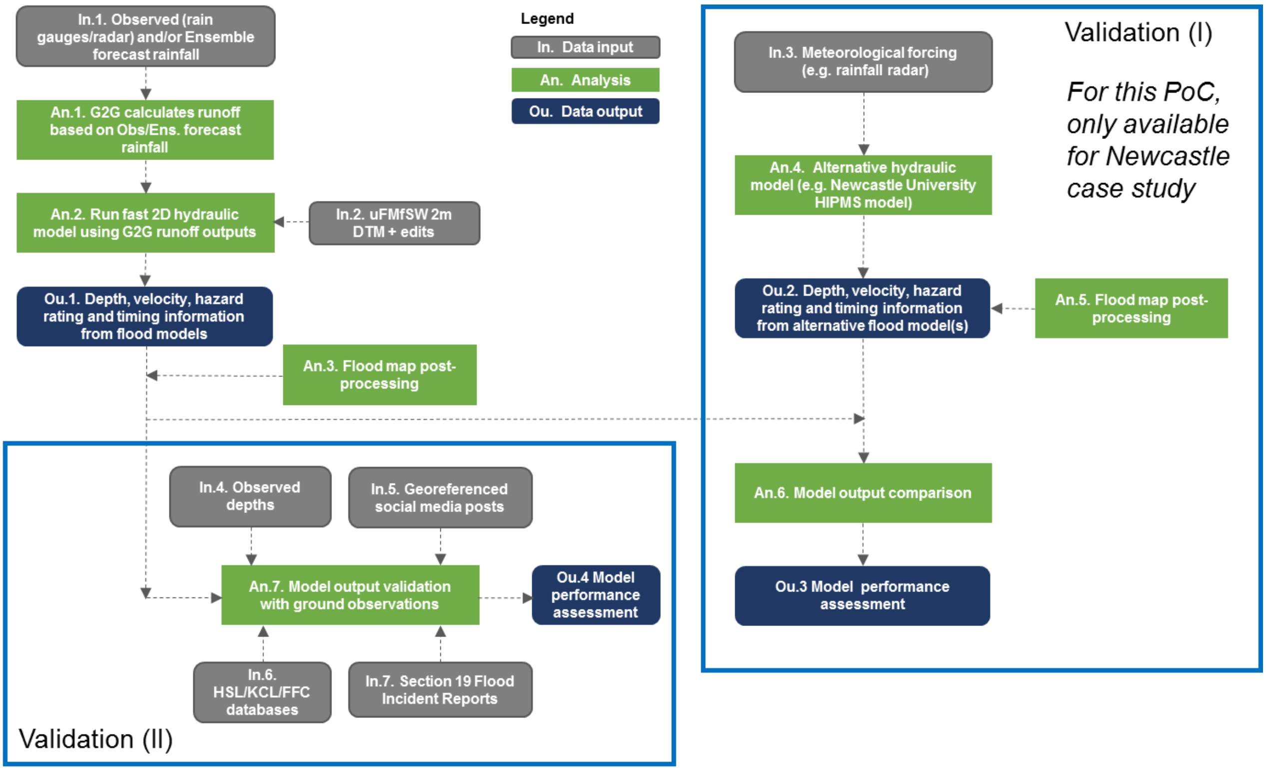


Figure 5.1 Flow chart showing PoC workflow for simplified surface water modelling

5.1 Operating the system

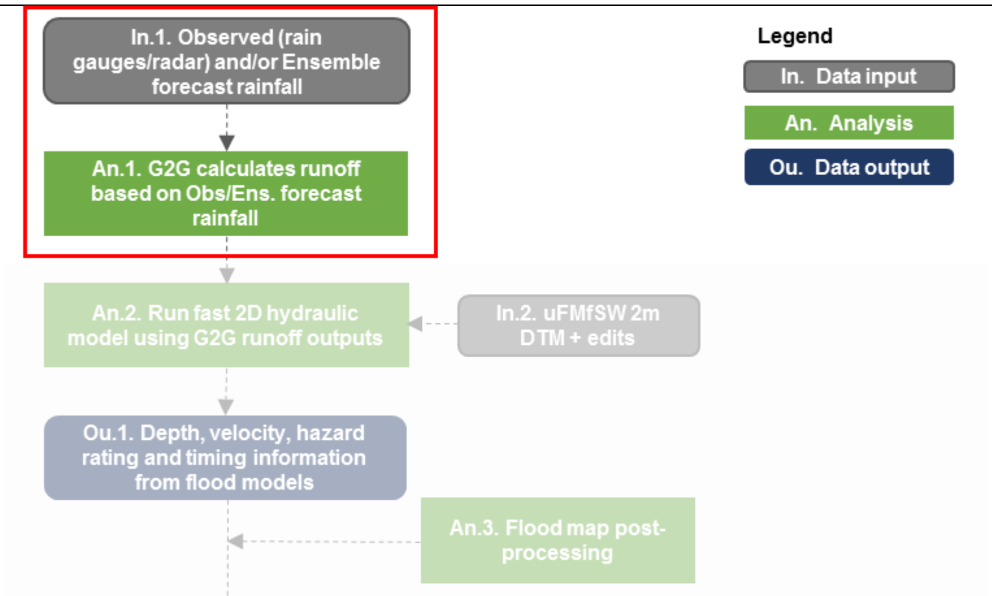
Table 5.1 Key considerations in using this option within an operational forecasting system

Description	Priority
The model run times are acceptable for use in operational forecasting. This may limit use of real-time direct rainfall modelling across large areas within a single model domain. However, multiple smaller models could be launched to cover wide areas where significant rainfall and/or surface run-off is forecast.	High

Description	Priority
Appropriate sources of real-time boundary conditions (G2G run-off estimates and/or rainfall radar grids)	High
Transfer of model results – output files can be large and might require the transfer of large volumes of data across networks, particularly if map outputs are required at regular intervals as well as simulation maximums.	Medium
Post-processing of model runs will require GIS routines to combine outputs from potentially multiple models and extract flood extent polygons. Overheads associated with post-processing the high resolution model outputs can be significant.	Medium
Post-processing of model runs will require GIS routines to intersect modelled flood outlines/depths with receptors (for example, properties).	Medium
Integration within forecasting systems (for example, general adapters or application programming interfaces, APIs) will be required to populate model boundaries and execute the model run(s). Adapters for the Flood Early Warning System (FEWS), the software that underpins the National Flood Forecasting System (NFFS), already exist for some model software packages.	Medium

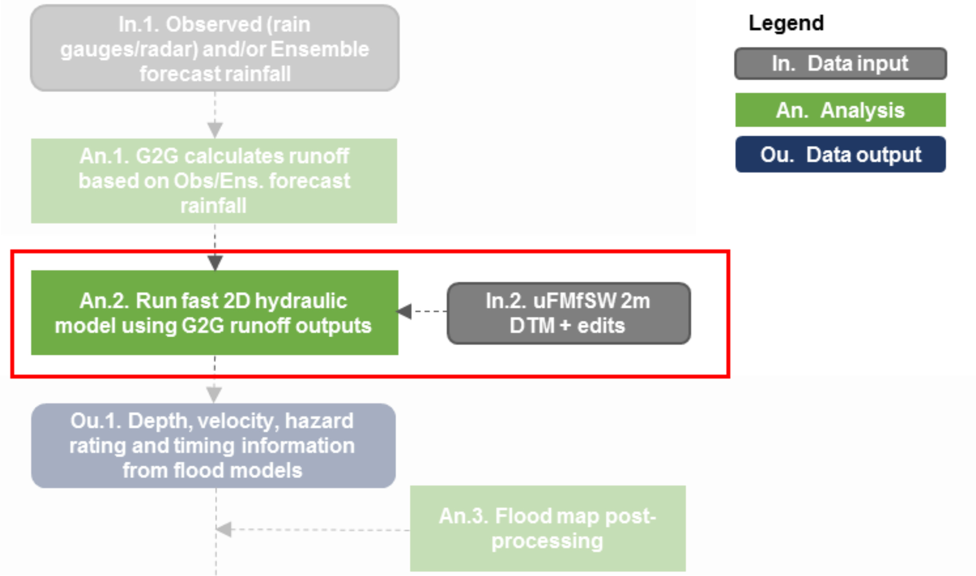
Table 5.2 Detailed considerations

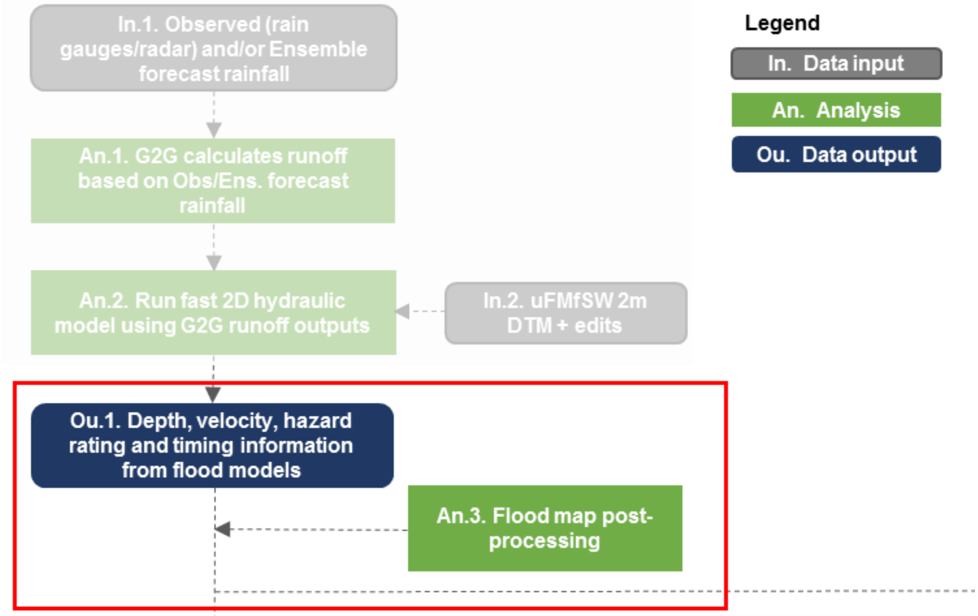
In.1. Input data (Observed and/or Ensemble forecast rainfall), An.1 G2G calculated run-off based on Obs/Ens. Forecast rainfall



Description	Observed (rain gauged/radar) and/or ensemble forecast rainfall products are the main input required for this option.
Data overheads	High – files are provided in standard ESRI ASCII file format (.asc). For example, the Canvey Island model boundary used in this study was around 2.10GB × 24 ensemble members and 725MB of simulation data.
Run times	Run times have the potential to be high, given the large number of ensembles and datasets involved. However, NWP and G2G products are already readily available and used in operational

	forecasting.
Software	G2G model environment
Hardware	Depends on model software

An.2. Run fast 2D hydraulic model simulation using G2G runoffs outputs, In.2. uFMSW 2m DTM + edits	
	
Description	A fast surface water inundation model, in this case JFlow, driven by G2G run-off outputs was used here.
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. For example, the Newcastle simulation took 30.88 hours for 24 hours of simulation data.
Software	A fast 2D model
Hardware	Depends on model software

Ou.1 Flood model outputs, An.3 Post-processing	
	
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.
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: • .tiff files can be read by most GIS packages (ArcGIS, MapInfo, QGIS) • .accdb files (a format used by JFlow)
Hardware	Reliable internet connections to transmit large volumes of model results to other systems.

5.2 Implementation and ongoing maintenance of an operational system

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

Overview
This option can be implemented efficiently by reusing flood models and data developed as part of the updated Flood Map for Surface Water project. However, while this project used the best data available at the time (summer 2012), the accuracy and currency of the data will inevitably diminish over time. Rainfall and/or run-off information, used to provide boundary conditions for the direct rainfall models, are already available as live data feeds. They can be combined within

existing flood modelling software via adapters within the FEWS software that underpins the NFFS. Limited additional skills or training should be required to implement and maintain the system. However, consideration should be given to ongoing licensing costs (of model software) and the practicalities of updating an operational system with new software versions, models and relatively large input datasets (for example, 1–2m resolution DTMs with national coverage).			
Implementation			
Change required	**Low**	Moderate	Significant
	The option could be implemented very efficiently within existing forecasting systems, making using of existing live data feeds, models, data and software tools developed as part of the updated Flood Map for Surface Water project.		
Cost to implement	**Low**	Moderate	Significant
	As above		
Skills required to implement	Limited additional training or skills would be required. This option could make use of the existing models from the updated Flood Map for Surface Water project or use another standard hydraulic modelling package that would be familiar to the Environment Agency (though it is not envisaged that the users would interact with the flood models directly).		
Time/effort to implement	Simplified surface water flood models have already been utilised within existing forecasting systems. An adapter for JFlow already exists and its use for surface water flood modelling has been trialled in research applications.		
Ongoing maintenance			
Difficulty in accommodating change	**Low**	Moderate	Significant
	Changes to static data inputs (for example, DTMs) and model software can be made efficiently ‘behind the scenes’ without disruption to operational users. Direct rainfall modelling is very sensitive to topography and so significant changes in DTM inputs would need to be communicated to operational users.		
Cost to maintain	**Low**	Moderate	Significant
	Many modelling software packages require ongoing licensing. The cost required to update both the models and input data should also be considered.		
Skills required to maintain	Limited additional training or skills would be required to maintain the system once the models are set up. 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	Low – as with existing forecasting models in NFFS, third party support may be required to improve or update models and input datasets.		

6 Scope for further development

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

Description	**Impact**	**Recent examples**
Perform flood modelling based on catchments rather than arbitrary 6km × 6km tiles as used in the updated Flood Map for Surface Water	Overland flow routes and areas of accumulation are not erroneously truncated by external model boundaries	Surface water flood mapping produced by JBA in the UK, Canada and Belgium
Updates to, or higher resolution geometry data – more accurate topography may improve model results	Improved model accuracy, through increasing resolution, may increase model run times	Some LIDAR datasets are periodically re-flown
Functionality to undertake further DTM edits/adjustments as part of the operational system	Correct/improve any artefacts in the DTM that affecting the quality of the hydraulic model outputs	
Improvements to accuracy of rainfall and/or run-off forecasting	Model boundary conditions specified with greater accuracy, resulting in improved model performance Direct rainfall models are very sensitive to rainfall boundary conditions and run-off modelling assumptions	This project made use of G2G run-off outputs, driven by MOGREPS data that was available at the time of the Canvey Island event (July 2014). 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.
Improved methods of visualising and communicating uncertain flood maps based on ensemble forecasts	Users appreciate (and can convey) the considerable uncertainty in flood extents associated with surface water flooding	Work by Universities of Bristol, Lancaster and Reading to visualise ensemble-based flood mapping

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