1. Introduction

As part of the Great Yarmouth Surface Water Management Plan (SWMP) Capita Symonds URS constructed three hydraulic models to simulate surface water flooding using InfoWorks ICM (Integrated Catchment Modelling) software for the urban areas of Great Yarmouth, Gorleston, Bradwell and Southtown. These models represent surface water flooding from direct rainfall and sewer flooding. Three models of the area were needed to optimise overall model run times and data processing.

The baseline models were constructed to inform the Risk Assessment (Phase 2) of the SWMP, including the delineation of Critical Drainage Areas (CDAs), assessment of level of risk facing properties and communities in Great Yarmouth, Bradwell, Gorleston and Southtown, and identification of options. The models were adapted to model the potential impacts of the proposed options for each of the CDAs to inform the Options Assessment (Phase 3).

2. Model Data

Topographic Data

The 2D surface of the model was created in most areas using Light Detecting and Ranging Data (LiDAR). LiDAR is a method of optical remote sensing which uses light reflections to determine vertical heights. LiDAR data is provided in two formats; Digital Surface Model (DSM) that includes vegetation and buildings and a Digital Terrain Model (DTM), which is filtered to remove the majority of buildings and vegetation.

For the purpose of this study, the filtered LiDAR was used to create a DTM to represent the 'bare earth' elevation with buildings, structures and vegetation removed. Buildings have been taken into account during the model build process and the process for undertaking this is described in the Model Build (Section 3).

The LiDAR data supplied by the Environment Agency's Geomatics Group was flown in July 2011 and covers the majority of the model extents. The heights are recorded at a 1m resolution. The vertical accuracy is not specified.

Interferometric Synthetic Aperture Radar (IFSAR) data, obtained from Bluesky, was used to supplement the LiDAR data for an area of approximately 1.2km^2 to the south of Gorleston. As with the LiDAR data the 'bare earth' elevations were used. The heights are recorded at a 5m resolution. The vertical accuracy is not specified.

Model Hydrology

Direct Rainfall

Rainfall profiles were created using the Flood Estimation Handbook (FEH) rain generator in Infoworks ICM based on the catchment descriptors for the study area exported from the FEH CD-ROM version 3. So that an areal reduction factor was not applied the values were adjusted to match those for a 1km grid point rather than using the default catchment values. For all other values, including the urban catchment wetness index (UCWI), the default value was used.

Critical duration is a complex issue when modelling large areas for surface water flood risk. The critical duration can change rapidly even within a small area, due to the topography, land use, size of the upstream catchment and nature of the drainage systems. The ideal approach would be to model a wide range of durations. However, this is not always practical or economic when modelling large areas using 2D models which have long simulation times – such as within this study.

Two methods were used to calculate an estimate of the critical storm duration for the rainfall profiles used in the model. A summary of these methods is given below:

- The Bransby-Williams formula was used to derive the *time of concentration,* defined as the time taken for water to travel from the furthest point in the catchment to the catchment outfall, at which point the entire site is considered to be contributing runoff; and
- The FEH equation for critical storm duration - the standard average annual rainfall (SAAR) value for each a catchment has been extracted from the FEH CD-ROM v3 and the Revitalised Flood Hydrograph method (ReFH) model has been used to derive the time to peak (Tp) from catchment descriptors.

Based on this assessment a critical storm duration of three (3) hours was utilised within the direct rainfall models, with the model simulation initially being run for six (6) hours to capture the impacts of ponding and overland flow after a storm has passed. However, following inclusion of the sewer flows (described below) the model run time was extended to twelve (12) hours.

The rainfall profiles generated and used in the Great Yarmouth SWMP models are presented in Figure 1.

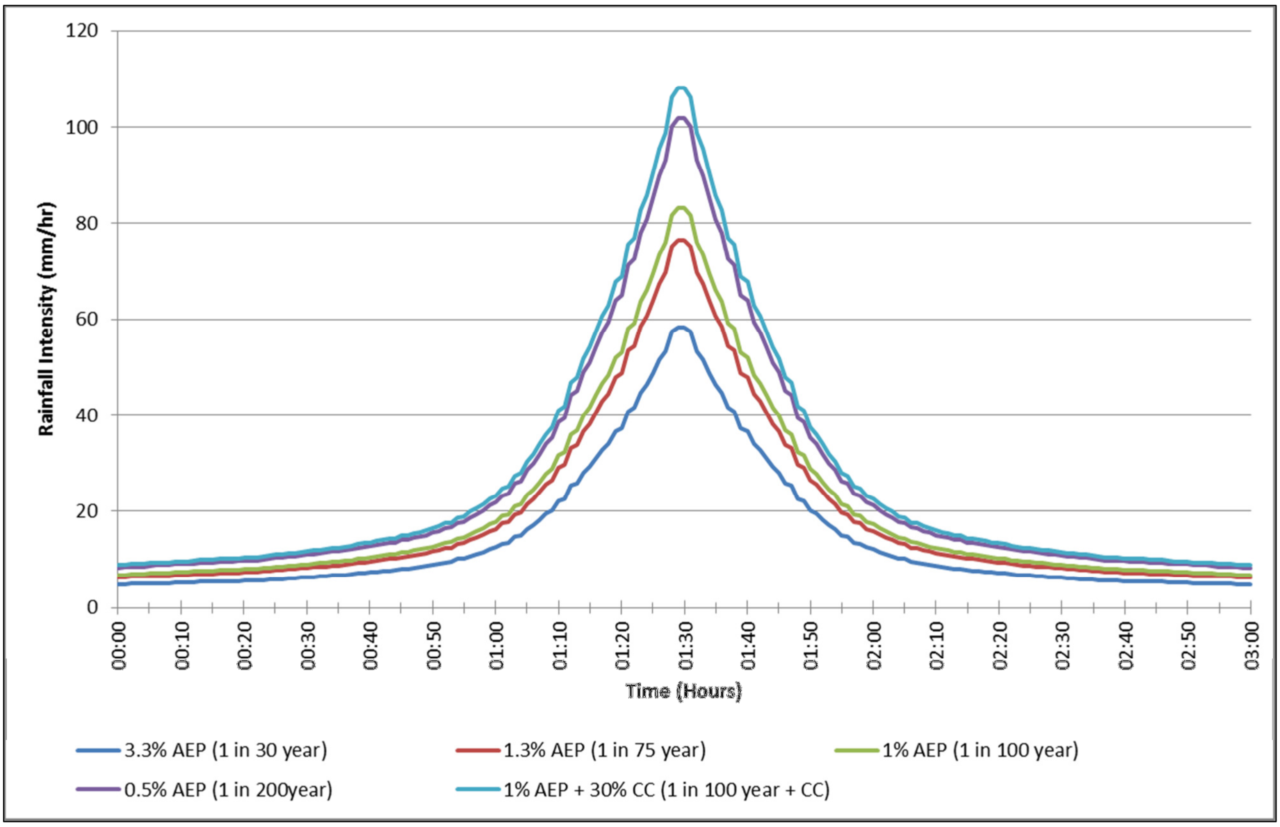


Figure 1 Great Yarmouth SWMP Models Design Rainfall Profiles

Sewer Flows

Given the flat nature of the study area, and interactions of previous flooding events with the sewerage infrastructure, including pipes, manholes and pumps, sewer flows have been incorporated into the three models. Anglian Water Services (AWS) provided data from 5 of their existing hydraulic sewer models for use in the SWMP modelling:

- Gorleston Model
- Martham Model
- Gt Yar Model

- Northgate Existing Model
- Northgate Scheme Model

AWS ran their existing hydraulic sewer models using the 1 in 30 year, 1 in 75 year, 1 in 100 year, 1 in 100 year including climate change (+30%) and 1 in 200 year rainfall profiles generated for the direct rainfall models (Figure 1). Two csv files were exported for each return period from each of the models;

- "_floodvolume" - a time series of data that contains the flood volume at each manhole location at each of the timesteps.
- "_flvol" - a time series of data that contains the cumulative volume lost from each of the manholes at each timestep, i.e., the total volume lost to the sewer system (surcharging) through flooding.

Data Summary

Table 1 provides a summary of the main data sources used in undertaking the Great Yarmouth SWMP modelling. These are discussed in further detail throughout this Appendix.

Table 1 Summary of Data Used in Great Yarmouth SWMP Modelling

Data	Source	Utilisation
LiDAR	Environment Agency (Geomatics Group)	Base topography in model (1m resolution)
SAR	Bluesky	Base topography in an area of BRG2 model (where LiDAR data is missing) (5m resolution)
OS Mastermap	Norfolk County Council	Delineating runoff coefficients, roughness values and land types
AWS Manholes	Anglian Water Services (AWS)	Location of manholes within the model act as 2D point sources of flooding
AWS Subcatchments	AWS	Subcatchment areas for AWS manholes
IDB Culverts	Waveney, Lower Yare & Lothingland IDB	Dimensions of 5 culverts in the BRG1 model network, taken from WLY&L IDB Burgh Castle District Water Level Management Plan 2007.
Design Rainfall Profiles	Generated using Flood Estimation Handbook (FEH) v3.0.	To simulate direct rainfall onto the models and to supply to AWS for us in their sewer models.

3. Model Build

Software Selection

All models have been run using InfoWorks ICM (Integrated Catchment Modelling) v3.0.0.6008 software (http://www.innovyze.com/products/infoworks_icm/). InfoWorks ICM is an industry standard hydraulic modelling package for integrated modelling of both urban and river catchments.

Model Extents

The data outlined in the previous section was used to construct three models:

- 'GRY1' – Great Yarmouth Model
- 'BRG1' – Bradwell and Gorleston Model 1; and,
- 'BRG2' – Bradwell and Gorleston Model 2.

The extents of the three models have been based on catchment boundaries delineated using LiDAR data to limit the amount of cross-boundary interaction between the models. Figure 2 illustrates the extent of the study area and the hydraulic models.

Model Naming Convention

Naming the model networks and run files within InfoWorks ICM consistently, logically and in a predictable way will distinguish similar model files from one another at a glance, and by doing so will facilitate their storage and retrieval, which will enable users to browse file names more effectively and efficiently. Naming files according to agreed conventions will enable users to quickly interpret model filenames.

Networks have been named 'ID_M' and run files have been named 'ID_V_M_RP_D', where:

- ID = Unique network identify found in the properties of the network.
- M = Model name (or abbreviated name).
- V = Network version number found in the properties of the network.
- RP = Return Period.
- D = Storm duration.

Table 2 provides examples from each of the models in the 1% annual probability event (1 in 100 year return period). For BRG 2, LL_SCHEME at the end of the model name has been used to recognise that the model includes the Lords Lane drainage system (see Incorporation of Sewer Flooding – BRG2 for further information).

Table 2 Model Naming Convention

Model Name	Naming Convention (100 year flood event example)
GRY1	ID1v39_GRY1_100yr_180min
BRG1	ID5_BRG1v35_100yr_180min
BRG2	ID4_BRG2v8_100yr_180min_LL_Scheme

Figure 2 Hydraulic Model Extent for Great Yarmouth SWMP

Common Assumptions

All of the models have the following common assumptions:

- Initial Loss – None.
- Infiltration Loss – None.
- No aerial reduction factor applied.
- A 'Summer' rainfall profile was used.
- Mannings 'N' does not vary with depth of water.

Mesh Generation

A 2-dimensional (2D) model was created in InfoWorks ICM using a flexible mesh. InfoWorks ICM allows the creation of a flexible mesh through the generation of triangular elements that cover the 2D model. A flexible mesh enables the triangular elements to be drawn aligned to important surface features such as buildings, bunds or roads which creates a more precise representation of flow paths. The elevation of each of the triangular elements is based on an average of the three points it comprises, shown in the example in Figure 3.

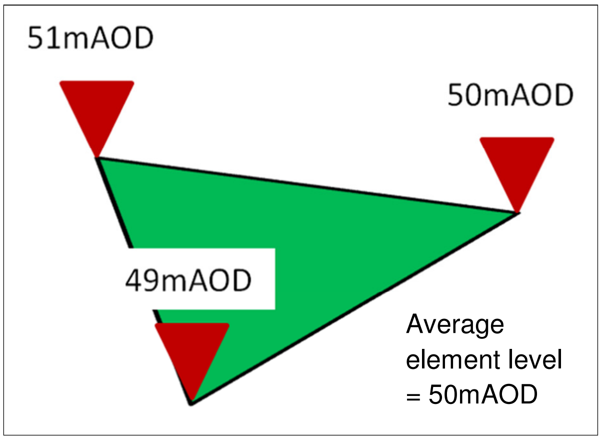


Figure 3 Example of the Elevation of a Triangular Element

The model run time is influenced by the resolution of the 2D mesh. A finer mesh results in a longer model run time. A balance between a mesh resolution that sufficiently represents the site as well as allowing efficient run times was sought.

The element size in the mesh was varied throughout the model domain depending upon the complexity of floodplain and any topographic features identified as important to flood propagation. In Infoworks ICM version 3 'terrain sensitive meshing' automatically increases the mesh resolution where the changes in topography is greater and vice versa. The maximum triangular area was set to 30m² and minimum element area was set to 5m².

Roughness Coefficients

OS Mastermap data has been used to determine Manning's roughness values applied across the models for the roads as these are generally the land features that act as the most significant flow paths. A global Mannings value of 0.05 has been applied across the model and specific features have been assigned the following Manning's values, where lower values represent a smoother surface:

- Road and paths – 0.020
- Buildings – 0.500
- Water – 0.030

- Railways – 0.200
- Grass and gardens – 0.040

Runoff Coefficients

OS Mastermap data was used to determine the runoff coefficients that are applied to the rainfall profiles (Table 3). These simulate an appropriate level of infiltration for each land use type. For example, the runoff coefficients simulate greater runoff from roads (85%) than from grass (35%).

Table 3 Runoff Coefficients and Losses

Feature Code	Descriptive Group	Comment	Runoff coefficient (as %)
10021	Building		90%
10053	General surface	Residential yards	50%
10054	General surface	Step	80%
10056	General surface	Grass, parkland	35%
10062	Building	Glasshouse	95%
10076	Land; Heritage and Antiquities		85%
10089	Water	Inland	100%
10111	Natural Environment (coniferous / non coniferous trees)	Heavy woodland and forest	20%
10119	Roads Tracks and Paths	Manmade	85%
10123	Roads Tracks and Paths	Tarmac or dirt tracks	75%
10167	Rail		35%
10172	Roads Tracks and Paths	Tarmac	85%
10183	Roads Tracks and Paths (roadside)	Pavement	85%
10185	Structures	Roadside structure	90%
10187	Structures	Generally on top of buildings	90%
10203	Water	Foreshore	100%
10210	Water	Tidal	100%
10217	Land (unclassified)	Industrial yards, car parks	85%

Formal and Informal Defences

A GIS layer containing defences from the Environment Agency's National Flood and Coastal Defence Database (NFCDD) dataset was provided. These defences have been represented in the model as a non-porous wall. The crest height of the defences has not been explicitly modelled as the defences are not overtopped in any of the scenarios (see Downstream Boundaries section).

1D structures

The following 1D structures were included in the models to represent the following:

- Underpasses - one culvert was added to the GRY1 model to represent an underpass. The dimensions of the underpass have been estimated from site photographs.

- Culverts – these were added to the BRG1 model to represent culverts on watercourses managed by the Waveney, Lower Yare and Lothingland Internal Drainage Board (IDB). The dimensions of the culverts were extracted from the Burgh Castle District Water Level Management Plan 2007 (Waveney, Lower Yare and Lothingland IDB, 2007).

Modelling parameters used for each of the 1D structures in the GRY1 and BRG1 models are detailed in Table 4. No 1D structures were explicitly modelled within BRG2.

Table 4 Modelled 1D Structures

Model	Structure Name in Model	Structure Type	Representation in Model	Dimensions	Approx. Location	
					X	Y
GRY1	Underpass	Underpass under the A149	Mesh zone	Invert level = 0mAOD Length = 13m Height = 3m	652210	308126
BRG1	MH_IDB_B1 (us node) MH_IDB_B2 (ds node) C_IDB_B (conduit)	Culvert under A12 near Ladbrooke Road	1D conduit	Diameter = 1.4m Length = 46m US invert level = -1mAOD DS invert level = - 1.1mAOD	651467	307340
BRG1	MH_IDB_C1 (us node) MH_IDB_C2 (ds node) C_IDB_C (conduit)	Culvert under A12 near Black Gate Farm	1D conduit	Diameter = 1.2m Length = 64m US invert level = -1.3mAOD DS invert level = -1.4mAOD	651532	306688
BRG1	MH_IDB_D1 (us node) MH_IDB_D2 (ds node) C_IDB_D (conduit)	Culvert under A12 near Gapton Hall retail park	1D conduit	Diameter = 1.2m Length = 52m US invert level = -1.2mAOD DS invert level = -1.3mAOD	651520	306275
BRG1	MH_IDB_E1 (us node) MH_IDB_E2 (ds node) C_IDB_E1 (conduit)	Culvert alongside Thamesfield Way	1D conduit	Diameter = 1.2m Length = 287m US invert level = -0.5mAOD DS invert level = -0.6mAOD	651827	306556
BRG1	MH_IDB_E2 (us node) MH_IDB_E3 (ds node) C_IDB_E2 (conduit)	Culvert under Thamesfield Way	1D conduit	Diameter = 1.2m Length = 41m US invert level = -0.6mAOD DS invert level = -0.7mAOD	651707	306731
BRG1	MH_IDB_E3 (us node) MH_IDB_E4 (ds node) C_IDB_E3 (conduit)	Culvert beside A1243	1D conduit	Diameter = 1.2m Length = 30m US invert level = -0.7mAOD DS invert level = -1 mAOD	651694	306694
BRG1	MH_IDB_E4 (us node) MH_IDB_E5 (ds node) C_IDB_E4 (conduit)	Culvert under A1243	1D conduit	Diameter = 1.2m Length = 54m US invert level = -1mAOD DS invert level = -1.1mAOD	651662	306683

Building Representation

The OS Mastermap has been queried to for buildings with an area >25m². These buildings have been included in the model to have a threshold level that is 0.1m greater than the average adjacent ground level. It is appreciated that in the site walkover threshold levels higher and lower than this were observed, so this level is deemed to be an approximate average.

In order to determine the influence raised building pads will have within the model, the following approach has been used for the representation of buildings in the models.

- A GIS layer containing the locations of all 'buildings' was created based on the buildings polygons in the OS Mastermap dataset.
- The DTM was then interrogated to obtain an average 'bare earth' ground level for each building polygon.
- This average ground level was applied to the building polygons to give them their base elevation in the models.
- The building polygons were then raised 100mm above their average 'bare earth' ground level to create 'stubby' building pads (reflecting an average building threshold level). This ensures that the buildings form an obstruction to flood water and that shallow flows must pass round the buildings (and not flow through them).

It was identified during the site walkover and a subsequent review of the aerial photography and LiDAR data that some properties with the GRY1 model have basements. The topography of these buildings has been lowered in the mesh to represent the basement level in the vicinity of Camperdown, Albert Square and Nelson Road South. The perimeter of the buildings has been delineated using the OS Mastermap dataset.

Incorporation of sewer flooding

GRY1 Model

The manholes from the AWS 'Gt Yar' and 'Northgate with Scheme' models were incorporated into the model as 2D point sources. The flow hydrographs, extracted from the 'flvol' and 'floodvolume' csv files provided by AWS, were associated with the corresponding manhole in the model.

The AWS' 'Northgate with Scheme' Model includes the AWS Northgate Scheme, installed following the flooding in the Northgate Street vicinity in September 2006, and designed to a 1 in 96 year standard. These outputs have been included in the GRY1 to represent the current-day (2013) sewer flooding predictions.

To avoid double counting of rainfall the sewer subcatchment boundaries were used to delineate where rainfall should be applied to the 2D mesh. The original intention was to use the subcatchments provided by AWS to form the subcatchment boundary, however the subcatchments are delineated as circles rather than defining the boundary of the catchment. Therefore, a dummy 'subcatchment' was generated and agreed with AWS for use in the GRY1 model (Figure 4). Table 5 outlines the approach (direct rainfall vs. sewer flooding) used for each of the different areas within the GRY1 model.

Table 5 GRY1 Modelling Summary

GRY1	AWS Model	Direct Rainfall Applied (%)	AWS Sewer Flows?	Assumptions
Area within subcatchment	Gt Yar	0%	Yes	• All rainfall that falls within the subcatchment drains to an AWS sewer and has been applied in the AWS model
Area within subcatchment	Northgate with Scheme	0%	Yes	• All rainfall that falls within the subcatchment drains to an AWS sewer and has been applied in the AWS model • Northgate scheme model includes new AWS infrastructure implemented by AWS since Sept. 2007 flooding

GRY1	AWS Model	Direct Rainfall Applied (%)	AWS Sewer Flows?	Assumptions
Area outside subcatchment	None	100%	No	• Areas are not drained / included within AWS models

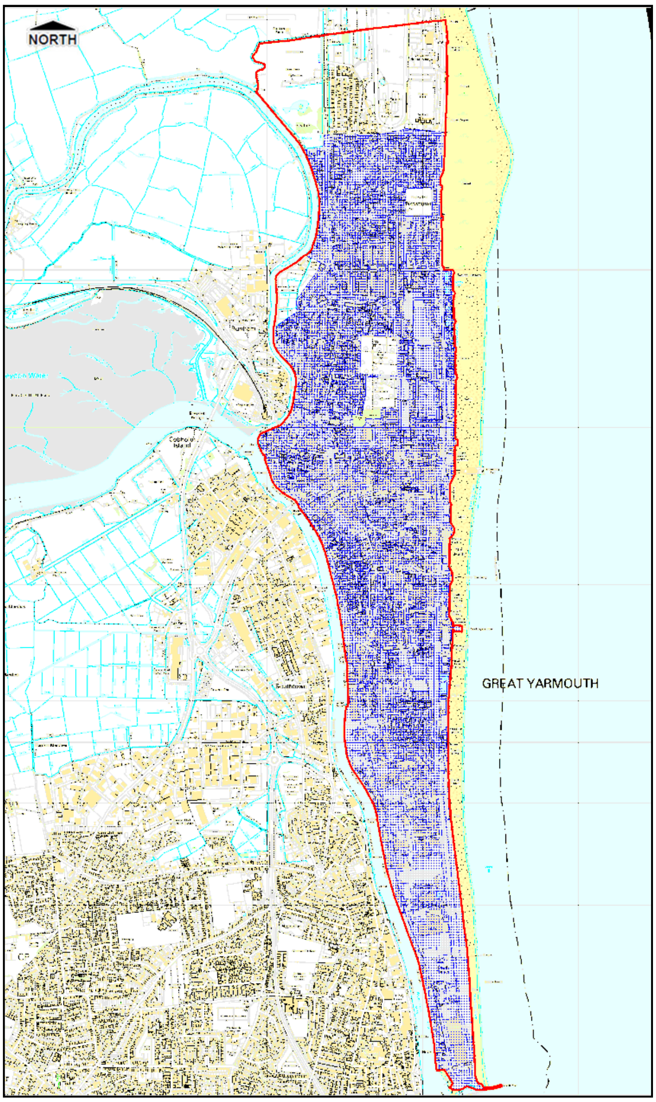


Figure 4 GRY1 Modelled Subcatchment Boundary

BRG1 Model

The manholes from the AWS 'Gorleston' model were incorporated as 2D point sources within InfoWorks ICM and an inflow extracted from the 'flvol' and 'floodvolume' csv files provided was applied. To avoid double counting of rainfall the subcatchments provided by AWS has been used to act as a boundary within which direct rainfall is not applied to the mesh. The subcatchment boundary for the BRG1 model is shown in Figure 5.

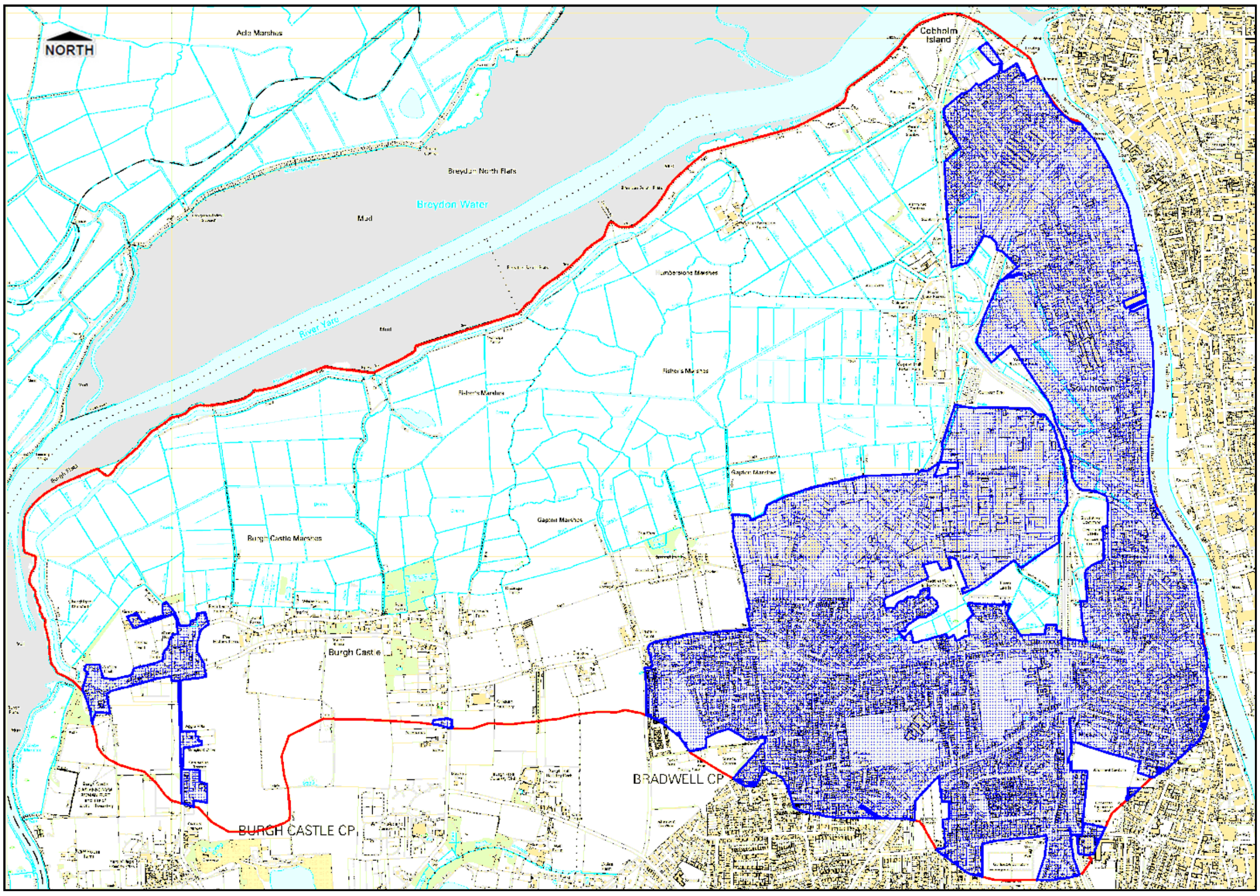


Figure 5 BRG1 Modelled Subcatchment Boundary

To avoid double counting of rainfall the sewer subcatchment boundaries were used to delineate where rainfall should be applied to the 2D mesh. Following model verification of the BRG1, it was determined that predicted flooding depths in the Southtown and Cobholm area were under predicted compared to local and historical knowledge. Further model runs were undertaken, applying a percentage of direct rainfall to the Southtown and Cobholm subcatchment in addition to the AWS sewer outputs, to determine a predicted level of flooding that was considered to be in conformity with local and historical knowledge. The outputs were discussed with the SWMP Steering Group and it was agreed that 30% direct rainfall should be applied to the Southtown and Cobholm subcatchment in addition to the inclusion of the AWS sewer flows. Table 6 outlines the approach (direct rainfall vs. sewer flooding) used for each of the different areas within the BRG1 model.

Table 6 BRG1 Modelling Summary

BRG1	AWS Model	Direct Rainfall Applied (%)	AWS Sewer Flows?	Assumptions
Area within subcatchment	Gorleston	0%	Yes	• All rainfall that falls within the subcatchment drains to an AWS sewer and has been applied in the AWS model
Area outside subcatchment	None	100%	No	• Areas are not drained / included within AWS models
Southtown / Cobholm	Gorleston	30%	Yes	• Direct rainfall percentage defined

BRG1	AWS Model	Direct Rainfall Applied (%)	AWS Sewer Flows?	Assumptions
area within Subcatchment				through verification exercise and sensitivity testing of outputs to meet local and historical knowledge of modelling in the catchment. • Not all rainfall is reaching the sewer network in this area. Site visits observed that there are areas where water is unlikely to reach the gullies and sewer system.

BRG2 Model

The manholes from the AWS 'Gorleston' model were incorporated as 2D point sources within InfoWorks ICM and an inflow extracted from the 'flvol' and 'floodvolume' csv files provided was applied. To avoid double counting of rainfall the subcatchments provided by AWS has been used to act as a boundary within which direct rainfall is not applied to the mesh. The subcatchment boundary for the BRG2 model is shown in Figure 6.

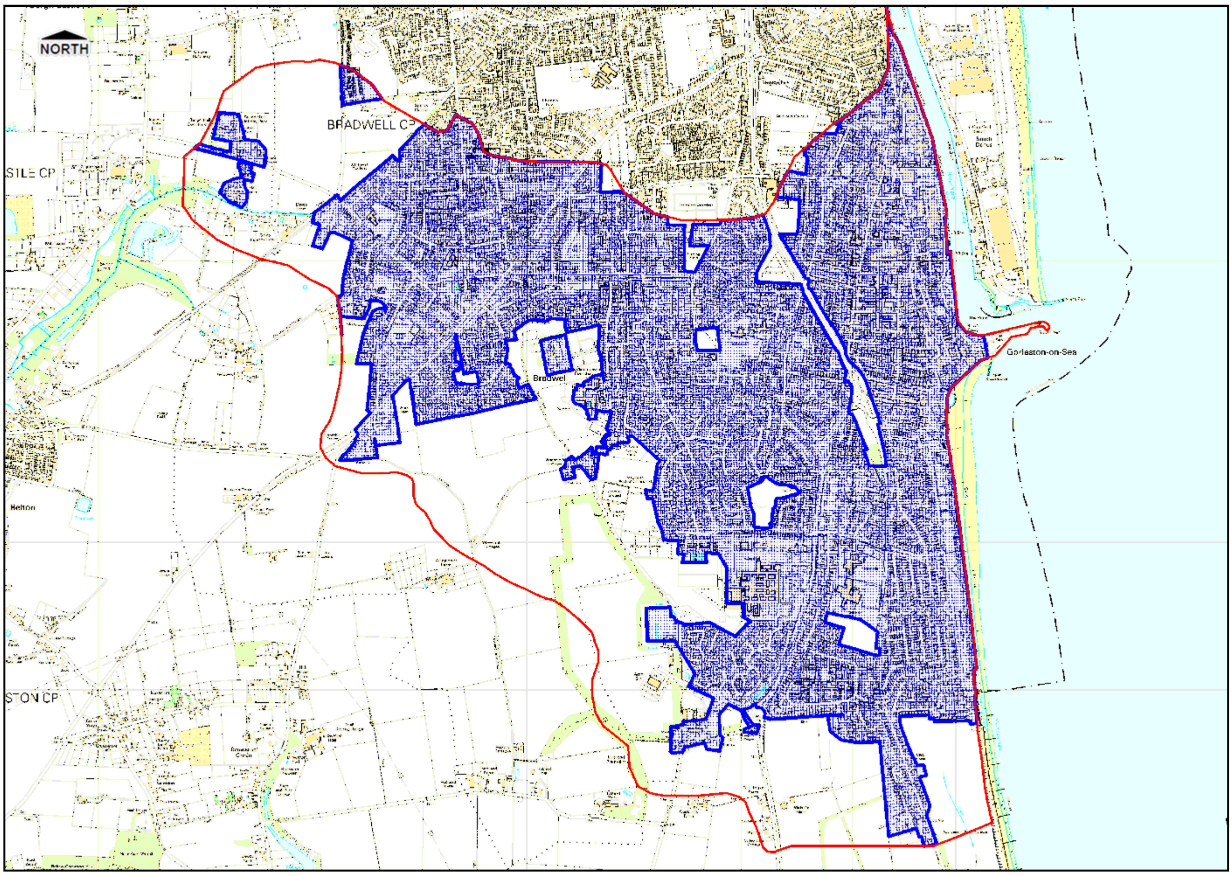


Figure 6 BRG2 Modelled Subcatchment Boundary

To avoid double counting of rainfall the sewer subcatchment boundaries were used to delineate where rainfall should be applied to the 2D mesh.

Historically, flooding has occurred in the Lords Lane area of Bradwell. To address this, Norfolk County Council has constructed a scheme that is designed to convey the 1 in 10 year flood event in the sewer system. This scheme is not included in the current AWS 'Gorleston' model. To try to represent the potential alleviation provided by the scheme within the BRG2 model, AWS agreed to undertake a further run of their 'Gorleston' sewer model for a 1 in 10 year rainfall event with a 3 hour storm duration. The sewer model outputs for the 1 in 10 year rainfall event were subtracted from each of the agreed model rainfall events, and these amended sewer flows included within the BRG2 model as 2D point sources to represent the Lords lane drainage scheme.

Table 7 outlines the approach (direct rainfall vs. sewer flooding) used for each of the different areas within the BRG1 model.

Table 7 BRG2 Modelling Summary

BRG2	AWS Model	Direct Rainfall Applied (%)	AWS Sewer Flows?	Assumptions
Area within subcatchment	Gorleston	0%	Yes	• All rainfall that falls within the subcatchment drains to an AWS sewer and has been applied in the AWS model
Lords Lane catchment within subcatchment	Gorleston	0%	Yes	• Hydrographs reduced by 1 in 10 year return period to represent effect of Lords Lane drainage scheme in catchment
Area outside subcatchment	Gorleston	100%	No	• Areas are not drained / included within AWS models

Downstream boundaries

Within InfoWorks ICM the flow permitted out of the model (i.e. across the perimeter of the mesh) was defined as a 2D boundary. Two types of boundaries were applied to the model:

- Along the coastline and tidal River Yare where there are defences – an initial review of the defences found that they are all greater than 1m above the ground level. It was therefore assumed that no surface water will be able to overtop this and these boundaries were represented as an infinite wall. Following the model runs the depth of water behind the defences was reviewed but no significant depths occurred that would ordinarily overtop the defences.
- All other boundaries - The perimeter of the mesh was set with a 'normal depth' 2D boundary that is defined in InfoWorks ICM as *'it is assumed that slope balances friction forces (normal flow). Depth and velocity are kept constant when water reaches the boundary, so water can flow out without energy losses'*.

Run parameters

The InfoWorks ICM default values were used for the majority of run parameters. The main model run parameters are presented in Table 8.

Table 8 Main Run Parameters

Parameter	Value
Time step	2 seconds
Results Timestep Multiplier	150 seconds
Duration	12 hours
Cell Wet/Dry Depth	0.001m
Maximum Velocity Cut-off Depth	0m/s

4. Model calibration and verification

Calibration

Calibration is the process of adjusting the model parameters to make a model fit with measured conditions, usually flows. This process should be followed by verification using a different data set than that used to calibrate the model, normally with events of different magnitude and duration. No detailed calibration data was available for this study and therefore verification was used to review the model performance and outputs and make any model parameter adjustments, as required.

Verification

A number of data sources have been used to check the validity of the model outputs, including the following:

Ground-truth Model

This stage of verification involved reviewing the hydraulic model outputs against the initial site inspections/assessment to ensure that the predictions were realistic and considered local topography and identified drainage patterns. Where previous site inspection data did not provide sufficient information on a specific area within the study, the model outputs were assessed against photography from third party sources (e.g. Google and Bing maps) to assist in the model verification.

EA National Surface Water Mapping

The Environment Agency has produced two national surface water datasets using a coarse scale national methodology:

- Areas Susceptible to Surface Water Flooding (AStSWF); and
- Flood Map for Surface Water (FMfSW).

As a method of validation, the outputs from these datasets have been compared to the SWMP modelling outputs to ensure similar flood depths and extents have been predicted. There are slight variations, due to the more accurate methodology used in the SWMP risk assessment, but generally the outputs with relation to ponding locations and flow paths are very similar.

Flood History and Local Knowledge

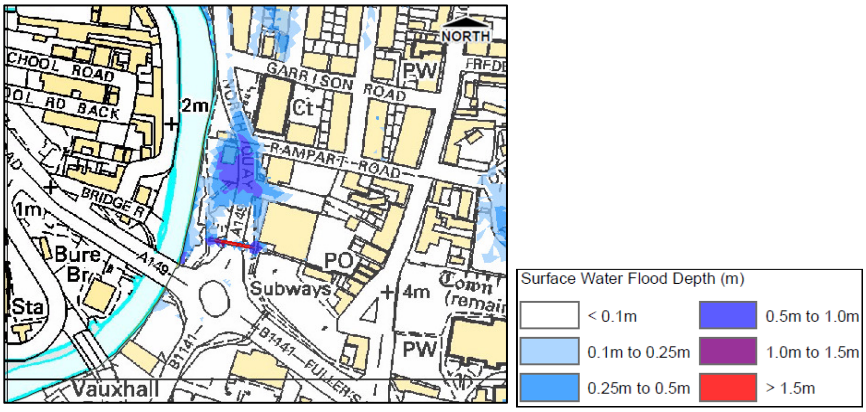
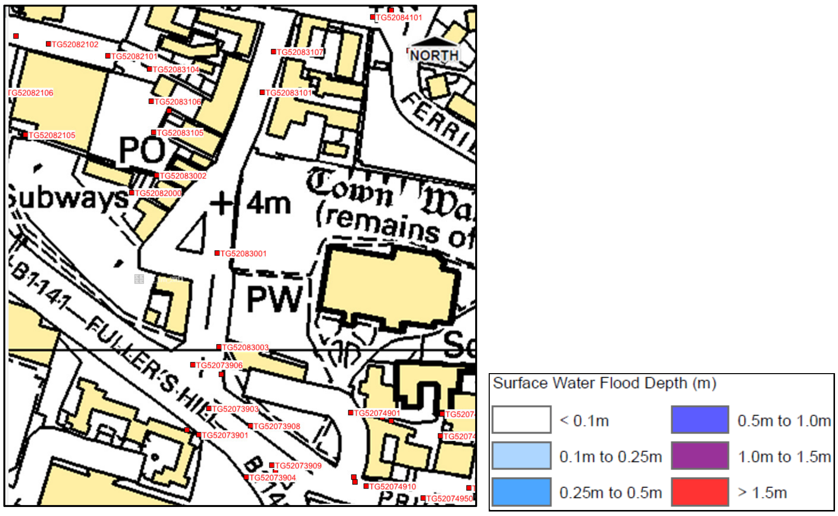
Recorded flood history has also been used to verify areas which are identified as being at risk of flooding with previous known flood events. Information on historical flood events were collected from a number of sources, and in particular, information relating to the September 2006 flooding, a 1 in 96 year rainfall event, has been used to verify the modelling outputs for the 1 in 100 year rainfall event. In addition to this, members of the SWMP Steering Group, have an extensive knowledge of the study area and the drainage and flooding history through living locally.

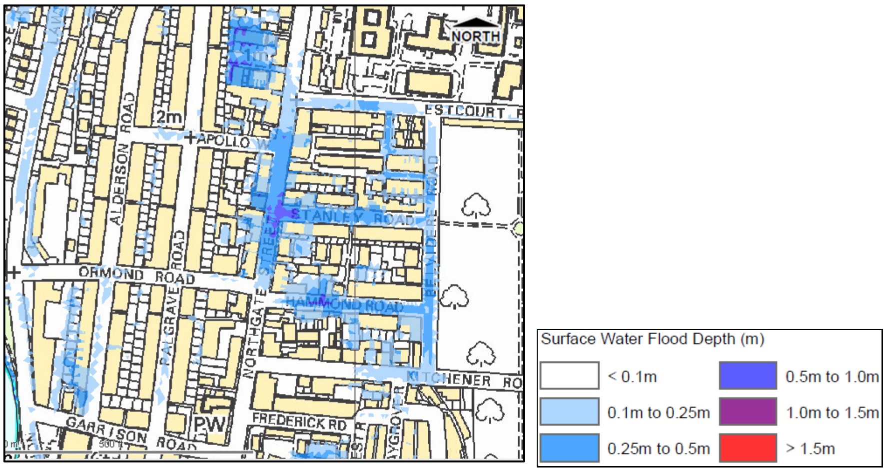
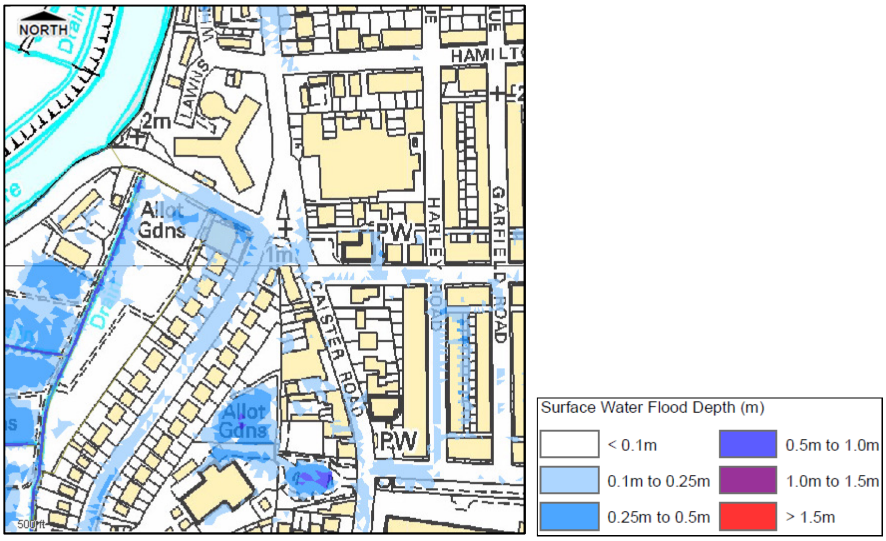
The use of a Steering Group workshop and public 'drop in' sessions were also used to validate the model outputs. The attendees of the events examined the modelling outputs and were able to provide anecdotal information on past flooding which confirmed several of the predicted areas of ponding.

Verification Summary

Within the study area there are a number of local flood resilience forums that, amongst other tasks, collect reports on historical flooding. During the site walkover and in subsequent meetings with the SWMP Steering Group and stakeholders locations of known flooding hotspots have been provided as descriptions and in some cases photographs. All of the historical flooding points are identified in the main SWMP report. Following the initial model runs the results were reviewed against this verification data and a comparison of the key locations presented Table 9.

Table 9 Model Verification at Key Locations

Anecdotal evidence	Modelled results
GRY1	
Underpass under A149	
The underpass under A149 is known to flood.	 The modelled results show that the underpass floods to an approximate maximum depth of 1.8m in the 1% annual probability including the effects of climate change.
South end of Northgate Street	
Flooding is known to occur at the south end of Northgate Street	 This area is entirely covered by the Anglian Water models and therefore any potential flooding in this area will derive from the manholes shown above. An inspection of the AWS data for these manholes shows that limited flooding is modelled to occur from these manholes in the 1% annual probability event.

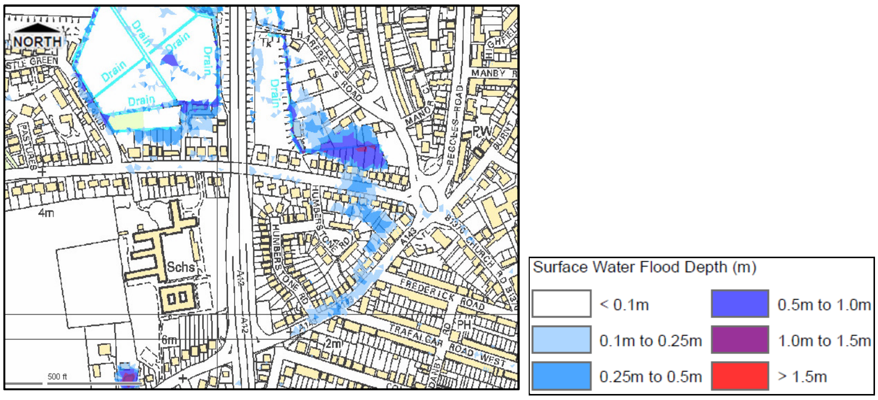
Anecdotal evidence	Modelled results
Northgate Street	
Northgate Street experienced significant floods in 2006 (prior to the Northgate Scheme)	 The model shows the maximum flood depth on Northgate Street in the 1% annual probability including the effects of climate change to be approximately 0.6m.
Junction at the north end of Northgate Street	
It is known that flooding occurs on Lawn Avenue (outside the doctors surgery)	 The model shows the maximum flood depth on Lawn Avenue in the 1% annual probability including the effects of climate change to be approximately 0.3m.

Anecdotal evidence	Modelled results
BRG1	

Burgh Road

Anecdotal evidence: Flooding is known to occur to the north of Burgh Road

Modelled results:

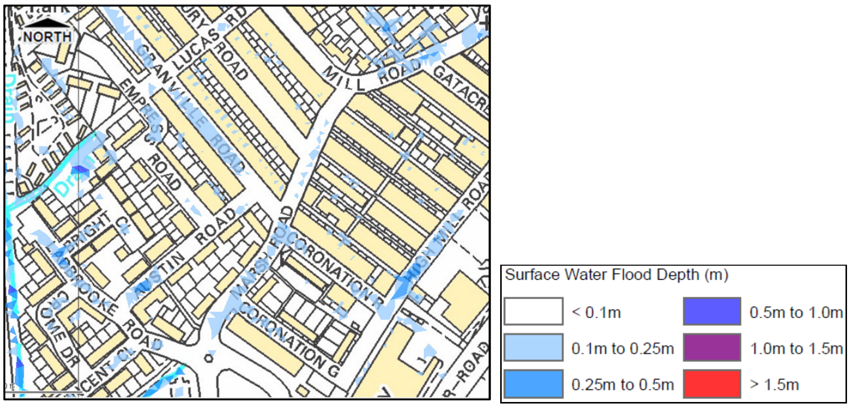


The model shows the maximum flood depth to the north of Burgh Road in the 1% annual probability including the effects of climate change to be approximately 1.1m.

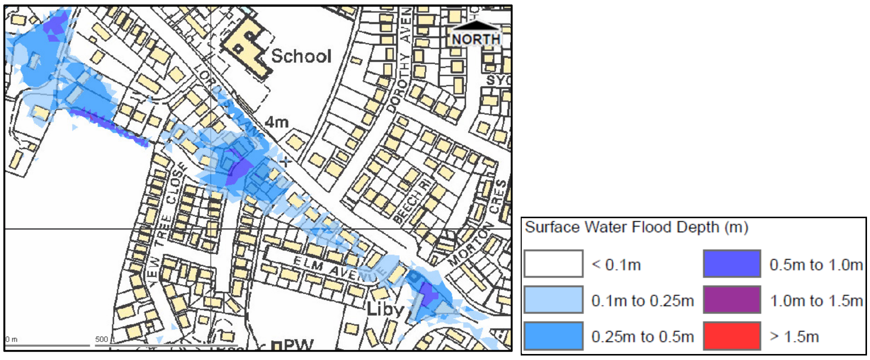
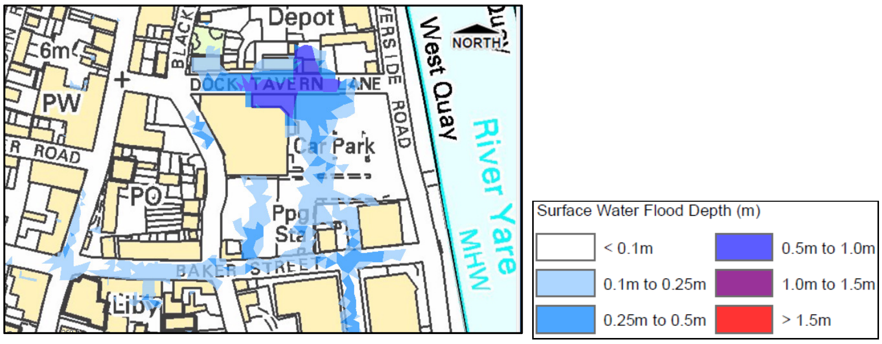
Southtown

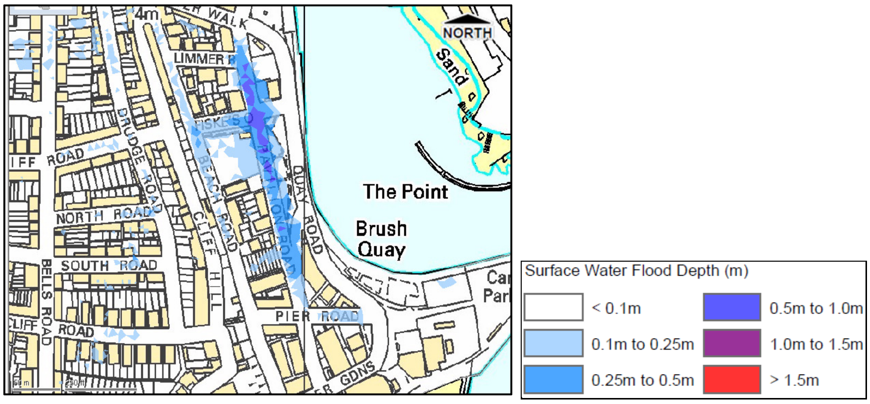
Anecdotal evidence: Streets in Southtown that have been identified as known flooding points are: Coronation Road and Granville Road. These were reported to flood to kerb height (approx. 150mm).

Modelled results:



The model shows the maximum flood depth in the vicinity of Coronation Road and Granville Road in the 1% annual probability including the effects of climate change to be approximately 0.2m.

Anecdotal evidence	Modelled results
BRG2	
Lords Lane	
Lords Lane and Yew Tree Close have been known to flood.	 The model shows the maximum flood depth on Lords Lane in the 1% annual probability including the effects of climate change to be approximately 0.4m. The maximum flood depth for Yew Tree Close, for the same event is approximately 0.6m.
Dock Tavern Lane	
Dock Tavern Lane has been known to flood in the past.	 The model shows the maximum flood depth on Dock Tavern Lane in the 1% annual probability including the effects of climate change to be approximately 0.6m.

Anecdotal evidence	Modelled results
Pavilion Road	
Flooding from Beach Road to Pavilion Road has been known to occur and cause a landslide	 © Crown Copyright. All rights reserved Norfolk County Council. Licence No.100019340 (2013). The model shows the maximum flood depth on Lords Lane in the 1% annual probability including the effects of climate change to be approximately 0.6m.

5. Sensitivity Testing

Sensitivity testing is the process of quantifying the change in model results, typically in terms of changes in water levels and/or flood extents, in response to a variation of a model parameter (e.g. a fixed percentage increase/decrease in roughness coefficients or structure representation).

The results of sensitivity analyses provide an indication as to the reliance of the model outputs on specific assumptions, which have been made by the modelling team, and the potential variation in the results if a different assumption is applied. This section details the sensitivity testing undertaken on the hydraulic model to derive an associated statement of confidence in modelled results.

Model Sensitivity Parameters

Sensitivity testing was undertaken on the BRG1 model for the 1% annual probability event. Testing comprised of adjusting the following parameters:

- Mannings N roughness coefficients increased by 25%;
- Mannings N roughness coefficients decreased by 25%
- Runoff coefficients increased to 100%;
- Runoff coefficients decreased by 25%;
- Time step reduced to 1 second;
- 2 hour storm duration; and,
- 4 hour storm duration.

Model Sensitivity Results

Flood depths have been extracted from 5 flooded locations in the BRG1 model for all of the sensitivity runs (Figure 7). The results from the sensitivity runs are presented in Table 10 and Table 11.

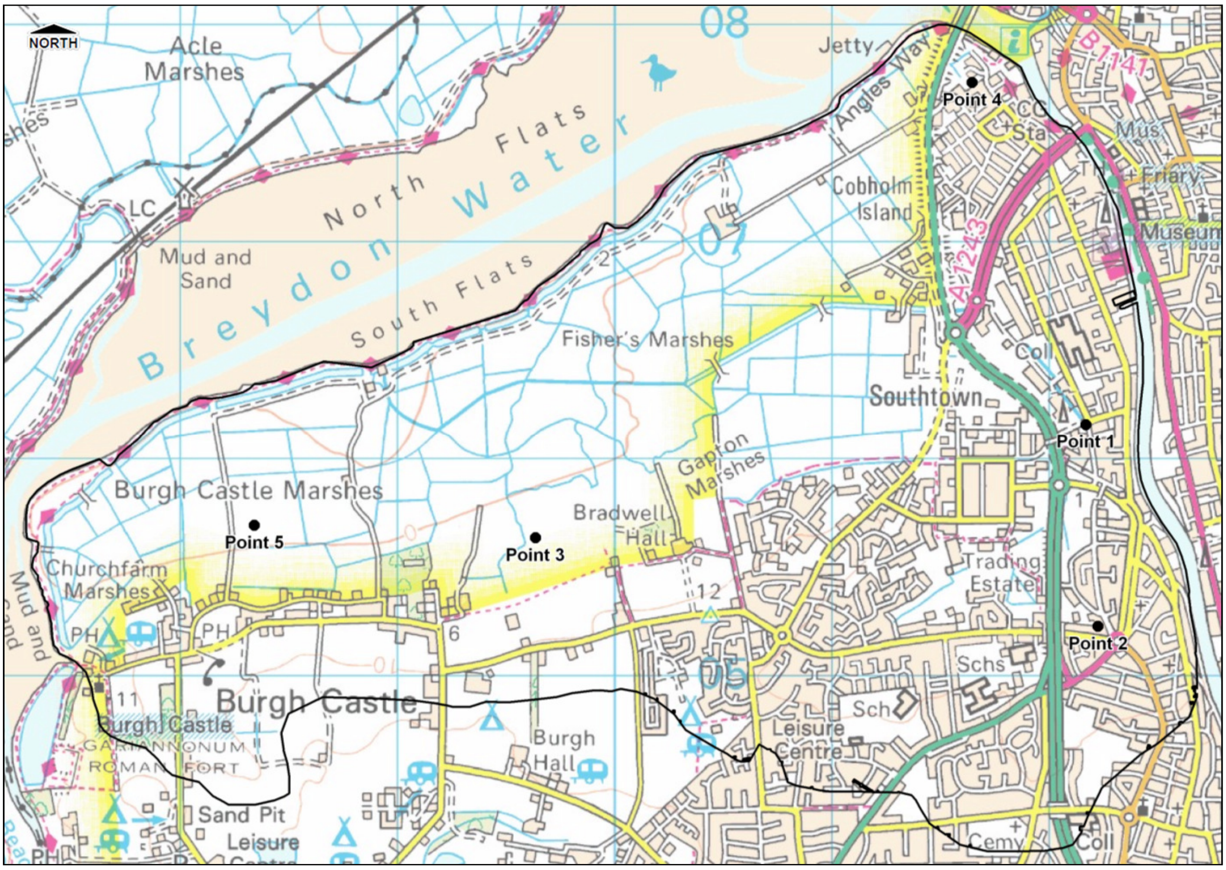


Figure 7 BRG1 Sensitivity Points

Table 10 Sensitivity testing results for BRG1 in the 1% annual probability event (1 in 100 year return period)

Point	Depth (m)								
	Base	100% runoff coefficient	Difference (m)	Minus 25% runoff coefficient	Difference (m)	N increased by 25%	Difference (m)	N decreased by 25%	Difference (m)
1	0.22	0.24	0.02	0.22	0	0.22	0	0.22	0
2	0.62	0.76	0.14	0.56	-0.06	0.62	0	0.62	0
3	0.19	0.33	0.14	0.14	-0.05	0.19	0	0.19	0
4	0.2	0.26	0.06	0.16	-0.04	0.2	0	0.2	0
5	0.14	0.2	0.06	0.12	-0.02	0.14	0	0.14	0

Table 11 Sensitivity testing results for BRG1 in the 1% annual probability event (1 in 100 year return period) continued

Point	Depth (m)						
	Base	1 sec timestep	Difference (m)	2 hour storm duration	Difference (m)	4 hour storm duration	Difference (m)
1	0.22	0.22	0.00	0.23	0.01	0.23	0.01
2	0.62	0.62	0.00	0.63	0.01	0.66	0.04
3	0.19	0.19	0.00	0.21	0.02	0.22	0.03
4	0.2	0.20	0.00	0.21	0.01	0.21	0.01
5	0.14	0.14	0.00	0.15	0.01	0.15	0.01

In summary, the sensitivity testing demonstrates that:

- When the roughness coefficients varied by 25% the differences at the extraction points was negligible (less than 5mm).
- When the timestep is reduced to 1 second the differences at the extraction points was negligible (less than 5mm).
- When the storm duration is reduced to 2 hours or increased to 4 hours the flood depths at the extraction points varied up to 40mm.
- When the runoff coefficient was set to 100%, this led to an overall increase in flood depths at the extraction points to a maximum of 140mm. When the runoff coefficients were reduced by 25% there was a reduction in flood depths at the extraction points of up to 60mm.
- The model uncertainty is approximately +/- 140mm.

6. Options Modelling

Introduction

The baseline models were updated to include the proposed options for each of the CDAs to inform Phase 3: Options Assessment of the Great Yarmouth Surface Water Management plan.

Methodology Overview

Strategic options were selected for the CDAs during workshops held by Capita Symonds URS in June 2013. To inform a high-level cost-benefit analysis these options have been represented in the three baseline models. The options comprise:

- Flood wall and embankments.
- Formalised overland flow routes.
- Property level protection.
- Increased conveyance.
- Sustainable Drainage Systems (SuDS).

A summary of the options selected is presented in Table 12. For further details on individual options and the location of these please refer to the SWMP main report.

Table 12 Summary of the Proposed Options Modelled

Model	Number of each Option Proposed				
	Flood Wall or Embankment	Formalised Overland Flow Route	Property Level Protection (Area)	Increased Conveyance	SuDS
GRY1	0	0	2	2	16
BRG1	4	0	0	0	2
BRG2	1	5	9	6	6

The options were assessed and modelled in combination, i.e. no model runs were undertaken for each of the individual option scenarios. Each model was run for the 5 return period storm events: 1 in 30 year; 1 in 75 year; 1 in 100 year; 100 year including the effects of climate change; and, 1 in 200 year to allow a comparison against the baseline model results.

It should be acknowledged that the model outputs are not to be used for the design of specific options but to inform strategic decisions. More detailed modelling of the options would need to be carried out to inform outline or detailed design.

Flood Walls and / or Embankments

Polylines were imported from GIS as Base linear structures (2D) in InfoWorks ICM. These have been set to have a 0% porosity value so that flood waters cannot pass through and to have an infinite height so no flood waters will overtop the flood walls.

Formalised Overland Flow Route

Overland flowpaths have been represented in the model using mesh zones that have lowered the area by 150mm below the existing ground levels. The roughness coefficient local to the overland flow route has also been reduced by 25%.

Property Level Protection

The Property Level Protection (PLP) has been represented by increasing the level of the buildings included within the polygons indicated (represented as mesh zone) by 600mm. Where PLP has been applied to basement properties, the level of the buildings have been raised to the surrounding ground level plus 600mm.

Increased Conveyance

To represent increased conveyance of the surface water drainage network 1D conduits and manholes were incorporated into the model. The manholes within the 2D zone were set to be 2D manholes, so they are able to receive flows from the 2D mesh. Downstream manholes that are outside the model extent were modelled as 2D outlets (if within the 2D domain) or simply a free outfall (if outside the 2D domain). Where applicable, it is assumed that the invert levels provided will allow a free fall into the River Yare in one direction and that no tide-locking will occur.

SuDs

The potential impact of SuDS techniques are to both attenuate flood waters and allow more infiltration. Given the strategic nature of the baseline modelling undertaken and the uncertainty over the specific SuDS techniques to be implemented at specific locations it was agreed that SuDS would be represented in the Options models by applying infiltration losses within the areas where the use of SuDS has been identified as an option.

The baseline models apply infiltration losses through using runoff coefficients so these values have been varied to represent more infiltration into the surface and less runoff. However, this approach could only be applied to those areas that are modelled to receive direct rainfall, the infiltration rates applied to the areas within the subcatchments will have been applied by AWS during their sewer model simulations.

The selected option areas partly fall within areas where direct rainfall has been applied and partly where it has not (i.e. they are within subcatchments). So, to represent the use of SuDS option, three approaches were adopted:

- Use of SuDS representation in urban areas that receive direct rainfall - the underlying runoff coefficient polygon was amended to represent a ‘general surface’ so that a greater volume of infiltration occurs.
- Use of SuDS in rural areas that receive direct rainfall - the runoff coefficient polygon has been amended to have 100% infiltration within the SuDS area.

- Use of SuDS representation in urban areas that do not receive direct rainfall - the 2D point sources that simulate flooding from a manhole (supplied by AWS) were amended so that the volume of water surcharging from each manhole was reduced by 30mm per hour.

7. Conclusions and Recommendations

The hydraulic models constructed for Phase 2 of the Great Yarmouth Surface Water Management Plan represents an 'intermediate' approach to identify areas at risk of surface water flooding. It represents a significant refinement on the previously available information on surface water flooding in the study area. It is envisaged that these models (or parts of) could be used as base models for designing options. However, it is recommended that for future improvements to the models include (but are not limited) to the following:

- Reduction in overall model extent so that the model can be more detailed near to the option proposed.
- Inclusion of threshold surveys.
- Inclusion of river flows and channel capacity (where applicable).
- If applicable to the proposed option, incorporate the IDB watercourses as 1D river channels so the interaction between the surface water network and the IDB watercourses can be modelled more accurately.
- Further investigation on the runoff coefficients local to the options being modelled, followed by a suite of sensitivity runs to determine the most appropriate runoff coefficient.