Appendix B – Modelling Details

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1 Introduction

The purpose of this study is to analyse the impact of significant rainfall events across the study area by assessing flow paths, velocities and catchment response. This method consists of building a virtual representation of the ground topography, applying water to the surface and using a computational algorithm to determine the direction, depth and velocity of the resulting flows. Further explanation of this industry standard 'direct rainfall' method is available in the Defra SWMP Guidance – Annexes C and D.

A linked 1D-2D hydraulic model of the study area has been constructed using TUFLOW (**T**wo-Dimensional **U**nsteady **Flow**) software. TUFLOW was chosen as it solves the full two-dimensional depth averaged shallow water equations and allows for dynamic linking between the 1D and 2D components of the model. The underlying sewer network and road gullies have been represented in 1D and the floodplain has been represented in 2D.

The study area covers the urban extent of Chelmsford within the Chelmsford City Council administrative area. The area was split into three models in order to minimise computational run time.

1.1 Model Extent

Figure 1 illustrates the study area and model extents. The study area is based on the urban extent and surrounding hydrological catchment of Chelmsford City.

The study area was divided into three separate models in order to minimise model run time. The model extents are based on topographic features represented in the DTM. Each of the three models is separated from the others by a main river. There is no surface water or 1D pipe network interaction between the models.

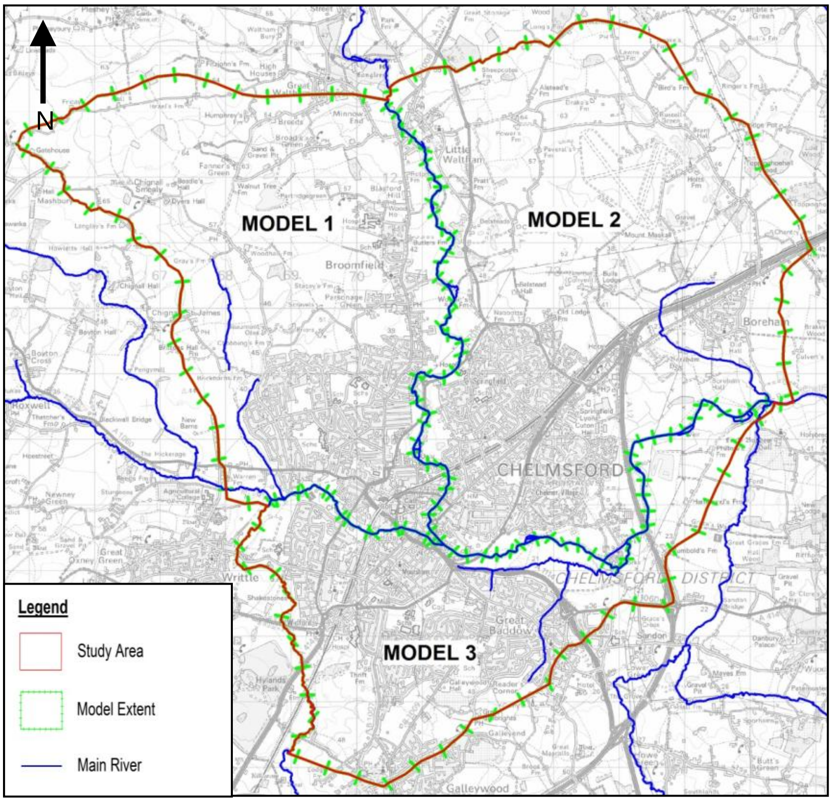

Figure 1: Model Coverage

2 Model Parameters

2.1 Model Boundaries

2.1.1 Model Inflows

Total rainfall depths were extracted from the FEH CD-ROM (v3) Depth Duration Frequency (DDF) model at 1km grid points for several locations across the modelled area. A comparison between the peak rainfall depths for the locations was completed and showed less than a 2% difference in rainfall depth between the sampled locations. Following a precautionary approach, the location which produced the greatest rainfall depth was used to generate hyetographs (NGR 569600 208500). Figure 2 shows hyetographs at this location, which were generated for the following rainfall events:

- 1 in 20 year
- 1 in 75 year
- 1 in 100 year
- 1 in 100 year plus climate change (1 in 100year +30%)
- 1 in 200 year

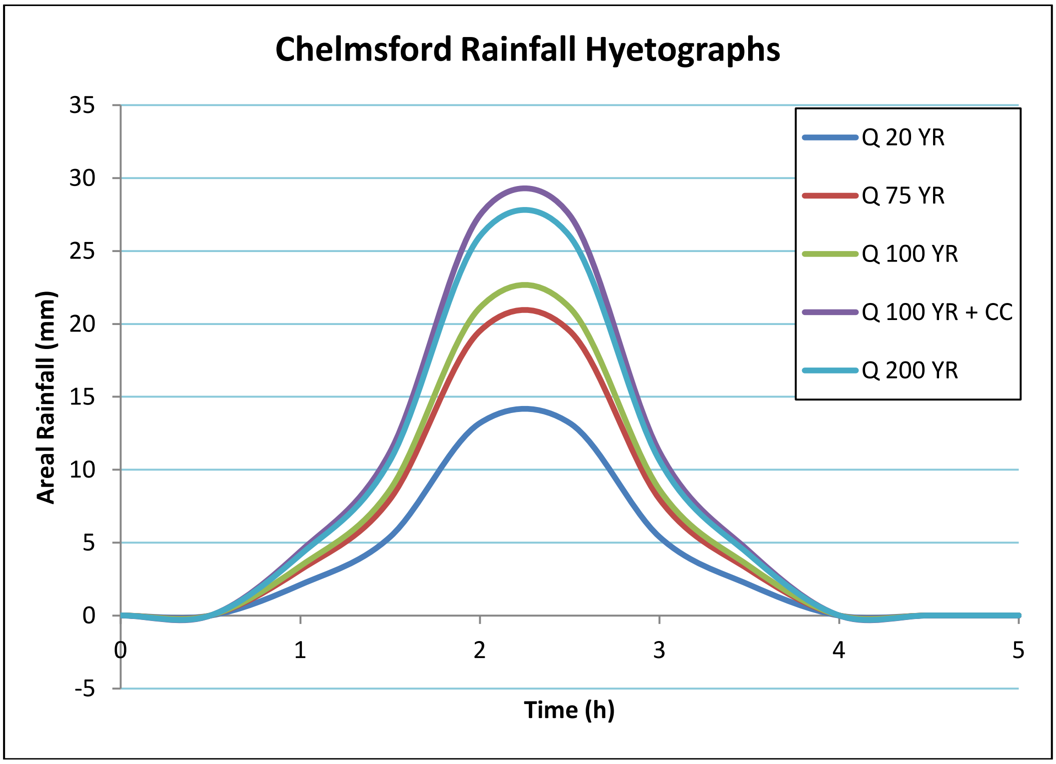

Figure 2: Rainfall Hyetographs for Chelmsford

The hyetographs were applied as inflows into the models using a 2d_rf layer, which consists of a polygon covering the model domain. This boundary condition layer references the boundary condition database, which enables TUFLOW to apply the rainfall hyetograph corresponding to each event and duration as an 'areally' distributed rainfall.

There are no 1D inflows or outflows at the extents of Model 1 or Model 2, as the 1D pipe network corresponding to the urban extent of Chelmsford falls entirely within each 2D model extent. The 1D pipe network crosses the southern boundary of Model 3 in two places. These are small discrete network regions outside of the area of interest and have not been included in the hydraulic model.

2.1.2 Critical Duration

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 hydraulic model was simulated for a range of storm durations to determine the critical duration for the study area. The durations tested were 1 hour, 3 hours, 6 hours, 10 hours and 12 hours. The maximum flood depth and extent of surface water flooding for the five durations were compared and it was found that there was no significant difference in the results overall. The 3 hour duration tended to produce the largest flood extent and maximum flood depth in the areas where there was a difference,. This duration was selected as it provided the most conservative results.

2.1.3 Downstream Boundaries

Model 1

The River Can, to the south, and River Chelmer, to the east, define the downstream extents of Model 1. The initial water level in each river was assumed to be to be the surface elevation provided by the DTM. In the 1D domain, this has been applied by assigning a 1D constant head boundary, set at the LiDAR elevation, to all outfalls. This is automatically applied in the 2D domain as the topography is defined by the LiDAR DTM. No further downstream boundary conditions have been applied along the rivers and water is allowed to build up along the boundaries. This was deemed suitable as the purpose of this study is to investigate surface water, rather than fluvial flooding, and the areas in which water builds up correspond to fluvial flood zones.

Model 2

The River Chelmer to the west and south defines the downstream extent of Model 2. The initial water level in the river has been assumed to be to be the surface elevation provided by the DTM. This water level has been assumed in both the 1D and 2D domains. In the 1D domain, this has been applied by assigning a 1D constant head boundary, set at the LiDAR elevation to all outfalls. To the west, no further downstream boundary has been applied, following the same rationale as for Model 1. In the south east of the model domain, where the Chelmer flows to the east, an automatically generated stage-discharge relation, based on the gradient taken from the LiDAR DTM, has been applied to account for the flow of the Chelmer out of the model domain.

Model 3

The River Wid to the west and the rivers Can and Chelmer to the north define the downstream extents of Model 3. The initial water level in the rivers has been assumed to be to be the surface elevation provided by the DTM and no further downstream boundaries have been applied, as described above for Models 1 and 2. . In the 1D domain, this has been applied by assigning a 1D constant head boundary, set at the LiDAR elevation, to all outfalls. This is automatically applied in the 2D domain as the topography is defined by the LiDAR DTM.

2.2 Drainage Network

2.2.1 Network Data and Assumptions

The drainage network in Chelmsford has been modelled in 1D and has been defined using data collected from the following sources:

Anglian Water data - sewer layer
Anglian Water data – manhole layer
Essex Highways data – gully layer

The network data provided by Anglian Water fell almost entirely within the 2D model extents, with the exception of two small isolated regions along the southern extent of Model 3, which have not been incorporated in the model (as described previously). Gulley data provided was trimmed to the 2D model extents.

Surface water pipes and manholes, denoted as purpose 'S', and combined pipes and manholes, denoted as purpose 'C', were extracted from the sewer and manhole layers. All other pipes and manholes have been excluded from the hydraulic model.

In some parts of the study area, isolated pipes were found with no apparent connection to the remainder of the drainage network. In such cases, the results of a model run without the drainage network were analysed to determine if the pipe in question provided an important drainage path to the area. If not, the pipe was removed from the drainage network model.

Both manhole and sewer data had limited information available. Therefore automatic procedures were applied to fill in the missing data in a number of regions:

For all pipes, the upstream invert was missing; in addition, a large number of pipes were missing downstream inverts and/or and pipe dimensions.
All of the pipes were digitised in the wrong direction: in correcting this (i.e. reversing the line direction), many of the pipes changed position slightly, and in some cases this caused misconnections which had to be manually amended.
The snap tolerance within TUFLOW (the distance within which pipes are connected to other pipes or manholes) was increased to 0.1m to allow for misconnections caused by correcting the direction of the culverts.

For all manholes the type and chamber dimensions were missing. A number of manholes were also missing cover and invert levels. The following automatic procedures were used to apply the missing data:

- **Cover and invert level:** Where no cover level was assigned in the original data, it has been assumed that the cover level is the ground level as defined by the LiDAR DTM. Where invert levels were missing, these were interpolated from upstream / downstream pipes using a constant gradient or assumed to be the cover level minus 1.5m. .

- **Chamber size:** An average manhole dimension of 1050mm was applied to all manholes. A manual check was then done to ensure that the correct chamber size was assigned according to pipe size. It has been assumed that the chamber diameter is always larger than the pipe diameter, and increases incrementally as follows: 1050mm, 1200mm, 1500mm, 1800mm, 2100mm, and 2400mm.

Where missing, pipe dimensions were defined manually by assuming that the pipe dimension would increase going downstream. The surrounding pipes were also checked and a number of pipe sizes were modified, where it was believed that incorrect values had been entered into the data set.

The following manual checks were done on the drainage network:
- The pipe downstream invert level is always less than the upstream level;
- The pipe dimensions always increase in the downstream direction ;
- The pipe invert levels are greater than or equal to the connecting manhole invert levels.

In locations where the topography is flat or undulates slightly some of the pipes were assigned the levels in the reverse order, which meant that the downstream was higher than the upstream. These locations have been checked, and some locations have been left unchanged where the area is flat and there is not a large difference between the levels. However, in most of the locations the invert levels were manually changed and the topography used to determine the appropriate level.

2.2.2 Regions of Poor Network Data

In all three models there were regions in which the network data available was particularly poor. The uncertainties arising from the assumptions required to incorporate the 1D pipe network in these areas would outweigh the benefits of incorporating the network. The most notable lack of data were the invert levels of pipes and many were also missing dimension data. In such regions, the network was not incorporated in the model. I Instead a continuous loss of 3mm/hour was applied to all impermeable surfaces through a separate soils layer, to account for the drainage network.

2.2.3 Gullies

The gully layer provided by Essex Highways was used as the principal means of connecting the 2D (surface) model to the 1D drainage (sub-surface) model. A "pit search distance" command was entered into the ESTRY control file (ecf file). This enabled gullies to automatically connect to the nearest manhole within a specified distance. Manual checks were done to ensure that gullies connect to the correct part of the network.

The relation for discharge into the gullies was specified by using a pit inlet database, which allows a stage-discharge relationship to be applied based on the gully type, cross fall and longitudinal gradient of the road. A standard UK "Type R" gully was used throughout the model, based on a random sample of gullies viewed on the site visit, and a profile of "Steep-shallow", corresponding to a steep longitudinal road gradient and shallow cross fall, was applied[1].

2.3 Topography

LiDAR data provided by the Environment Agency was used to define the topography of the study area. The LiDAR data provided was of 2m resolution. In a number of regions where 2m LiDAR was not available, coarser resolution (5m) Flood Map for Surface Water DTM data was used. None of the urban areas were 'backfilled' with the lower resolution DTM data, so the impact on model outputs is minimal.

The topographic data sources were reviewed as part of the model build process and merged into a single DTM. It was observed in one location that the DTM showed inconsistent ground elevations where LiDAR data from the two different sources met. In addition, the FMfSW DTM does not filter out buildings. 2d z-shape layers were used to smooth the LiDAR in these regions to eliminate unrealistic ponding and backing up of water.

Information on fluvial flood defences(location and elevation) was obtained from the Environment Agency's National Flood and Coastal Defence Database. For most of the NFCDD defences elevation data was unavailable so elevations were obtained by performing a query on the DTM.

[1] Design Manual for Roads and Bridges (DRMB), Vol. 4, Section 2

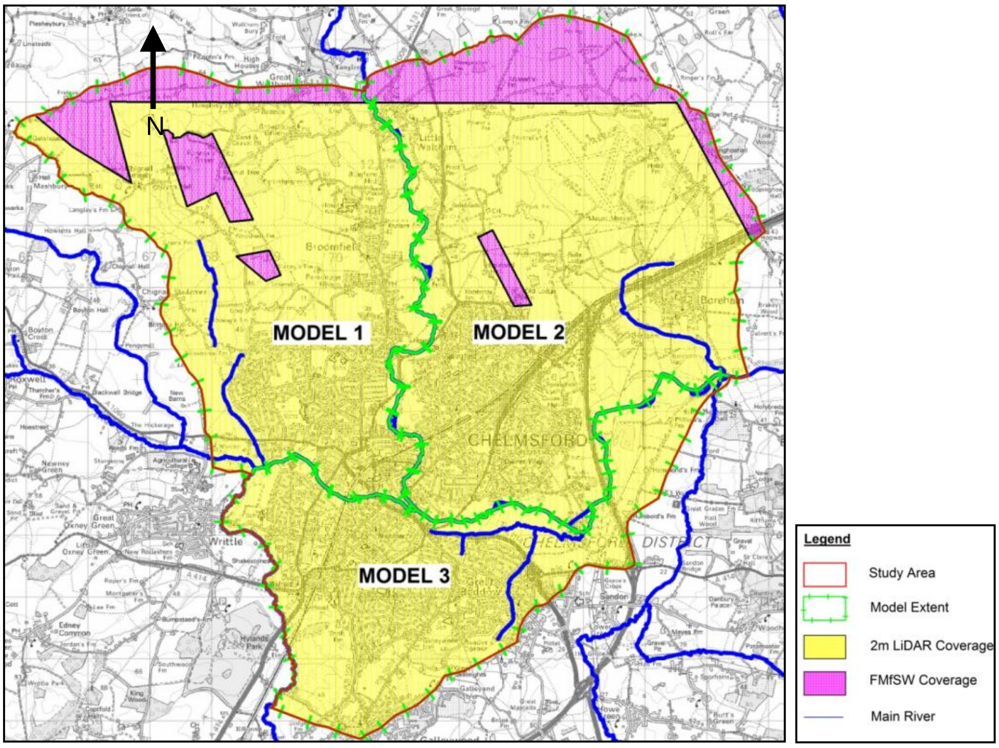

Figure 3: Topographic Data

2.4 Watercourses

Ordinary Watercourses have been represented in the TUFLOW model using “flow constriction” and “storage reduction factor” layers. The use of these layers allows for watercourses with a width narrower than the model grid size to be represented suitably in 2D. The location of the watercourses has been digitised from the LiDAR DTM and the Environment Agency “Detailed River Network”. A 10m flow constriction has been applied to all watercourses of width less than 10m, as determined by DTM inspection, in order to enable a continuous flow pathway in the 5m model grid. A percentage blockage has been specified in order to reduce flow corresponding to the actual channel width.

For rivers with a width of greater than 10m (generally Main Rivers), it has been assumed that the LiDAR resolution is sufficient to represent the channels without the need for an additional flow constriction. A 2d_SRF (storage reduction factor) has been used to adjust the available storage area in the cells

The elevations assigned to watercourses were extracted from the LiDAR DTM. Watercourse elevations obtained from LiDAR are likely to represent water levels in the watercourses at the time when the LiDAR was flown, rather than the underlying topography; therefore no further initial conditions have been applied.

2.5 Structures

Initially, a base hydraulic model was simulated without structures. Using these initial results as guidance, a site visit was undertaken to obtain details and clarifications of identified structures, in particular key structures such as large culverts and road underpasses. These were then added to the hydraulic model as 1D or 2D elements. Height and width dimensions were obtained by approximate measurement on site. The length of culverts was based on the digitised 1D elements in the model. Elevations were obtained from the DTM. The key structures observed on site and explicitly modelled in 1D are listed in Table 4.

Table 4: List of Observed 1D Structures

Name	NGR	Brief Description
M01		
K_Culvert	570708, 210290	Arched culvert
O_Culvert	567087, 211695	Circular culvert
M02		
E_Culvert	574294, 210184	Circular culvert
D_Culvert	573901, 209248	Circular brick culvert
D_Culvert_2	573901, 209248	Circular culvert
J_Culvert	570980, 212850	Irregular culvert: circular with bottom third cut off
F_Culvert	575990, 210540	Circular culvert
H_Culvert	571920, 209810	Circular culvert
M03		
R_Culvert	572860, 204770	Rectangular box culvert

A number of structures which were not observed on site were identified and explicitly modelled in 1D using the LiDAR DTM and aerial mapping., The locations of these structures are shown in Table 5.

Table 5: List of Assumed 1D Structures

Name	NGR	Brief Description
M01		
ADDED_1_013b	570421, 211443	Circular culvert
ADDED_2_013	570902, 210389	Rectangular box culvert
ADDED_3_014	570777, 211433	Rectangular box culvert
ADDED_4_014	570937, 208239	Rectangular box culvert
ADDED_5_014	571031, 210430	Rectangular box culvert
M02		
ADDED_1_013	570421, 211443	Circular culvert
ADDED_2_013	574118, 207587	Rectangular box culvert
ADDED_3_014	571238, 208891	Rectangular box culvert
ADDED_4_014	571457, 208979	Rectangular box culvert
ADDED_5_014	571701, 212392	Rectangular box culvert
ADDED_7_014	572103, 206433	Rectangular box culvert
M03		
UNDERPASS_1_	570437, 205412	Rectangular box culvert
CULVERT_2_01	572767, 204506	Circular culvert
ADDED_1_013c	572861, 204610	Rectangular box culvert

In addition to the structures outlined above, details of a fluvial flood defence in Chelmer Village (NGR 573960, 207705) were provided by Chelmsford City Council. The defence was modelled in 2D using a raised Z shape. The corresponding surface water storage chambers were represented in 1D by a single node with storage area corresponding to the dimensions provided, with connecting pits allowing water to enter. Pipes draining the storage chamber into a nearby ditch were also modelled in 1D, and an SX connection added to allow water to pass from the 1D to 2D domain.

2.6 Building Representation

Buildings within the study area have been represented using raised building pads. These have been included in the model as described below:

- A GIS layer containing the locations of all ‘buildings’ was created based on the building polygons in the OS MasterMap dataset;
- The LiDAR DTM was then interrogated to obtain an average ‘bare earth’ ground level within each building polygon;
- This average ground level was applied to the building polygons to give them their base elevation in the TUFLOW model; and
- 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 approach ensures that the buildings form an obstruction to flood water and that shallow flows must pass round the buildings (and not flow through them). A high Manning’s n value (n = 0.5) was applied to the buildings to represent the high resistance that buildings have to flow. However, for very shallow depths of flow (up to 30mm) a lower Manning’s n value (n = 0.015) was applied to ensure that shallow flows did not incorrectly accumulate within the building footprint.

The TUFLOW model constructed is a direct rainfall model which applies a rainfall hyetograph to every active cell within the 2D model extent. This includes the cells representing buildings. The Manning’s n value for buildings is reduced for these very shallow depths so that the flow which is created on buildings as a consequence of the application of direct rainfall is able to flow away from the building. If the Manning’s n value was not reduced for these shallow depths, the rainfall applied to the building cells would pond here in an unrealistic manner.

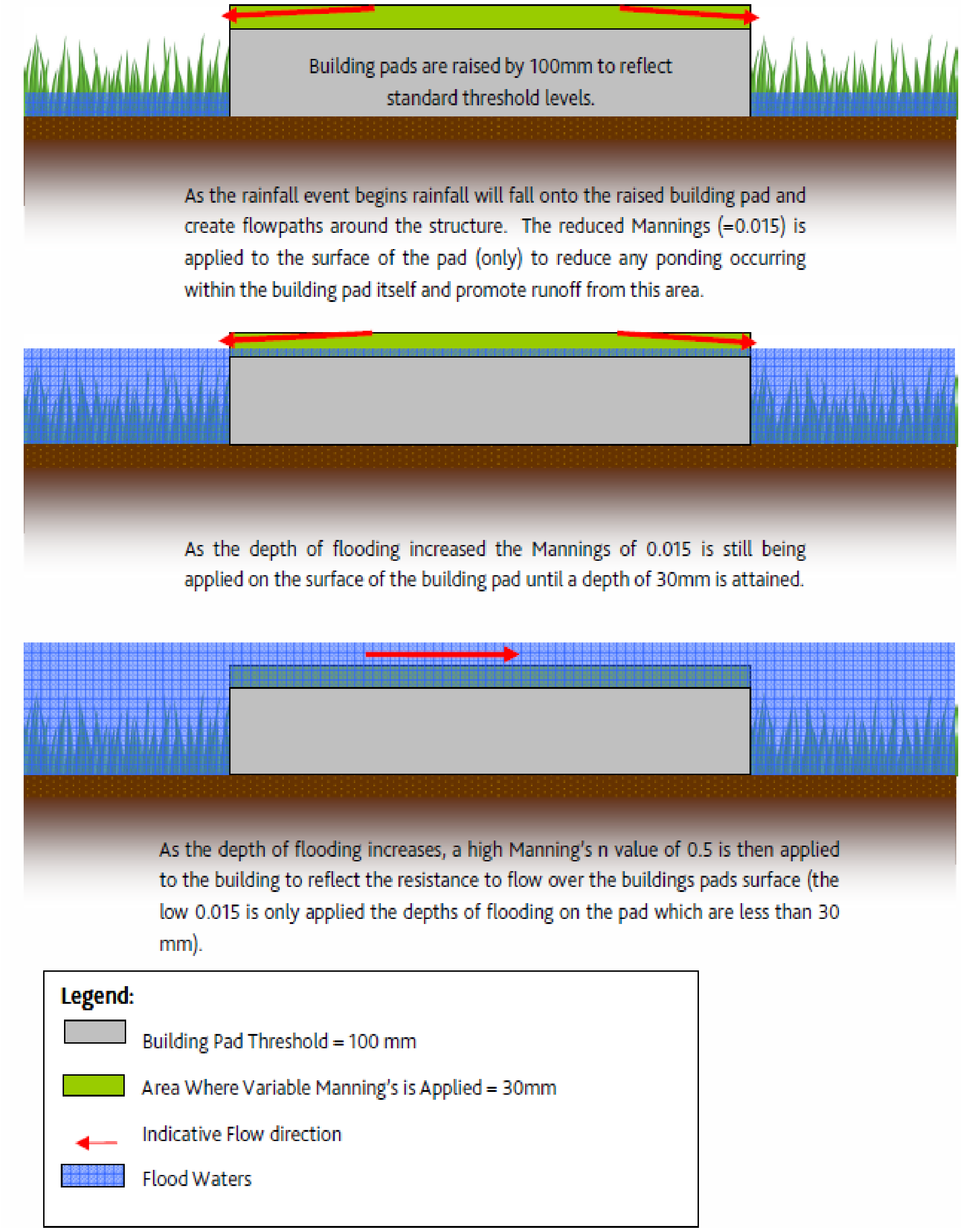

Figure 6: Building Pad Methodology

2.7 Manning's Roughness Values

The Manning's roughness coefficient values contained shown within Table 7 have been used throughout the 2D floodplain. The various land uses in the 2D component of the model have been demarcated by the use of OS MasterMap data. The "Feature Code" attribute in the data set has been used to identify the different land uses and assigned a roughness value.

Table 7: Manning's Roughness

Feature Code	Descriptive Group	Comment	Manning's Roughness
10021	Building		0.500
10053	General Surface	Residential yards	0.040
10054	General Surface	Steps	0.020
10056	General Surface	Grass, parkland	0.050
10057	General Surface	Manmade	0.020
10058	General Surface		0.030
10062	Building	Glasshouse	0.500
10076	Land; Heritage And Antiquities		0.500
10089	Water	Inland	0.045
10093	Landform		0.100
10096	Landform	Dense vegetation, Cliff, Cultivation areas	0.100
10111	Natural Environment (Coniferous/Non-coniferous Trees)	Heavy woodland and forest	0.120
10112	Natural Environment (Coniferous/Non-coniferous Trees)	Scattered	0.075
10113	Natural Environment (Coppice or Osiers)		0.110
10114	Marsh Reed or Saltmarsh		0.055
10115	Scrub		0.070
10119	Roads Tracks And Paths	Steps, manmade	0.015
10123	Roads Tracks And Paths	Tarmac or dirt tracks, manmade	0.035
10167	Rail	Manmade	0.025
10168	Rail	Natural	0.050
10172	Roads Tracks And Paths	Tarmac	0.017
10183	Roads Tracks And Paths (Roadside)	Pavement	0.030
10185	Structure	Roadside structure	0.040
10187	Structure	Generally on top of buildings	0.500
10193	Structure	Pylon	0.040
10203	Water	Foreshore	0.040
10210	Water	Tidal water	0.035
10217	Land (unclassified)	Industrial Yards, Car parks	0.035

A Manning's roughness value of 0.015 was applied to all 1D elements in the model, including surface water / combined sewers, and the structures shown in Tables 4 and 5.

2.8 Infiltration Losses

Infiltration has been represented in the model using the Green-Ampt method. This method allows infiltration losses to be applied to permeable surfaces based on the underlying soil textural class. TUFLOW uses the hydraulic properties (hydraulic conductivity, suction and porosity) corresponding to each soil textural class and the initial moisture content to vary the rate of infiltration over time. The entirety of the model extent is assumed to be unsaturated at the start of the simulation.

Throughout the simulation, TUFLOW monitors the amount of water infiltrated, such that once the soil is saturated, no further infiltration occurs. A 2d_soil layer was created, within which polygons were digitized to represent the soils present in the study area based on the Soilscapes Viewer from Cranfield University's National Soil Resources Institute (NSRI), supported by Defra[2]. These polygons were then allocated a unique code according to textural class. The soil textural classes and corresponding TUFLOW codes applied within Chelmsford shown in Table 8 and Figure 9.

Table 8: Soil Textural Class

Tuflow Soil Code	Description
2	Silty Clay
4	Clay Loam
5	Silty Clay Loam
7	Silt Loam
8	Loam
99	No infiltration

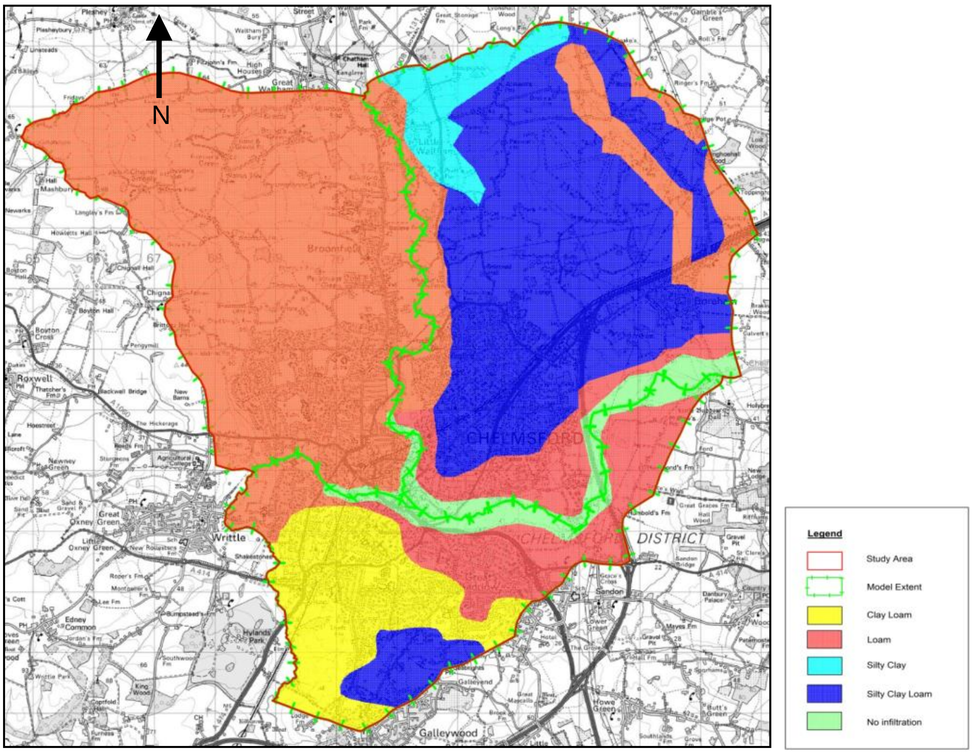

Figure 9: Soil Textural Classes

[2] [https://www.landis.org.uk/soilscapes/] Accessed: 11th November 2012

A zero infiltration layer was created to ensure that infiltration losses were not applied to impermeable surfaces (such as buildings and roads) or watercourses.

It should be noted that the hydraulic properties of soils within the study area are assumed to correspond to the values hardcoded into the TUFLOW software. These values (suction, hydraulic conductivity and porosity) are derived from non-UK soils. Textural classifications have been found to be more complex that the simplified hydraulic properties represented in TUFLOW. Best practice has been applied in adapting the non-UK soil parameters to fit with UK soil types. However, it is recommended that further analysis is undertaken in determining the hydraulic properties of UK soil types.

2.9 Model Grid Size

The model was constructed with a 5m grid size. This grid size was chosen as it represented a good balance between the degree of precision (i.e. ability to model overland flow paths along roads or around buildings) and model run ("simulation") times. For example, refining the grid size from a 5m grid to a 3m grid would significantly increase the model simulation time to days rather than hours.

3 Model Simulation

The hydraulic model was run using TUFLOW build 2012-05-AE-iDP-w64. This represents the latest version of the software at the time of model construction. The was run on the 64bit version of this build to take advantage of the faster simulation times and advanced handling of larger models.

The model naming convention adopted is detailed below:

CHE_Mxx_xxxxR_xxHR_xxx

CHE: Chelmsford
Mxx: Model Number (01, 02 or 03)
xxxxR: Rainfall Event Probability
xxHR: Duration Event
xxx: Version number

e.g. CHE_M01_0200R_03HR_010 denotes the model run for a 200 year return period storm event of 3 hour duration, for version 10 of Model 1.

3.1 Simulation Time

All design events for the Chelmsford model have been simulated for 6 hours (double the critical storm duration). The model was then assessed to determine whether this duration was suitable for the model. This was carried out by viewing the model results for the final few time steps. The results were checked to determine if water depths in the floodplain were still increasing significantly, and whether new flow paths were forming or existing flow paths still propagating. If either of these conditions were found to exist, the simulation time was extended for a further hour after which the checks were repeated until none of the conditions were satisfied.

3.2 Timestep

The model was simulated with a 2 second time step in the 2D domain, and a 1 second time step in the 1D domain. The chosen time steps have been deemed suitable for the model grid size and have been shown to produce stable model results.

4 Model Stability

Assessing the stability of a model is a critical step in understanding the robustness of a model and its ability to simulate a flood event accurately. Stability in a TUFLOW model is assessed by examining the cumulative error (or mass balance) of the model as well as the warnings output by the model during the simulation. Figures 10, 11 and 12 show that the cumulative error of all three models is within the recommended range of +/-1% throughout the simulation for all assessed rainfall events.

No 1D or 2D negative depths occurred in the majority of model simulations. The single exception to this was the occurrence of two 2D negative depths in the run for the 75 year return period event for Model 2. These corresponded to a small steep dip along the main railway cutting through Chelmsford and are not considered to be of significance.

Warnings occurred when 2d cells were lowered by more than 0.3m to 1d node bed level, due to the use of a “Z” flag on SX connections. All locations where this occurred were manually checked and deemed appropriate. There were also warnings where manholes were not used due to a lack of connecting inlet culvert or gully. These occurred where the manhole was at the upstream end of a section of the pipe network, and were not considered to have a significant impact on the model.

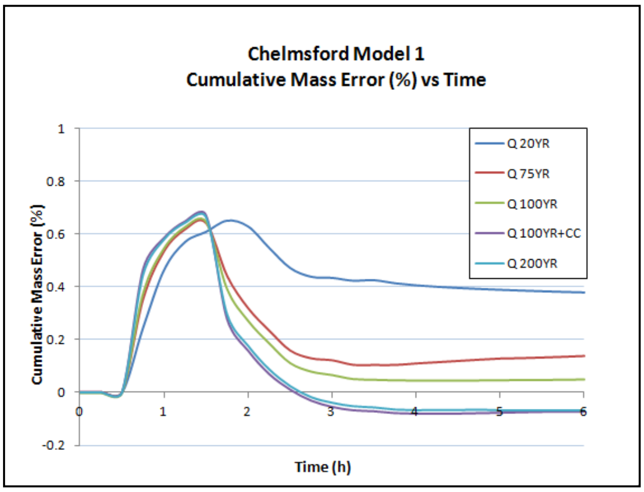

Figure 10: Mass Balance of Chelmsford Model 1

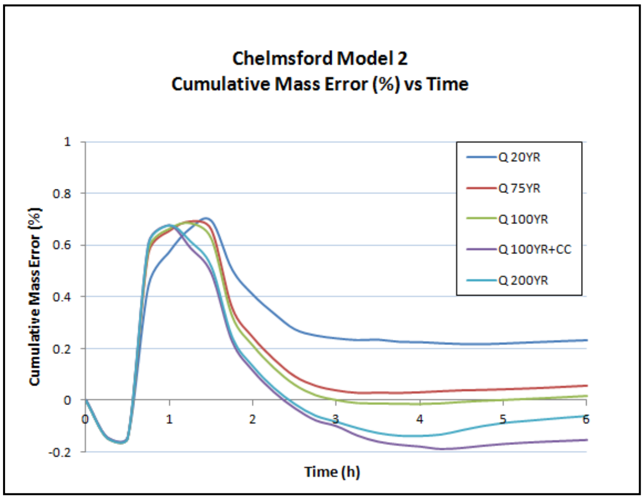

Figure 11: Mass Balance of Chelmsford Model 2

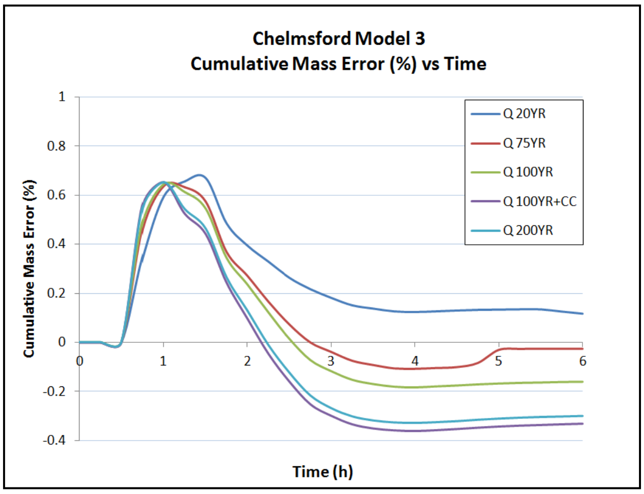

Figure 12: Mass Balance of Chelmsford Model 3

5 Consistency of Model Results

Peak water level results were checked for consistency where the extents of the different models meet. In two regions, shown in Figure 13, there were significant differences in water level between the different models. As such, the model results have a low confidence at these locations.. These regions were not considered to be of significance for this surface water study as they lie within the main river corridors and therefore have little impact on surface water flood risk.

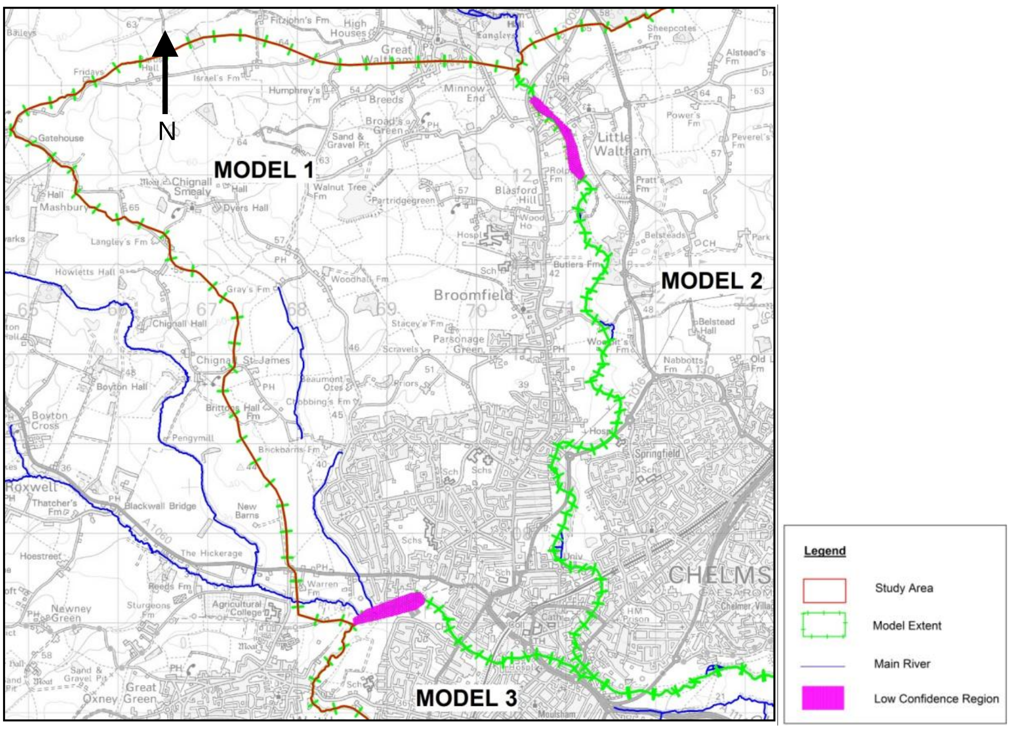

Figure 13: Consistency of Results

6 Conclusions and Recommendations

The hydraulic model constructed for Chelmsford Surface Water Management Plan represents an 'intermediate' approach to identifying 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.

Recommendations for future improvements to the model include (but are not limited to) the following:

- Improved data for the 1D network, particularly in key areas of risk, including pipe diameters and invert levels for all pipes
- Inclusion of survey data for critical structures
- Inclusion of river flows and channel capacity (where applicable)
- Reduction in model grid size in key areas of risk
- The use of better quality or more up to date topographic information particularly in areas of recent development
- More detailed study into soil textural classes and the representation of hydraulic properties in TUFLOW (particularly for UK soils)