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Appendix B: Norwich Urban Area Local Flood Mitigation Options Assessment

Model Build Report

Prepared for Norfolk County Council

UNITED KINGDOM & IRELAND

Norfolk County Council

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1. INTRODUCTION

1.1 Project Background

As part of the Norwich Surface Water Management Plan (SWMP)[1], three Critical Drainage Areas (CDAs) were identified as having a higher susceptibility to surface water flooding. As part of the SWMP broad-scale hydraulic models were constructed of Norwich and the CDAs to quantify the baseline risk from surface water flooding and to identify the predominant flow paths.

As part of the '*Norwich Urban Area Local Flood Mitigation Options Assessment*' further hydraulic modelling has been carried out.

The overall aim of this modelling was to review and update where necessary the baseline SWMP models. The intention of this update is to provide up-to-date baseline surface water flood risk mapping and flooded property counts which were then used as part of an option analysis to determine the feasibility of flood risk mitigation options in each of the CDAs.

This Model Build Report describes the development of 4 hydraulic model used to support the *Norwich Urban Area Local Flood Mitigation Options Assessment*. All models have been constructed using TUFLOW Build 2012-05-AA-iDP-w32.

A list of every model run completed during the building of the model, including for various roughness's can be viewed in the Model Build Report Appendix A.

2. BASELINE MODELLING METHODOLOGY

2.1 Norwich Wide Model

As part of the Norwich SWMP a broad-scale direct rainfall model of covering the Norwich City Council administrative area was constructed, referred to as the 'Norwich Wide Model'. This model has been updated to make use of newly available datasets including, Light Detecting and Ranging Data (LiDAR) and Ordnance Survey (OS) MasterMap Data. In addition, the model was run with revised losses to the sewer network (see Section 2.5), and building threshold levels (see Section 2.5).

The Norwich Wide Model has been revised to provide updated information on surface water flood risk across the Norwich area. In addition, the Norwich Wide Model has been run to provide inflows for the Critical Drainage Catchment (CDC) models (see Section 2.3.1).

2.2 Critical Drainage Area / Critical Drainage Catchment Models

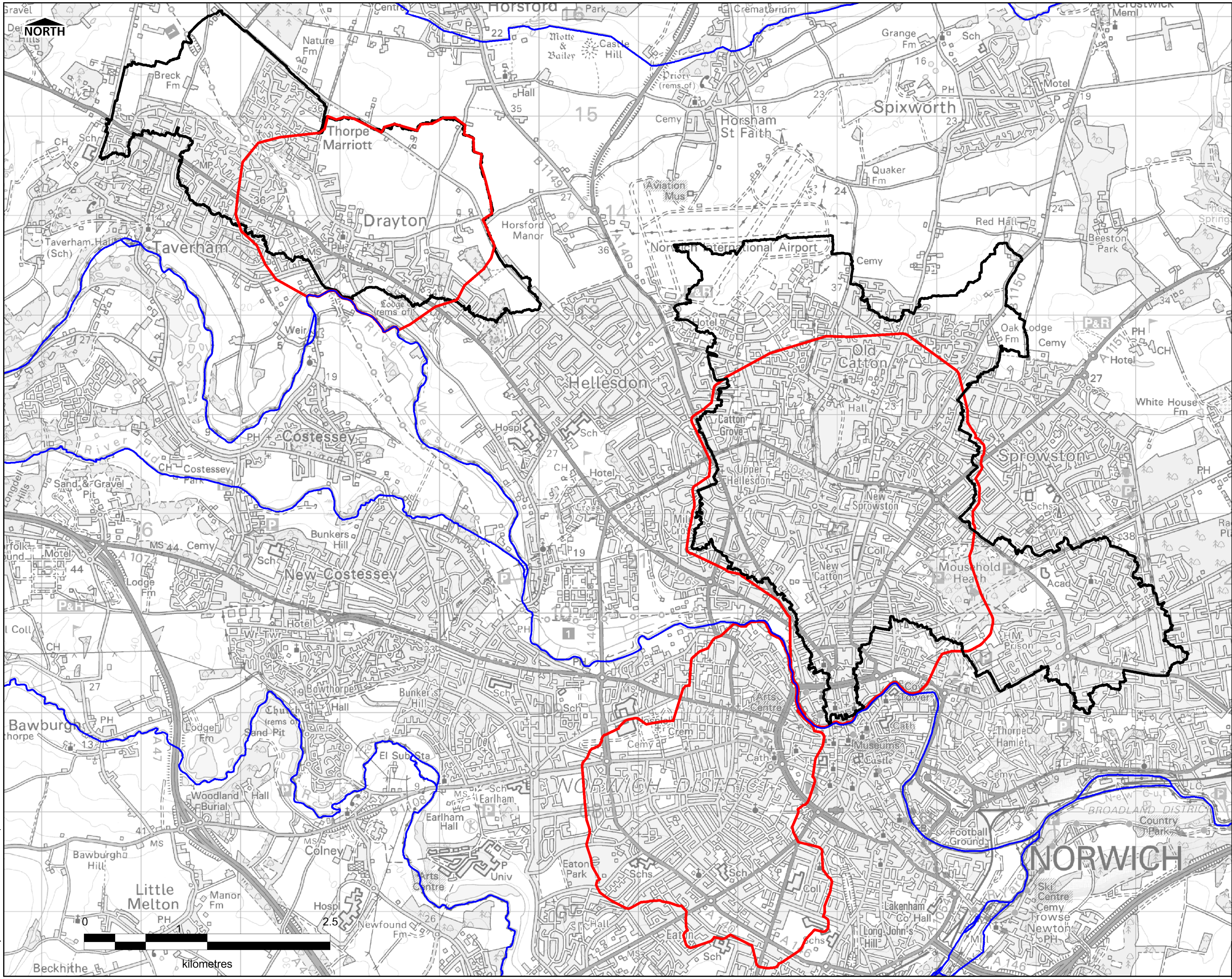
As part of this update the CDAs identified as part of the Norwich SWMP were reviewed. An exercise was undertaken using Arc GIS to determine the watershed areas across the entire Norwich area. This involved the use of LiDAR and river network data to determine the sub catchments, based on topography of each river tributary. These catchment areas have been termed Critical Drainage Catchments (CDCs) and thus replace the CDAs previously identified. The three CDAs have therefore been re-defined as:

- CDC1 – Drayton;
- CDC2 – Catton Grove & Sewell; and
- CDC3 – Nelson & Town Close.

The CDCs have been used as the starting point for delineating the model extents. CDC1 and CDC2 areas are relatively large at 6.3 km^2 and 12.7 km^2, respectively. To reduce the model run times but maintain the level of detail, the model areas for CDC1 and CDC2 have been reduced to focus on central and downstream areas. The influence of the upper catchment is however not lost as inflows are accounted for as described in more detail in Section 2.3.1.

[1] URS Scott Wilson (2011) '*Norwich Surface Water Management Plan',* URS Scott Wilson: Basingstoke.

The catchment area of CDC3 is small enough (5 km^2) to allow for the entire catchment to be incorporated into the model. Figure 2-1 presents the CDC areas in relation to the model extents.



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LEGEND

- Critical Drainage Catchment (CDC)
- Model Boundary
- Main Rivers

Notes

1. This drawing has been prepared based on results of hydraulic modelling undertaken using TuFLOW modelling software. For further details on the hydraulic modelling methodology and its limitations refer to the accompanying report (URS (May 2014) 'Norwich Urban Area Local Flood Mitigation Options Assessment Technical Report', URS: Basingstoke.)

Revision Details	By	Check	Suffix

Purpose of Issue

DRAFT FOR CLIENT COMMENT

Client

Norfolk County Council

Project Title

NORWICH URBAN AREA LOCAL FLOOD MITIGATION OPTIONS ASSESSMENT

Drawing Title

CDC OVERVIEW & MODEL BOUNDARIES

Drawn	Checked	Approved	Date
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Drawing Number: **FIGURE 2-1** | Rev: **1**

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2.3 Boundary Conditions

Hydraulic model boundaries control how flows are received by or exit from the modelled domain. The downstream boundary allows flows to leave the model domain, so as not to cause excessive retention of water within the model, whilst rainfall boundaries specify inflows to the model.

2.3.1 *Upstream Boundary Conditions (Inflows)*

- Overland Flows

The upstream boundary conditions represent the inflow(s) into the model. As CDC1 and CDC2 are part of larger catchments, it is considered important to represent the inflows from the wider catchment area. Flows that cross into the CDCs models were recorded using plot output lines within the larger Norwich Wide Model and added as inflows to the refined CDC models.

- Rainfall Profiles

Rainfall profiles within this study have been modified to represent the catchment specific rainfall. The FEH CD-ROM (v3) was used to identify rainfall catchments for each of the CDCs. For each of the catchments, the critical storm duration and rainfall profiles (hyetographs) were determined based on the catchment descriptors within the FEH CD-ROM database.

Rainfall profiles were generated for each of the catchments using the industry standard software MicroDrainage WinDES®. The rainfall profiles for each catchment are a factor of the various catchment descriptor values and are generated automatically based on the Flood Estimations Handbook methodology2. In order to enable the comparison of the model results, one rainfall profile has been generated that combines the different catchment characteristics.

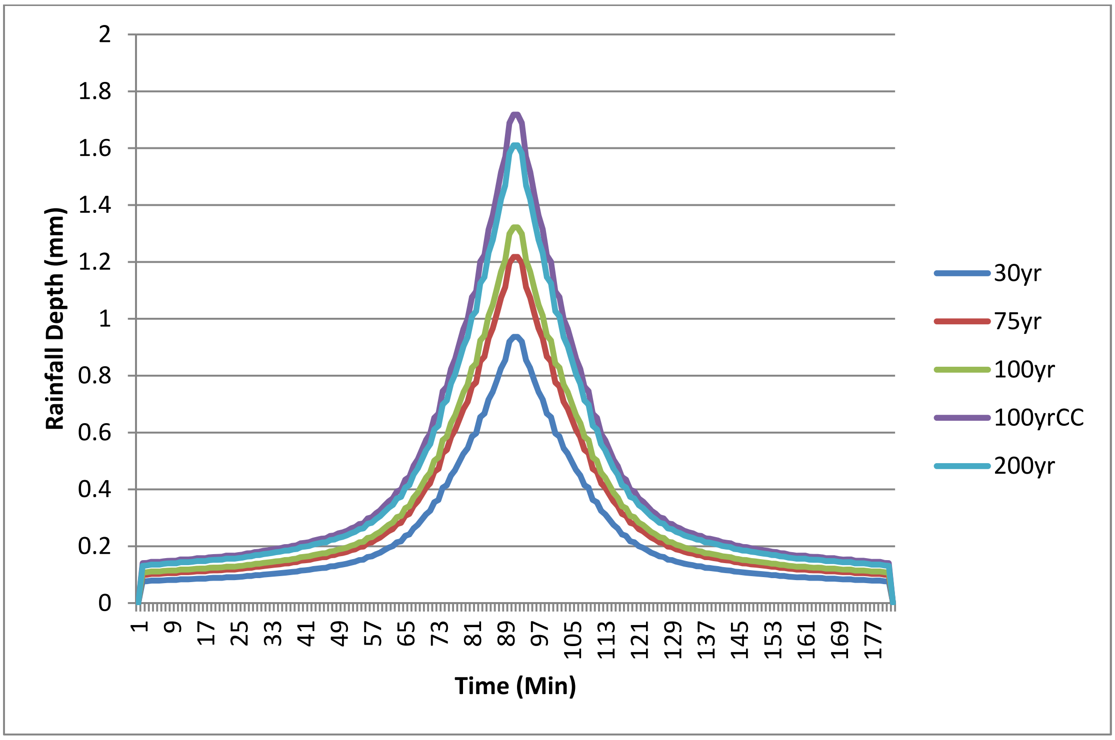
The critical duration storm duration was determined using the Revitalised Flood Hydrograph (ReFH) spreadsheet that utilises the FEH CD-ROM catchment descriptor values. The critical storm durations for the catchments equated to approximately 3 hours. A weighted 3 hour rainfall profile has therefore been developed.

The functionality of WinDES® software enables the modelling of both summer and winter season storm profiles as required. The summer storm was specified in this instance, as this option produced the rainfall profile with the greatest intensities and rainfall depths. Hyetographs for the following rainfall return periods (with justification for their selection) were generated (see Figure 2-2):

- 3.3% annual probability event (AEP) (1 in 30 year) - for use in Flood and Coastal Erosion Risk Management Grant in Aid (FCRM GiA) applications, corresponding to 'very significant' flood risk. This also corresponds to the updated Flood Map for Surface Water (uFMfSW) 1 in 30 year;
- 1.3% AEP (1 in 75 year) – for use in FCRM GiA applications corresponding to 'significant' flood risk. This also corresponds to Association of British Insurers threshold;
- 1% AEP (1 in 100 year) – for use in planning and also corresponds to the uFMfSW 1 in 100 year;
- 1% AEP (1 in 100 year) plus an allowance for climate change(30%) – for use in planning; and,
- 0.5% AEP (1 in 200 year) - for use in FCRM GiA applications corresponding to 'moderate' flood risk.

[2] Faulkner, D. (1999) *'Flood Estimation Handbook Procedures for Flood Frequency Estimation'* Institute of Hydrology: Wallingford.

Figure 2-2: Rainfall hyetographs for different return period events (summer storm of 180 minutes duration)



2.3.2 *Downstream Boundary Conditions (Outflows)*

The downstream boundary conditions influence how the water exits the model.

A proportion of the downstream boundary for all three CDC models is defined by the presence of the River Wensum. For the CDC1 model it is assumed that there is no restriction on surface water leaving the model, i.e. the river is not flooding and water can discharge freely into the river channel.

For the CDC 2 and CDC3 models, as there is a tidal influence along the eastern section of the Wensum, there is the potential for high water levels to restrict the amount of surface water that can discharge to the River. Therefore, to simulate the high water levels, no downstream boundary has been applied to prevent the discharge of surface water from the model.

2.4 Model Geometry

2.4.1 *Digital Terrain Model (DTM)*

Light Detecting and Ranging Data (LiDAR) was used as the basis for the model topography. LiDAR data is an airborne survey technique that uses a laser to measure the distance between an aircraft and the ground surface. The vertical accuracy of LiDAR is typically +/- 0.15 m; however it may vary according to the specification to which the LiDAR was 'flown'.

LiDAR records the vertical height of terrain as the eye would see it from above, and therefore includes all buildings, structures and vegetation; this is known as the Digital Surface Model (DSM). Because the DSM contains all features, including those that will not influence the propagation of flood water cross the floodplain, a Digital Terrain Model (DTM) is derived. The DSM is processed, using algorithms to detect the presence of buildings, to filter the LiDAR data and produce a DTM, where the majority of buildings, structures and vegetation are removed and the actual ground levels are represented.

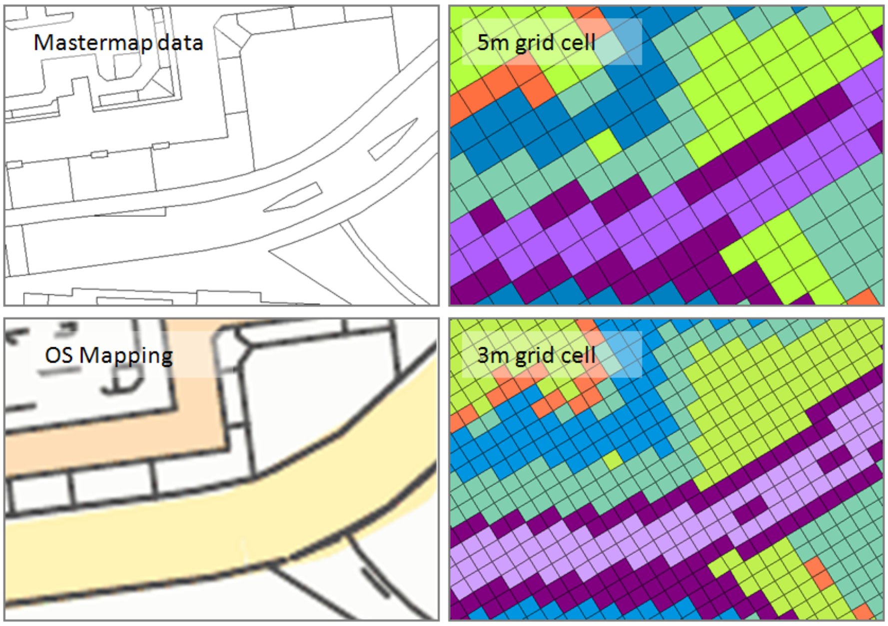
The most recent LiDAR data available for the LBHF area was flown in February 2011 at a 2 m resolution and was acquired from the Environment Agency. The extent of the LiDAR data available is considerable greater than that available during the completion of the SWMP modelling, allowing for larger areas (upstream catchment areas) to be modelled. This data was used as a basis for the topography within the 2D model grid.

2.4.2 *Model Grid Size*

To represent the topography of the model TuFLOW generates a 'grid'. The resolution of the grid determines the intervals at which the DTM is interrogated to define the model topography and the higher the grid resolution the better the representation of variances in the model environment.

To provide a more detailed representation of the topography the model grid resolution has been increased for the CDC models from 5 m, used in the Norwich Wide Model, to 2 m. This reduction allows for a better representation of variations in the local topography and in turn a greater degree of accuracy in representing overland flow paths. An example of how increase in grid resolution can make a difference in the representation of land features is presented in Figure 2-3 where OS MasterMap data has been more accurately represented.

Figure 2-3: Effect of grid resolution on representation of land features



2.4.3 *Local Topography*

Review of the LiDAR DTM indicated a good representation of the land surface across the model areas. There was however a couple of instances where the filtering process had removed structures, such as bridges and underpasses that could potentially influence the flow of surface water.

Raised structures have been modelled by using the ZSHP function within TUFLOW. The ZSHP function allows the user to specify the object width and height and has been used where sections of road have been filtered out of the LiDAR. Underpasses have been modelled by using ESTRY 1D links. The benefit of using ESTRY 1D links is that the widths of structures are not limited by the grid size (i.e. structure width is not restricted to a multiple of the grid size). The use of ESTRY 1D links allows flow pathways within underpasses to be modelled without altering flow pathways to the road or railway line above.

2.4.4 *Building Thresholds*

As the LiDAR DTM data has been used as the basis for the 2D ground model, buildings across the area of study are not represented within the data grid itself. Whilst during times of flood properties would become inundated, the rate of onset would be reduced in reality, as flood flows would be forced around and through buildings within the flood area.

Building thresholds were represented in the model using a similar approach to that used in the Norwich SWMP. That is, building thresholds are represented in the model by raising the model ground level at the building and increasing the roughness coefficients, simulating the reduced conveyance of flood flows through buildings. The buildings are located in the model using OS MasterMap data.

In the absence of surveyed floor levels for each building, the minimum ground level within each building footprint was sampled from the DTM and then raised by 100 mm to represent a typical building threshold level.

2.4.5 *Kerbsides*

The presence of a roadside kerb can be a significant influence on the movement of flood water. The vertical accuracy of the LiDAR (as described in section 2.5.1) often means that the distinction between the road level and the pavement is not necessarily accurately represented. Therefore the road channels (defined by the OS MasterMap layer) have been lowered by 125mm to define this difference and represent the potential flow path.

2.5 Infiltration

The urban areas within the CDCs are served by an Anglian Water sewer network. During storm events this network collects rainfall from the surface and carries it to discharge points along the River Wensum. The amount of rainwater that the network can carry away varies depending on the design of the sewer but when the sewers have reached capacity they will surcharge the system and potentially cause flooding.

To represent the capacity of the sewer system the previous Norwich SWMP model included a constant loss of 11 mm / hour, this value has been reviewed further as part of this project.

Anglian Water provided modelled results from their InfoWorks 1D sewer model that covered the CDCs. The return period analysis function in InfoWorks provides the return period threshold of each of the gullies / manholes modelled i.e. at which return period they flooded. The results show that of the 17,535 manholes / gullies modelled 1% flood in a 1 in 1 year event, 3% in the 1 in 5 year event, 2% in the 1 in 10 year event, 6% in the 1 in 20 year event and 4% in the 1 in 30 year event; the remainder did not flood in these events. Although this information is useful it is not possible to translate this into a constant loss in mm/hr across each of the CDCs as the capacity changes on a very local scale. It was however, considered that the infiltration rate applied before was too high and was therefore lowered to 7 mm/hr for the baseline runs. Further sensitivity testing has been carried out to determine the degree of uncertainty associated with this assumption and is documented in Section 4.

2.6 Runoff Coefficients

Runoff coefficients were applied to each surface type within the model in order to represent the varying level of runoff/infiltration that would occur on each surface. For example, runoff coefficients were specified to simulate greater runoff rates from asphalt road surfaces than from parkland. The runoff coefficients applied to the models are presented in Table 2-1.

Table 2-1: Runoff Coefficients

Runoff Coefficients	Land Use Description
0.9	Building
0.5	General Surface (residential yards)
0.8	General Surface (step)
0.43	General Surface (grass, parkland)
0.95	Building (glasshouse)
1	Water (inland)
0.2	Natural Environment (coniferous/ nonconiferous trees)
0.85	Roads, Tracks and Paths (manmade)
0.75	Roads, Tracks and Paths (dirt tracks)
0.35	Rail
0.9	Structures (roadside structure)
0.85	Land (unclassified)

2.7 Roughness

Roughness values are used to allow the model to determine the nature of the flood flows across differing ground surfaces, as surface water will flow more slowly over vegetated areas than asphalt roads. Manning's roughness coefficients for various surfaces based on OS MasterMap layers were standardised throughout the models.

The different roughness values determined using the OS MasterMap land use categories are presented in Table 2-2. The varying roughness coefficients allow the effects of differing land use on flow and velocity to be represented.

A variable Manning's roughness was applied to buildings, relating to the depth of flooding above the building threshold. Where flood flows occur to a depth of less than or equal to 30mm, the roughness value of building footprints is set to 0.015. If flood flows exceed this 30mm threshold, depth-variable roughness coefficients are applied to represent less efficient flow rates through a building, as flows would naturally favour less rough routes around buildings.

This assumption for the building roughness is designed to reflect flow effects that occur as flood water entering a building will predominately access through certain points (doors, vents etc.) and hence will flow much less efficiently than in an open area.

Table 2-2: Roughness values based on Ordnance Survey MasterMap land use types

Manning's 'n' Value	Land Use Description
0.015 (Depth <= 30 mm) 0.500 (Depth > 30 mm)	Building

Manning’s ‘n’ Value	Land Use Description
0.040	General Surface (residential yards)
0.025	General Surface (step)
0.030	General Surface (grass, parkland)
0.015 (Depth <= 30 mm) 0.500 (Depth > 30 mm)	Building (glasshouse)
0.035	Water (inland)
0.100	Natural Environment (coniferous/ nonconiferous trees)
0.020	Roads, Tracks and Paths (manmade)
0.025	Roads, Tracks and Paths (dirt tracks)
0.050	Rail
0.030	Structures (roadside structure)
0.035	Land (unclassified)

2.8 Baseline Model Runs

The baseline models constructed have been simulated with a fixed time-step of 1.25 seconds and a total simulation time of 6 hours. All of the baseline model runs carried out and their associated TUFLOW control files are presented in Table 2-3.

Table 2-3: Baseline Model Runs

Scenario	TUFLOW Control File Name
Norwich Wide Model - 3.3% AEP (1 in 30 year)	Norwich_5m_1.25ts_30yr_v5.tcf
Norwich Wide Model - 1.3% AEP (1 in 75 year)	Norwich_5m_1.25ts_75yr_v5.tcf
Norwich Wide Model - 1% AEP (1 in 100 year)	Norwich_5m_1.25ts_100yr_v5.tcf
Norwich Wide Model - 1% AEP (1 in 100 year) including the effects of climate change	Norwich_5m_1.25ts_100yrCC_v5.tcf
Norwich Wide Model - 0.5% AEP (1 in 200 year)	Norwich_5m_1.25ts_200yr_v5.tcf
CDC1 - 3.3% AEP (1 in 30 year)	NOR1_30yr_2m_180min_05.tcf
CDC1 - 1.3% AEP (1 in 75 year)	NOR1_75yr_2m_180min_05.tcf
CDC1 - 1% AEP (1 in 100 year)	NOR1_100yr_2m_180min_05.tcf
CDC1 - 1% AEP (1 in 100 year) including the effects of climate change	NOR1_100yrCC_2m_180min_05.tcf
CDC1 - 0.5% AEP (1 in 200 year)	NOR1_200yr_2m_180min_05.tcf
CDC2 - 3.3% AEP (1 in 30 year)	NOR2_30yr_2m_180min_05.tcf
CDC2 - 1.3% AEP (1 in 75 year)	NOR2_75yr_2m_180min_05.tcf
CDC2 - 1% AEP (1 in 100 year)	NOR2_100yr_2m_180min_05.tcf
CDC2 - 1% AEP (1 in 100 year) including the effects of climate change	NOR2_100yrCC_2m_180min_05.tcf
CDC2 - 0.5% AEP (1 in 200 year)	NOR2_200yr_2m_180min_05.tcf
CDC3 - 3.3% AEP (1 in 30 year)	NOR3_30yr_2m_180min_05.tcf
CDC3 - 1.3% AEP (1 in 75 year)	NOR3_75yr_2m_180min_05.tcf

Scenario	TUFLOW Control File Name
CDC3 - 1% AEP (1 in 100 year)	NOR3_100yr_2m_180min_05.tcf
CDC3 - 1% AEP (1 in 100 year) including the effects of climate change	NOR3_100yrCC_2m_180min_05.tcf
CDC3 - 0.5% AEP (1 in 200 year)	NOR3_200yr_2m_180min_05.tcf

3. OPTIONS MODELLING METHODOLOGY

Following completion of the baseline model build an option appraisal was carried out to identify potential flood mitigation options for each of the CDCs. To aid the quantification of the potential benefits from each of the options some of them have been incorporated into the baseline models, a list of these is presented in Table 3-1 and descriptions of how they were represented in the models are in the proceeding paragraphs. To represent the options in the CDCs models dimensions have been estimated for indicative purposes only and will need to be further refined if any of the options are progressed further.

Table 3-1: Potential Flood Mitigation Options Modelled

CDC	Potential Flood Mitigation Option Reference and Description
CDC1 - Drayton	CDC1-1 – Flood storage area to the north-west of Drayton
	CDC1-3 – Infiltration swale in the east of Drayton
CDC2 – Catton Grove and Sewell	CDC2-1 – Flood storage area to the north of Oak Lane in Old Catton
	CDC2-2 – Swale alongside St Ives Road
	CDC2-6 – Storage feature in the green spaces in Sleaford Green
	CDC2-7 – Underground storage tank in the playground of Angel Road Junior School
	CDC2-9 – Underground storage features (e.g tanked permeable paving, tanked storage crates)
CDC3 – Nelson and Town Close	CDC3-1 – Retrofitting water butts

3.1 NOR1 – CDC1 Drayton

The options for the Drayton CDC comprised of a storage area and infiltration trench. To represent the storage capacity of these, the topography has been adjusted. This has been completed through the incorporation of ZTIN features which lower the ground elevations. Figures 3-2 and 3-3 below illustrate the elevations applied for each of these options.

The infiltration trench has been modelled based on a width of 1m at the base and 9m at the crest. The depth of the trench is 0.6m and it extends for a length of approximately 300 m.

The storage basin has been modelled to accommodate a minimum volume of 1500 m^3. This is through a base area of 1020 m^2 and crest area of 2120 m^2, with a depth of 1m. In addition, to ensure maximum capacity of the storage area, a bund of 1.5 m raised land has been modelled along the southern boundary.

Additionally, the continuous loss within the surface area of the trench has been increased to 36 mm/hr. This rate is equivalent to an infiltration rate (the rate soaks into the ground) of 1×10-5 m/s which is considered to be at the lower end of infiltration rates typical for chalk catchments, therefore providing a conservative estimate for the loss from the infiltration trench. The infiltration is incorporated into the model through the Roughness input, where a continuing loss can be applied. This assumes that the ground is not saturated at any point, therefore water is able to infiltrate at the above rate for the duration of the model run.

Figure 3-1: NOR1 Storage Basin Elevations

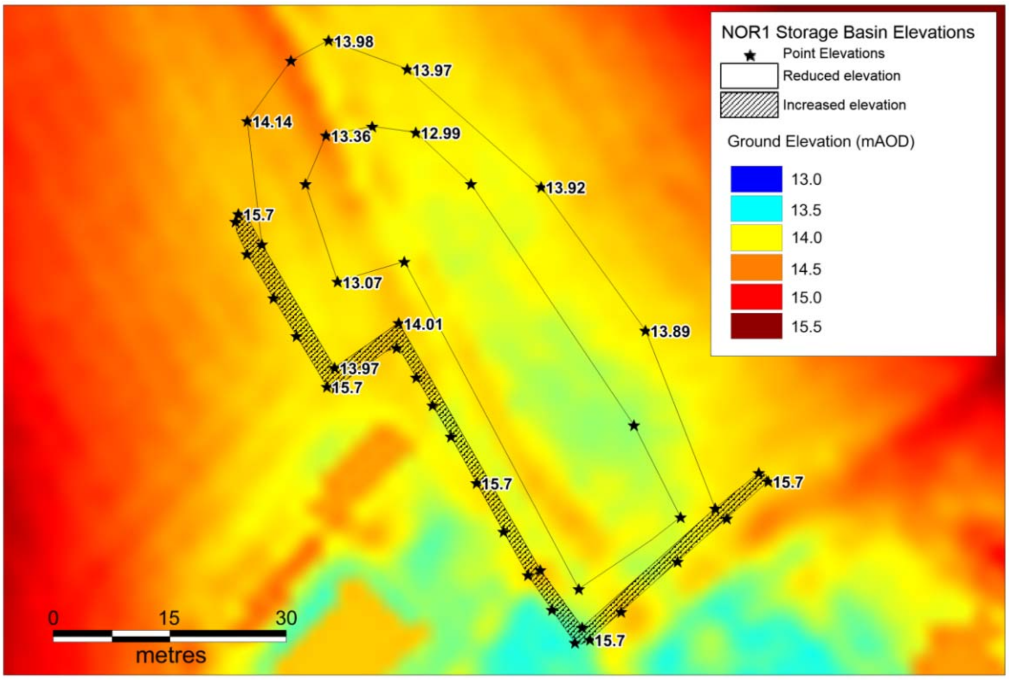
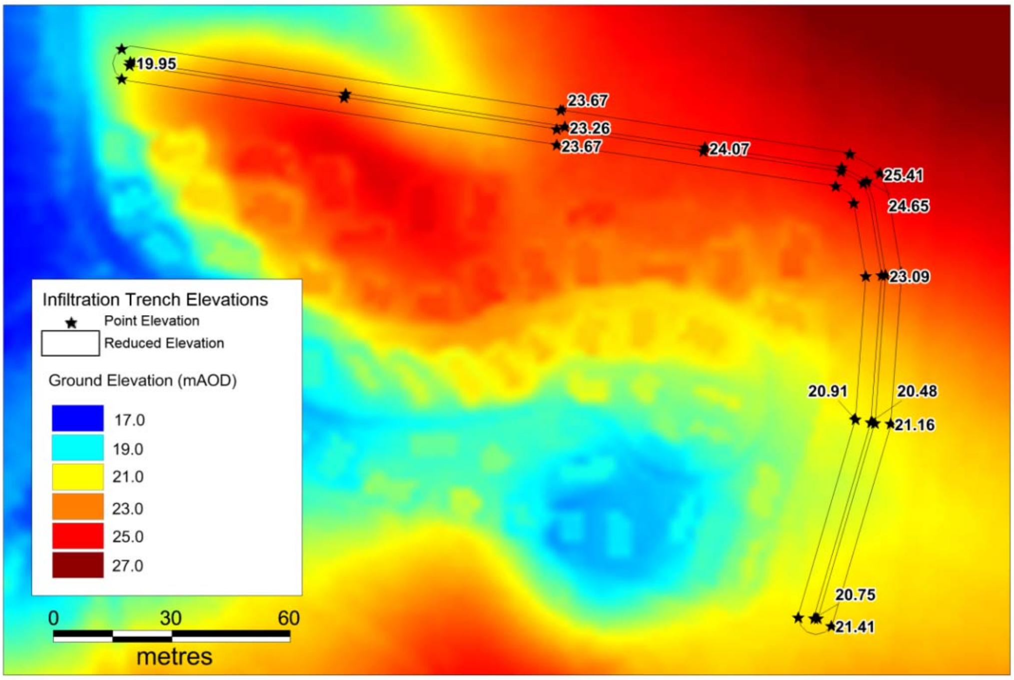


Figure 3-2: NOR1 Infiltration Trench Elevations



3.2 NOR2 – CDC2 Catton Grove

The options for CDC2 identified a suite of measures which have been implemented simultaneously across the CDC.

The storage basin at Oak Lane in Old Catton and the swale within the green space along Ives Road have been represented through the modification of the model DTM through the use of ZTIN features. The sizes of these have been based on the feasible space available. The location and scale of these can be seen in Figure 3-4.

The storage area has been modelled with a capacity of 1,500 m^3. This is assumed there is a base area of 1,000 m^2, a crest area of 2,500 m^2 and a depth of 1 m.

The swale has been modelled with a capacity of 1,000 m^3. This is for a swale with a length of 400 m, base width of 1 m, crest width of 9 m and depth of 0.6 m.

The storage tank options at Sleaford Green (Option 6), Angel Road Junior School (Option 7) and Lawson Road (Option 9) have been represented through the development of a 1D network. This works to drain all the water from the roof areas of the selected buildings, to a storage node, before water is then discharged at a given rate. The roof areas that have been drained are shown below in Figure 3-5.

In order to drain the water from the roof to the storage tanks, each cell that is specified as the roof area is connected to a 1D node via as an SX node with a CN connection. The storage node (na type) are given specific dimensions. This is based on the volume of water collected from the roof area, as well as with the feasible storage volume. A short network section is applied to connect the outfall node. The outfall node specifies water to be “lost” from the network at a specified rate (this is set up as a QT, flow – time, boundary).

The rate of loss is based on calculations of discharge equivalent to QBAR (the mean annual flood) which is then scaled to the hardstanding catchment area. MicroDrainage WinDES® software has been used to simulate the control of flow using a hydrobrake flow control device for each of the storage tanks. This assumes that the discharge to the Anglian Water Services network would be acceptable. This outflow rate is subject to change should capacity information from Anglian Water be specified. Table 3-1 details the tank dimensions and flow rates used within the model.

Table 3-2: - CDC2 Options: storage tank dimensions and discharge rates

Option	NAME	Area (m^2)	Depth (m)	Volume Storage (m^3)	Maximum Discharge Rate (l/s)
Option 6	Store_1	80	0.5	40	1.2
	Store_2	80	0.5	40	1.2
	Store_5	80	0.5	40	1.2
	Store_6	80	0.5	40	1.2
	Store_7	80	0.5	40	1.2
Option 7	Store_8	2000	0.5	1000	3.7
Option 9	Store_9	2500	0.5	1250	17.8

Figure 3-4: NOR2 swale and storage area elevations

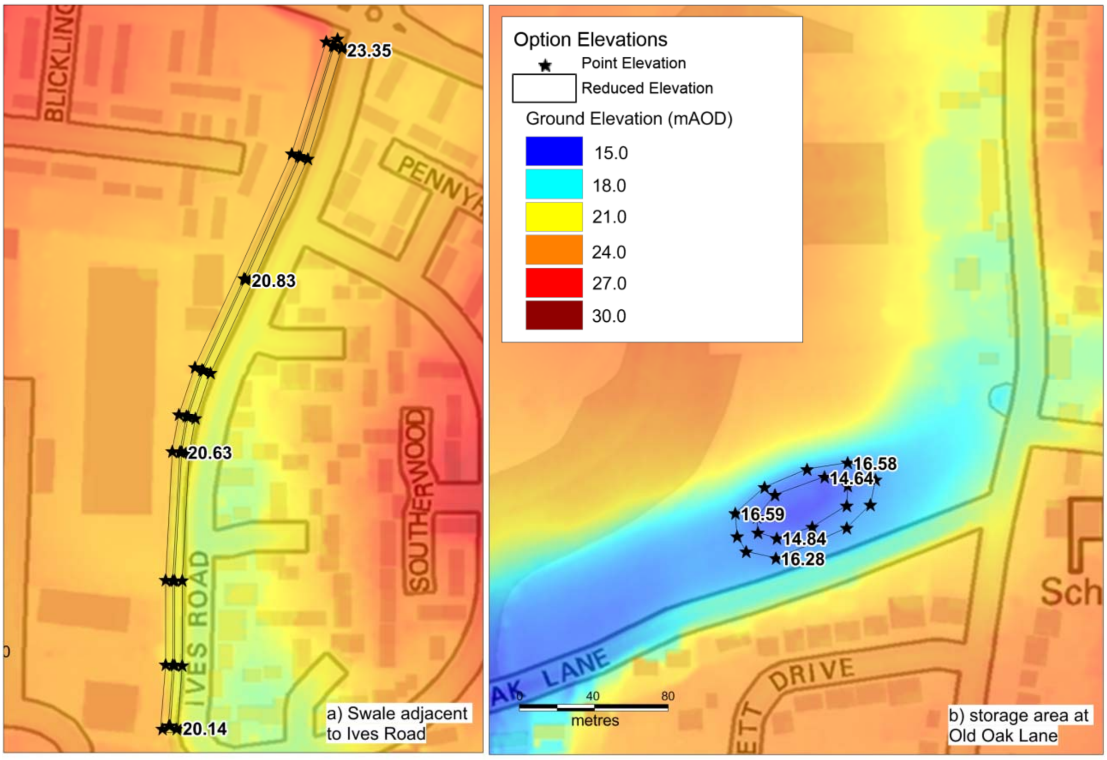
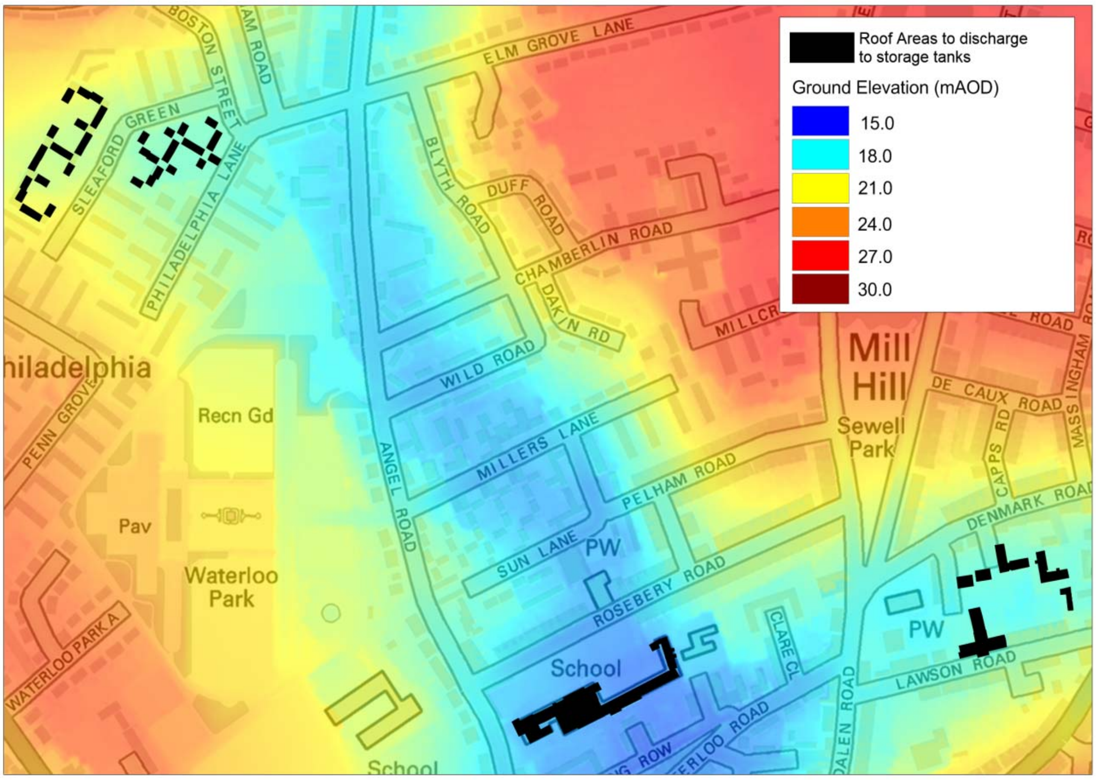


Figure 3-5: Geocellular storage option – contributing roof areas



3.3 NOR3 – CDC3 Nelson & Town Close

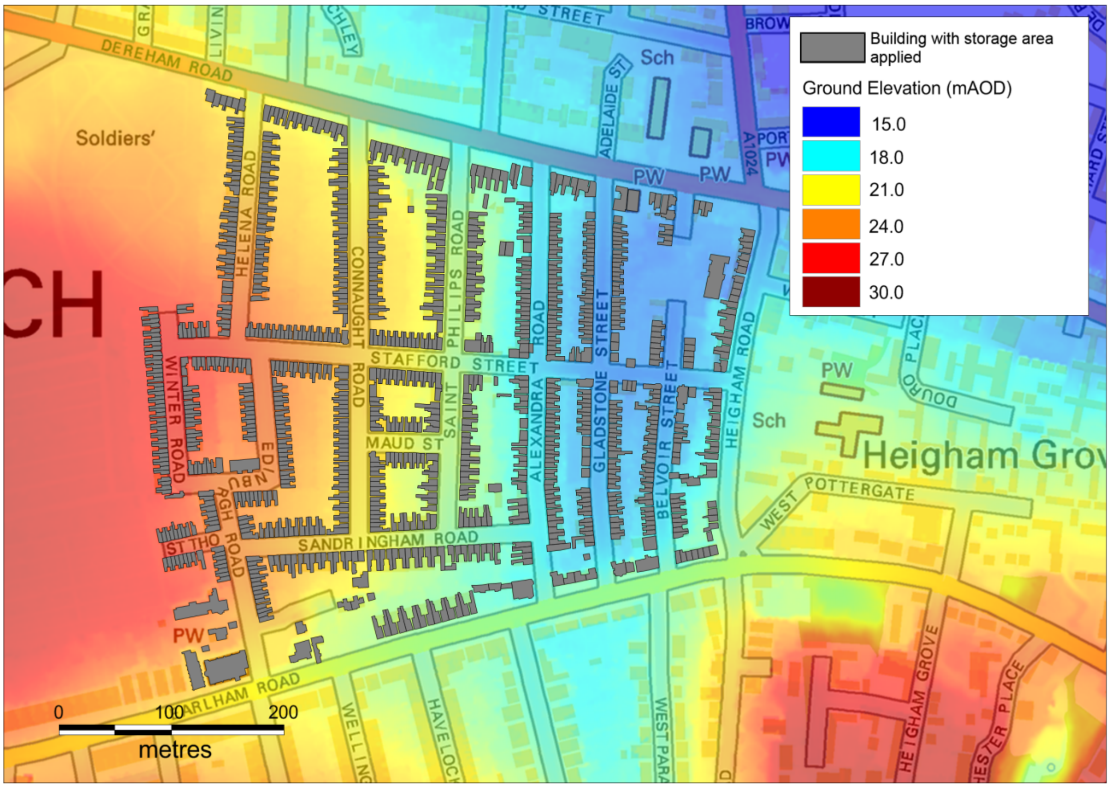
The retrofitting of water butts has been incorporated into a small section of the CDC. This has been done to see the relative impact that the implementation of this option can have on the wider area. 1,070 properties around the Gladstone Road area have been modelled. The location of these can be seen in Figure 3-6 below.

For this option, it was assumed that each property would have, as a minimum, 0.4 m^3 of storage of rainfall through the provision of water butts. These would therefore collect the first 0.4 m^3 of runoff from the roof areas before filling and spilling to the drainage network.

The average roof area in this section is equal to 52 m^2. The equivalent rainfall depth for 0.4 m^3 equates to 7.7 mm across the roof area. Therefore, within the model, it has been assumed that the first 7.7 mm of rainfall is “lost”. This method assumes that the water butts are empty to start with and that all the water from the roof would drain to the water butt. This loss is applied to the selected buildings as an initial loss within the Roughness file.

This methodology assumes that all water from the roof area would drain to the storage feature; therefore water would not spill from the gutters. The capacity of storage assumes a standard sized water butt that is free of debris and is empty at the start of the rainfall event. As water would discharge from the water butt at a controlled rate, the loss to the sewer network of 7 mm/hr has been maintained. The water butts therefore function to attenuate a proportion of runoff for a period at the start of the rainfall event.

Figure 3-6: NOR3 Roof areas with storage volumes



3.4 Option Model Runs

The baseline models constructed have been simulated with a fixed time-step of 1.25 seconds and a total simulation time of 6 hours. All of the baseline model runs carried out and their associated TUFLOW control files are presented in Table 3-3.

Table 3-3: Option Model Runs

Scenario	TuFLOW Control File Name
CDC1 – Baseline model with Option CDC1-3 infiltration swale to the east of Drayton; 3.3% AEP (1 in 30 year)	NOR1_30yr_05_Option_Trench.tcf
CDC1 – Baseline model with Option CDC1-1 Flood Storage Area to the north west of Drayton; 3.3% AEP (1 in 30 year)	NOR1_30yr_05_Option_Basin.tcf
CDC1 – Baseline model with Option CDC1-3 infiltration swale to the east of Drayton; 1% AEP (1 in 100 year)	NOR1_100yr_05_Option_Trench.tcf
CDC1 – Baseline model with Option CDC1-1 Flood Storage Area to the north west of Drayton; 1% AEP (1 in 100 year)	NOR1_100yr_05_Option_Basin.tcf
CDC1 – Baseline model with Option CDC1-3 infiltration swale to the east of Drayton; 0.5% AEP (1 in 200 year)	NOR1_200yr_05_Option_Trench.tcf
CDC1 – Baseline model with Option CDC1-1 Flood Storage Area to the north west of Drayton; 0.5% AEP (1 in 200 year)	NOR1_200yr_05_Option_Basin.tcf
CDC2 – Baseline model with Options CDC2-1, CDC2-2, CDC2-6, CDC2-7 and CDC2-9; 3.3% AEP (1 in 30 year)	NOR2_30yr_2m_180min_05_Option_2.tcf

Scenario	TuFLOW Control File Name
CDC2 – Baseline model with Options CDC2-1, CDC2-2, CDC2-6, CDC2-7 and CDC2-9; 1% AEP (1 in 100 year)	NOR2_100yr_2m_180min_05_Option_2.tcf
CDC2 – Baseline model with Options CDC2-1, CDC2-2, CDC2-6, CDC2-7 and CDC2-9; 0.5% AEP (1 in 200 year)	NOR2_200yr_2m_180min_05_Option_2.tcf
CDC3 – Baseline model with retrofitted water butts; 3.3% AEP (1 in 30 year)	NOR3_30yr_2m_180min_05_Option.tcf
CDC3 – Baseline model with retrofitted water butts; 1% AEP (1 in 100 year)	NOR3_100yr_2m_180min_05_Option.tcf
CDC3 – Baseline model with retrofitted water butts; 0.5% AEP (1 in 200 year)	NOR3_200yr_2m_180min_05_Option.tcf

4. MODEL SENSITIVITY

4.1 Introduction

Sensitivity runs have been completed to allow for a greater understanding of the relationships between key input variables and the influence they may have on model results.

Uncertainties associated with numerical coefficients used to simulate 'real life' factors have been assessed in order to reinforce confidence in model outputs. If sensitivity testing where to show that model outputs depend heavily on a particular factor, then further development of the model may be required in order to produce a more robust schematisation. Alternatively, model outputs would require a caveat to make users of the results aware of the dependency on a particular factor. Sensitivity testing has been carried out on the following parameters:

- Infiltration rate that simulates the loss to the sewer network;
- Manning's roughness coefficients;
- Downstream boundary conditions
- Storm duration; and,
- Storm profile.

In order to assess the magnitude of change arising from the sensitivity analysis, 30 points have been selected and the change in depth arising from each test analysed. The points chosen were based on areas of deep flooding and as well as random selection across the model area. The results of the sensitivity runs are discussed further in the following sections. All sensitivity runs have been undertaken using / compared to the 1 in 100 year baseline simulation and all of the sensitivity simulations carried out are presented in Table 4-1.

Table 4-1: Sensitivity Model Runs

Scenario	TuFLOW Control File Name
CDC3 – Baseline 1% AEP model with infiltration of 5mm	NOR3_100yr_2m_180min_05_5mm_Infiltration.tcf
CDC3 – Baseline 1% AEP model with infiltration of 9mm	NOR3_100yr_2m_180min_05_9mm_Infiltration.tcf
CDC3 – Baseline 1% AEP model with roughness (Manning's) increased by 25%	NOR3_100yr_2m_180min_05_plus25_Roughness.tcf
CDC3 – Baseline 1% AEP model with roughness (Manning's) decreased by 25%	NOR3_100yr_2m_180min_05_minus25_Roughness.tcf
CDC1 – Baseline 1% AEP model with modified HQ boundary	NOR1_100yr_2m_180min_05_HQ_Test.tcf
CDC2 – Baseline 1% AEP model with modified HQ boundary	NOR2_100yr_2m_180min_05_HQ_Test.tcf
CDC3 – Baseline 1% AEP model with modified HQ boundary	NOR3_100yr_2m_180min_05_HQ_Test.tcf
CDC3 – Baseline model with 1% AEP winter rainfall profile	NOR3_100yr_2m_180min_05_Winter.tcf
CDC3 – Baseline model with 1% AEP 120 minute summer rainfall profile	NOR3_100yr_2m_180min_05_Duration_120min.tcf
CDC3 – Baseline model with 1% AEP 240 minute summer rainfall profile	NOR3_100yr_2m_180min_05_Duration_240min.tcf

4.2 Infiltration

As described in section 2.9, there is a degree of uncertainty about the rate of infiltration applied to the models to simulate loss of surface water to the sewer network. In order to determine the sensitivity of the model to this loss, two simulations have been run, firstly with an increase in infiltration and secondly with a decrease in infiltration.

Increasing the infiltration rate to 9 mm/hr will mean that more water is lost from the model to the sewer network. The effect of this is a reduction in flood extent across the model area. The average change in flood depth across the points is a -23 mm decrease, with the maximum decrease of -80 mm. This equates to a percentage difference of 9% and 43% respectively.

Reducing the infiltration rate 5 mm/hr will result in less water leaving to the sewer network; as a result the extent of flooding is greater. The average change in flood depth across the points is 31 mm with maximum of 106 mm. This equates to a percentage difference of 13% and 17% respectively.

As altering the infiltration rate has a significant effect on flood depth, it is considered that the model is sensitive to the infiltration rate applied.

To reduce this uncertainty for future modelling, it is recommended that an integrated 1D – 2D network is developed, utilising the Anglian Water surface water model to refine local infiltration rates and areas of combined surface water and sewer flooding risk.

4.3 Roughness

As described in section 2.7, roughness is specified for each material type across the model domain. Roughness values are used to allow the model to determine the nature of the flood flows across differing ground surfaces, as surface water will flow more slowly over vegetated areas than asphalt roads.

The sensitivity of the model to the roughness coefficients has been tested through the completion of two runs with firstly an increase of 25% in roughness and secondly a decrease of 25% in roughness.

Altering the roughness has had a minor effect across the model area. As a result of increasing the roughness, the average change is a +1 mm (0.6% difference). Decreasing the roughness has resulted in an average change of -2 mm (1.5% difference). All of the sample points have a change in depth that is less than a 25% difference. The model is therefore considered not to be sensitive to variations in roughness.

4.4 Downstream Boundary Condition

As part of the methodology it was necessary to make assumptions of the downstream boundary parameters and their influence on the discharge of surface water at the border with the River Wensum. Each of the CDC models boarders the River Wensum (as can be seen previously in Figure 2-1).

For CDC1, it has been assumed that water can drain freely from the model (into the River Wensum). The rate of discharge is based on the gradient of the land up to the River. However, should the River be in a state of flood, or at bank full, surface water would not be able to drain freely and possibly exacerbate flooding. This sensitivity test therefore examines the impact of a bank full river on the surface water flooding.

The impact of removing the free outflow from the model is very significant within the CDC 1 model. There is a much greater accumulation of surface water within the land adjacent to the River (the floodplain). Point analysis shows that there is up to a 350 mm increase in flood depths within 10 m of the river. The change in flood depth further inland becomes less noticeable, with an average of a 44 mm increase in flood depth across the sample points.

The CDC2 and CDC3 models have been set with different downstream boundary to represent the potential influence of the tide on river levels. Within these models there is no discharge along the River.

The sensitivity test has then been completed to show the effect of applying a loss (assuming the river levels are low enough not to influence the discharge of water).

The CDC2 and CDC3 models are very susceptible to changes in the downstream boundary. Within the CDC2 model, the allowance for free discharge from the model boundary has resulted in an average decrease of 22 mm across the sample points. Within the CDC3 model, the allowance for free discharge from the model has resulted in an average decrease of 18 mm in flood depth across the sample points. The effect is most notable within the areas close to the model boundary, where the flood depth has decreased by 268 mm and 260 mm for the CDC2 and CDC3 models respectively.

The modelled options for each of the CDCs are all located within the middle or upper parts of the CDC models. Therefore, they are unlikely to sensitive to changes in the downstream boundary conditions.

These results highlight that all three models are sensitive to the downstream boundary conditions, especially within the areas of closest proximity to the River.

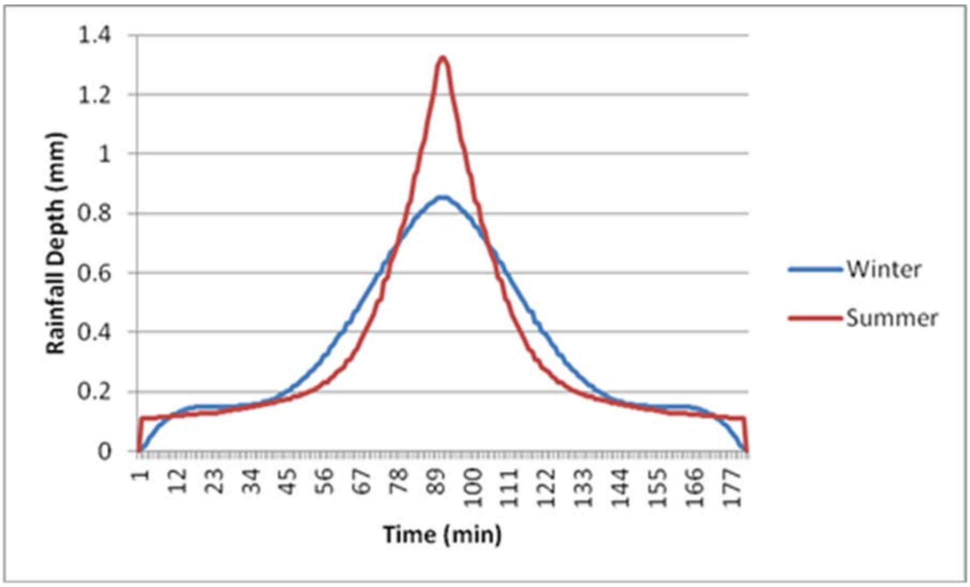
4.5 Winter Rainfall

The hyetographs of summer and winter rainfall profiles differ in their maximum intensity. As can be seen in Figure 4-1, the peak intensity of the summer rainfall profile is much greater than that of the winter rainfall profile. In addition, there is a more rapid increase in intensity during the summer event. It is considered that in terms of surface water flooding, summer rainfall events provide a worst case scenario, as the rapid increase and greater intensity is more likely to overwhelm a drainage network.

A sensitivity test has been carried out using the winter rainfall profile for the same storm duration and frequency (1% AEP, 3 hour storm duration). The results show there tends to be reduction in flood depths across the model extent of -6 mm on average. Across the points, there is a maximum of -48 mm reduction which equates to a percentage decrease of 18%. There is however an area around Gladstone Road, where flood depths have increased slightly by approximately 3 mm.

The impact of the flood depths is however not significant, suggesting that the model is not sensitivity to the rainfall profile applied.

Figure 4-1: Effect of season on rainfall hyetographs (1% AEP event of a 3 hour storm duration)



4.6 Model Duration

A shorter storm duration corresponds to an increase in the peak rainfall intensity, whereas an longer storm duration will reduce the peak but will result in rain falling for a longer period.

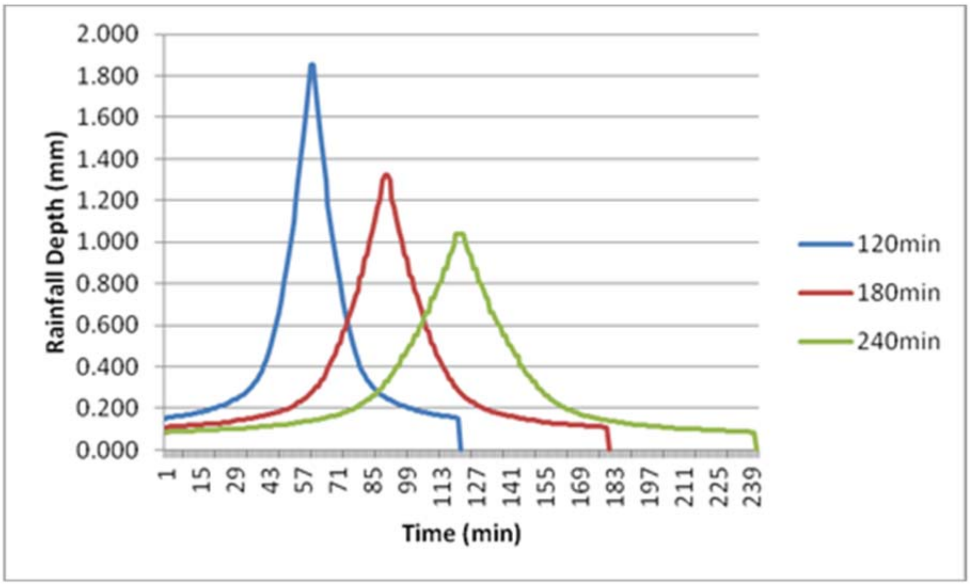
To examine the effect of storm duration on the model outputs, a sensitivity analysis was undertaken using the 1% AEP rainfall event run with 120 minute (2 hour) and 240 minute (4 hour) rainfall profiles. Based on the catchment descriptors and a weighted area average, the total rainfall depth for the 120 minute, 180 minute (baseline) and 240 minute storms are 56.7 mm, 60.6 mm and 63.7 mm respectively. Figure 4-2 shows how the rainfall hyetograph for these different rainfall durations differs.

The flood extent and depths resulting from the 120 minute rainfall event are generally greater than that of the 180 minute rainfall event. Although the total volume of water falling across the catchment is less, the greater intensity of rainfall will have exceeded the loss to the sewer network, resulting in a greater maximum depth as water accumulates at the ground surface. The 120 minute rainfall event has an average increase of flood depth of 15 mm which corresponds to a percentage increase of 7%.

By contrast, the flood extent and depths resulting from the 240 minute rainfall event are generally less, with an average flood depth reduction of -19 mm corresponding to a percentage decrease of -9.5%. This is a result of the rainfall intensity remaining less than or equal to the capacity of the sewer network for a greater proportion of the rainfall event, resulting in larger volumes of water being lost to the drainage network.

With the exception of one point, the sample points show minor changes in depth, indicating that the model is not sensitive to the duration of rainfall. One point however is sensitive with percentage changes of +42% and -49% for the 120 minute and 240 minute profiles respectively. This point is located on the outer extent of the flood hotspot around the Gladstone Road area, highlighting that the extent of the flooding hotspot within this model is sensitive to the model duration.

Figure 4-2: 1% AEP rainfall hyetographs of varying duration (summer storm profiles)



4.7 Summary of Sensitivity Testing

A summary of the results is presented in Table 4-1.

Table 4-1: Summary of Sensitivity Testing Results

Sensitivity Parameter	Mean change in flood depth (mm)	Maximum increase in flood depth (mm)	Maximum decrease in flood depth)
Infiltration of 5mm	31	106	0
Infiltration of 9mm	-23	2	-80
Roughness increased by 25%	1	20	-16
Roughness decreased by 25%	-2	7	-32
Winter rainfall profile	-6	4	-48
120 minute rainfall profile	15	65	-57
240 minute rainfall profile	-19	49	-69
CDC1 modified downstream boundary	44	350	-45
CDC2 modified downstream boundary	-22	78	-268
CDC3 modified downstream boundary	-18	6	-260

5. MODEL VERIFICATION

Understanding the performance of a model is fundamental to the modelling process, as the fitness for purpose of a model must be demonstrated in order to apply confidence to the model results. Verification of the model is important to provide assurance that model results represent the history of flooding in the study area appropriately.

Ideally there would be detailed information on historical flood events including depths, timings, return period and locations. This information can then be compared with the model results and if the comparison highlights differences a calibration exercise can be carried out to alter the model parameters until the model results correlate with the historical information.

In the absence of suitable calibration data, greater emphasis is placed on sensitivity testing (See Section 4) and verification. A verification exercise can be carried out with much less data, typically photographs of historical flooding incidents, to provide an indication of whether the model results broadly correlate with real incidents.

To verify the model, the correlation of flood records to modelled flood depth has been assessed. Discussions with Norfolk County Council indicate that, with the exception to the recent flooding event on the 27th of May 2014, there have been no significant surface water flood incidences within the CDCs since the Norwich SWMP was completed within 2010. The flood records gathered for the Norwich SWMP has therefore been used for this verification exercise.

Within the CDC1 model there are 11 records of flooding, predominately along Low Road. The detailed modelling shows a good correlation with the flood records, with the flood records correlating to flood depth of 0.13 m or greater for the 1% AEP event.

Within the CDC2 model, there are 25 records of flooding which are predominantly distributed around the main flow paths across the CDC area. There are also a number of points that correspond to isolated areas of flooding. Each of the flood records has a flood depth of 0.11m or greater for the 1% AEP event.

There are 10 records of flooding within the CDC3 area, located predominately around the main flooding hotspots. The flood records correlate to flood depths of 0.13 m or greater for the 1% AEP event.

5.1 Summary

The verification exercise shows that where there are records of flooding, the modelling results also predict the potential for flooding. There are however a larger number of areas that the model predicts to be flooded where there are no historical records, however, it should be noted that the absence of flood records does not necessarily mean there has been no incidences of flooding.

6. HYDRAULIC MODEL RESULTS

Following completion of the model runs the model results have been post-processed to produce the following outputs:

- Flood depth mapping;
- Flood hazard mapping;
- Flood depth difference mapping; and,
- Flooded property counts.

6.1 Flood Depth Mapping

For each extreme rainfall event the maximum surface water depth grids have been extracted from the TUFLOW modelling results and thematically mapped in GIS (MapInfo) according to the maximum depth classifications provided in Table 6-1.

Table 6-1: Depth mapping colour scale

Depth of flooding (maximum depth)	Legend colour
< 0.1m	
0.1m to 0.25m	
0.25m to 0.5m	
0.5m to 1.0m	
1.0m to 1.5m	
1.5 to 2.0 m	
> 2.0 m	

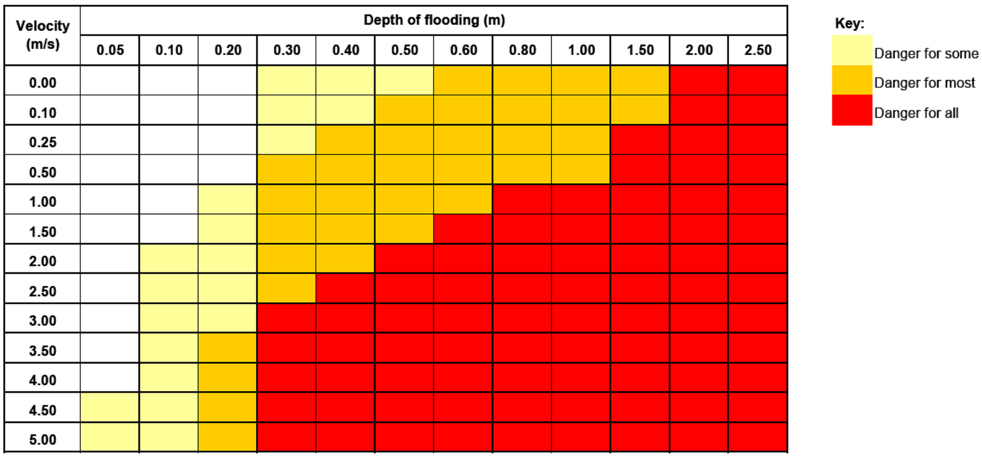
It should be noted that this mapping only shows the predicted likelihood of surface water flooding for defined areas. Due to the coarse nature of the source data used, the maps are not detailed enough to define risk for individual addresses. Individual properties therefore may not always face the same probability of flooding as the areas that surround them.

6.2 Flood Hazard Mapping

Guidance set out by Defra (2005)[3] categorises the danger to people for different combinations of flood water depth and velocity as shown in Table 6-2.

[3] Defra and Environment Agency. (October 2005) '*Framework and Guidance for Assessing and Managing Flood Risk for New Development'*, Flood Risk Assessment Guidance for New Development. FD2320 R&D Technical Report 2. Defra London. Table 13.1, Pg. 118.

Table 6-2: Danger to people relative to flood depth and velocity (Taken from Table 13.1 of the Defra/EA FD2320/TR2 report).



The flood hazard rating (HR) was calculated within TUFLOW according to the following formula from these reports:

The flood hazard classification was calculated to Defra R&D Technical Report FD2320/TR23, FD23214 and the May 2008 EA/HR Wallingford supplementary guidance note[5].

HR = d (v + 0.5) + DF

(d = depth of flooding, v = velocity of flooding and DF = Debris factor)

The debris factor was selected as described in FD2320 and its supplementary guidance note, i.e. DF = 0.5 if d≤0.25 m and DF = 1 if d>0.25 m or v>2 m/s.

Flood Hazard ratings in spatial data format were included in the outputs from the model. The flood hazard ratings are classified into the flood hazard categories shown in Table 6-3. These model outputs were incorporated into Flood Hazard mapping.

Table 6-3: Flood Hazard Classification from Supplementary Guidance Note

Flood Hazard Rating	Degree of Flood Hazard	Description
<0.75	Low	**Caution** – "Flood zone with shallow flowing water or deep standing water"
0.75 – 1.25	Moderate	**Dangerous for some (i.e. children)** – "Danger: Flood zone with deep or fast flowing water"
1.25 – 2.5	Significant	**Dangerous for most people** – "Danger: flood zone with deep fast flowing water"
>2.5	Extreme	**Dangerous for all** – "Extreme danger: flood zone with deep fast flowing water"

[4] Defra and Environment Agency. (March 2006) '*Flood Risks to People*', FD2321/TR2, Defra: London.
[5] Supplementary note on flood hazard ratings and thresholds for development planning and control purpose (2008).

6.3 Flood depth difference mapping

To present visually the impact of the potential flood mitigation options the difference in maximum flood depth in the baseline model and the baseline model with the option has been calculated using MapInfo Vertical Mapper (version 3.7). The results have been thematically mapped in GIS (MapInfo) according to the maximum depth classifications provided in Table 6-4.

Table 6-4: Maximum Flood Depth Difference mapping colour scale

Difference in Maximum Flood Depth between the baseline model results and option model results	Legend colour
< -0.100m	
-0.06m to -0.100m	
-0.030m to -0.060	
-0.030m to -0.015m	
-0.015 to +0.015m	
+0.015m to +0.030m	
+0.030m to +0.060m	
+0.060m to +0.100m	
> 0.100m	

6.4 Flooded Property Counts

As part of the cost benefit analysis the number of flooded properties are needed to quantify the potential damages. The attribute data of the Environment Agency National Receptor Database (NRD), the MasterMap building layer and the modelled maximum flood depth grids were utilised to carry out this exercise.

The MasterMap building layer has been used to determine the centre point of each building polygon. To inform the cost benefit analysis, the attribute data from the NRD is then included to provide details such as building type (flat, terrace etc.) or if it commercial or residential.

A property was deemed to be flooded if the maximum flood depth was modelled to be greater than 0.1 m at the property centre point.

7. MODEL LIMITATIONS

Although the model has been greatly refined, there are still a number of limitations and assumptions that should be noted.

The model is not coupled with the Anglian Water sewer network, so a continuous loss across the CDC has been assumed. Sensitivity analysis has shown that surface water flooding within the CDC areas is sensitive to the loss to the sewer network and the flows assumed to outfall into the River Wensum (particularly near the River). Likewise, there is no account of potential surcharging of sewers across the catchment where they may reach capacity.

The threshold levels applied to the buildings has been set to 0.1 m; this is considered to be a representative estimate of the threshold levels across the CDC areas, however in some instances this may be an underestimation. It is recommended that where properties are highlighted to potentially be at risk of surface water flooding, a site examination is undertaken to determine the true susceptibility to surface water flooding.

Due to the methodology adopted to determine the building level, there are a number of instances where buildings are below ground (predominantly on larger buildings on a steep slope). As a result, there is a tendency for larger volumes of water to accumulate within the building footprint.

It should be noted that the modelling and mapping only shows the predicted likelihood of surface water flooding for defined areas. Due to the coarse nature of the source data used, the maps are not detailed enough to define risk for individual addresses. Individual properties therefore may not always face the same probability of flooding as the areas that surround them.

There may also be particular occasions when flooding has occurred in the past that does not match the predicted patterns shown on these maps. The maps reflect all the suitable and relevant data provided and have been produced using expert knowledge to create conclusions that are as reliable as possible. It is essential that users of these maps understand the complexity of the data and modelling utilised in their production and is also aware of the associated limitations and uncertainties in the mapping. The maps are not intended to be used in isolation.

8. CONCLUSION

TUFLOW has been used to develop three detailed models for the CDCs of Drayton, Catton Grove & Sewell and Nelson & Town Close within the Norwich Urban Area. These detailed models have been developed from the modelling competed for the Norwich SWMP. As part of the detailed modelling, the following enhancements have been made:

- Model extent based on the hydrological catchment area;
- use of catchment specific rainfall profiles;
- updated LiDAR topographic data;
- increased resolution (smaller grid size) to gain additional detail in spatial representation of ground level and features;
- review and modification of topographic data to incorporate features such as bridges and underpasses;
- inclusion of area specific building threshold levels and definition of road structures; and,
- inclusion of a specific rate of loss to the Anglian Water sewer network.

The detailed modelling completed provides an enhanced baseline representation of surface water flooding across the model areas.

For each of the CDCs, potential flood mitigation options were identified through an options appraisal. These have been incorporated into the detailed TUFLOW models to provide a high level indication of the effect such options would have on surface water flooding and the results utilised to inform a cost-benefit analysis. The following options have been modelled:

- CDC1: Flood storage area and infiltration trench;
- CDC2: Suite of measures including a flood storage area, swale and geocellular storage; and,
- CDC3: Retrofitting water butts across a sample of buildings.

Sensitivity testing completed shows the models to be sensitive to the assumptions made about the downstream boundaries and the infiltration rates. It is recommended that if further modelling is carried out, for example, for option feasibility design that a model is created that includes representation of a 2D surface, a sewer network and the River Wensum to 1) identify the relationship between surface water and sewer flooding; and 2) to determine how fluvial flooding would interact with surface water flood extents.