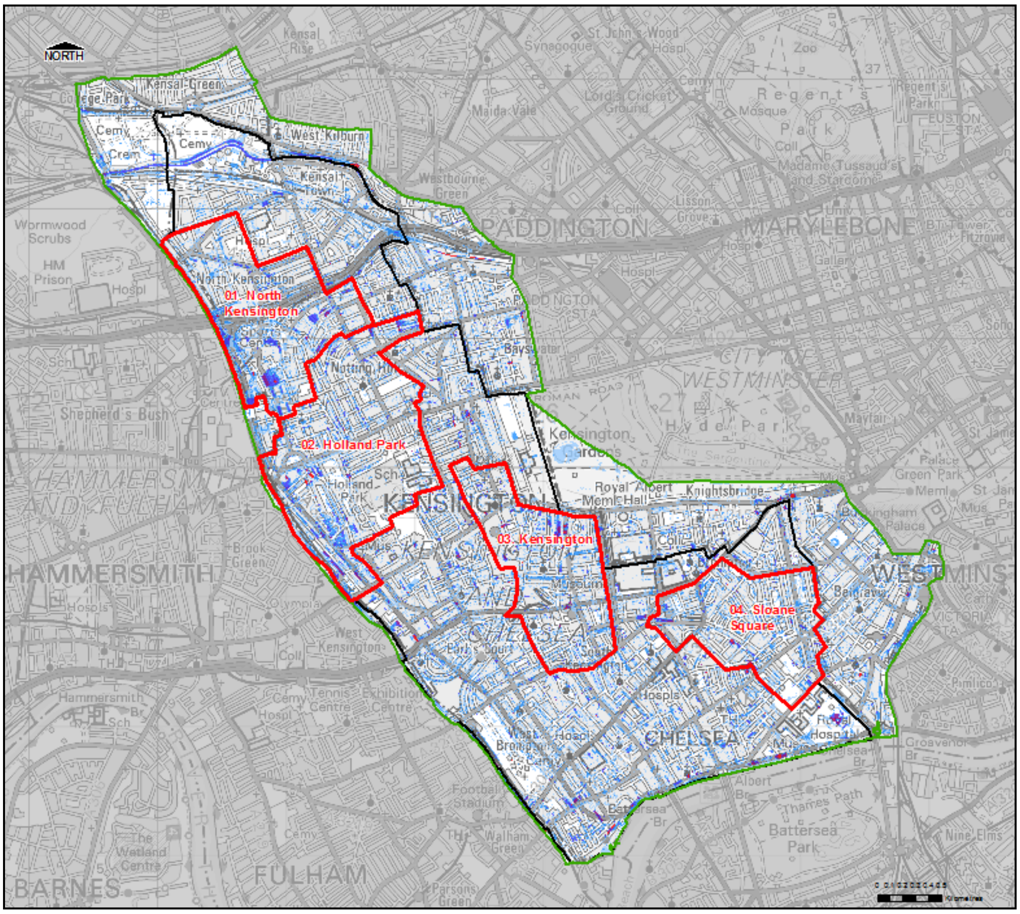
CAPITA URS

The Royal Borough of Kensington and Chelsea Surface Water Management Plan

Appendix B - Modelling Details

January 2014



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1. Introduction

The purpose of this modelling task was to analyse the impact of significant rainfall events across the study area by assessing flow paths, velocities and catchment response. This method consisted of building a virtual representation of the ground topography and then 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 method is available in the Defra SWMP Guidance – Annexes C and D[1].

[1] Defra, 2010. *Annexes to Surface Water Management Plan Technical Guidance.* London: Department for Environment, Food and Rural Affairs.

2. Model Methodology

A linked 1D-2D hydraulic model of The Royal Borough of Kensington and Chelsea was 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 were represented in 1D. Overland flow was represented in 2D.

2.1 Model Extent

Figure illustrates the study area and model extents. The study area, shown as a red line, is The Royal Borough of Kensington and Chelsea. The model extent, shown in green, was extended beyond the borough boundary, and is based on the hydrological catchment corresponding to the borough, in order to capture all inflows into the study area. The 2D model extent is based on topographic and micro-topographic features represented in the DTM. The extent of the model 1D pipe network was based on the 2D domain, but extended further in order to minimise downstream boundary effects.

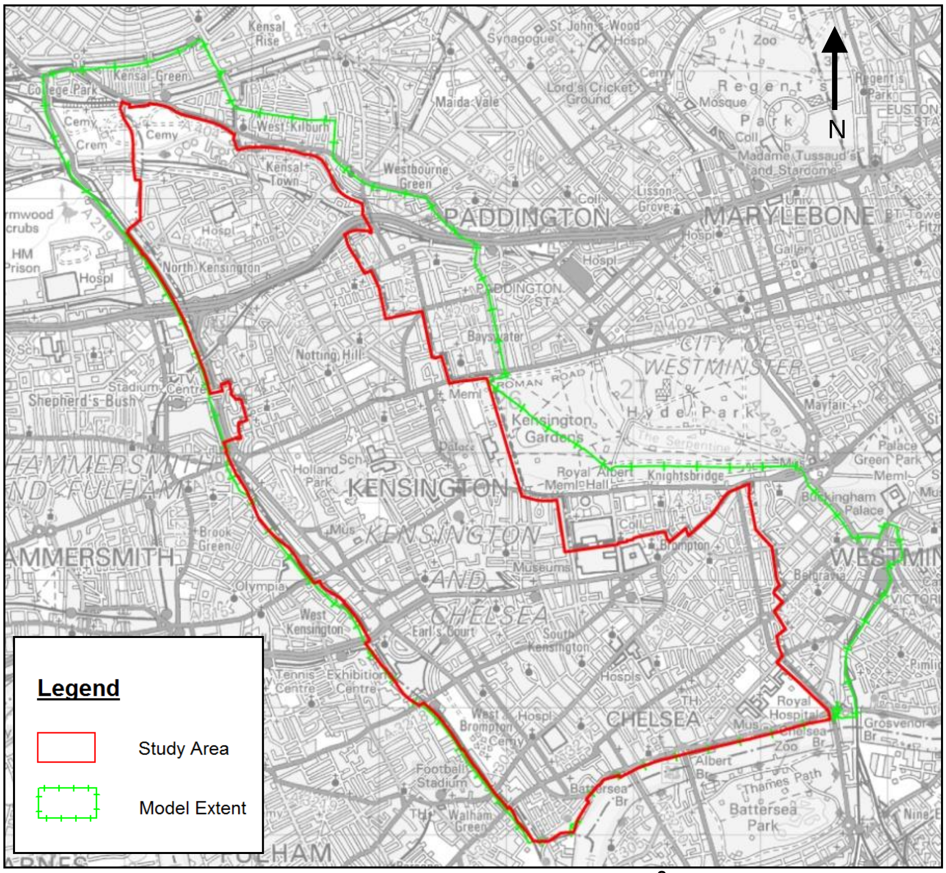

Figure 1: Model Coverage[2]

[2] © Crown copyright and database rights 2013 Ordnance Survey Licence No. LA100019223

2.2 Model Inflows

2.2.1 2D Inflows

Total rainfall depths for a range of return periods were extracted from the FEH CD-ROM (v3) Depth Duration Frequency (DDF) model at 1km grid points for several locations across the modelled area for Kensington and Chelsea. A comparison between the peak rainfall depths for the locations was completed and showed an 8% to 15% difference in rainfall depth between the sampled locations. The location which produced the median rainfall depth was used to generate hyetographs: this was at TQ 25000 80000.

Error! Reference source not found. shows hyetographs at this location, which were generated for the following rainfall events:

- 1 in 10 year
- 1 in 20 year
- 1 in 30 year
- 1 in 50 year
- 1 in 75 year
- 1 in 100 year
- 1 in 100 year plus climate change (1 in 100year +30%)
- 1 in 200 year
- 1 in 1000 year

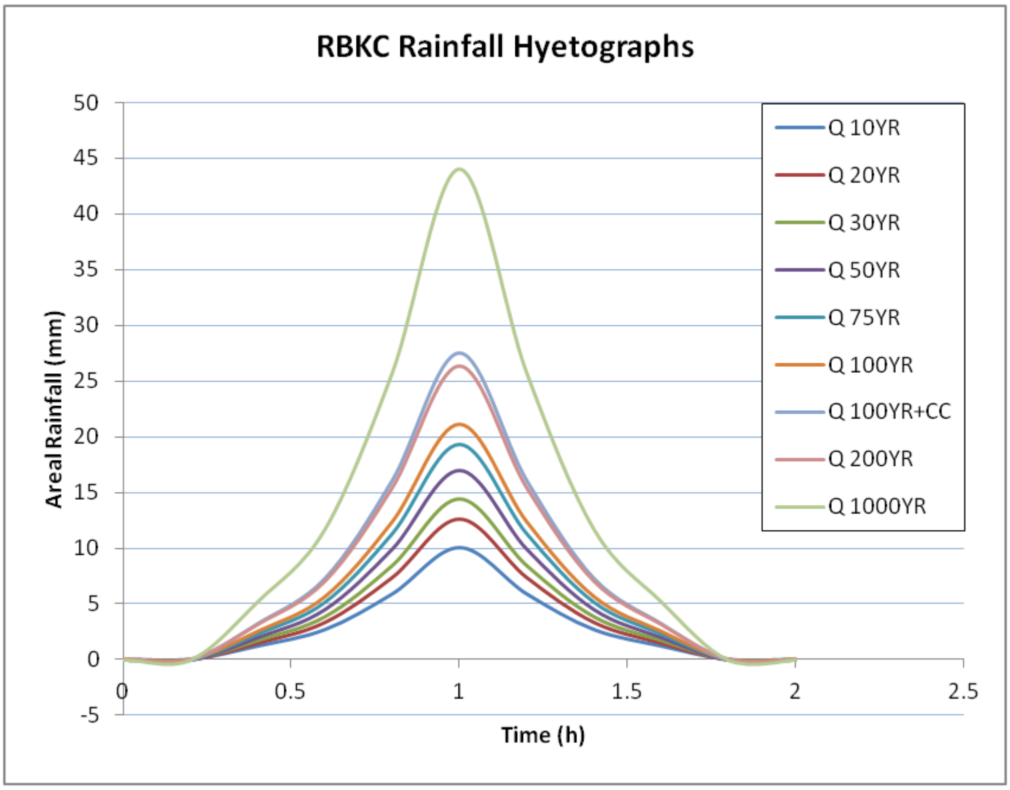

Figure 2: Rainfall Hyetographs for Kensington and Chelsea

The hyetographs were applied as inflows into the models using two layers. The first layer consists of a polygon covering the model 2D domain with the areas corresponding to buildings (defined using OS MasterMap) removed. This boundary condition layer enables TUFLOW to apply the rainfall hyetograph corresponding to each event and duration as a distributed rainfall to the whole model except where buildings are located. No rainfall is applied directly onto buildings, to reflect the routing of rainfall from roofs into the subsurface drainage network.

The second layer accounts for the rainfall onto roofs. In this layer the rainfall was scaled to correspond only to the area of the buildings in the domain. This rainfall was equally distributed to all 2D grid cells in which pits are present, to better represent the routing of rainfall into the network through gutters and drainpipes. This process is described in more detail in section 2.9.

At a number of locations along the western extent of the model, inflows were obtained from a concurrently built surface water model of Hammersmith and Fulham. These were extracted from the models for all events using Plot Output (PO) lines, and applied as flow-time boundaries.

2.2.2 1D Inflows

The network was considered to be dry at the start of the simulation; therefore, no 1D inflows were explicitly applied in the model. A 12.5% blockage was applied to all combined and foul pipes in the network to account for dry weather flow, based on data provided by Thames Water. No blockage was applied to surface water pipes.

2.2.3 Critical Duration

Critical duration is a complex issue when modelling large areas for surface water flood risk. The critical duration can vary greatly 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 used to simulate a range of storm duration events to determine the critical duration for the site. The durations tested were 1 hour, 1.5 hours, 2 hours, 3 hours and 4 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. In the areas where there was a difference, the 1.5 hour duration tended to produce the largest flood extent and maximum flood depth, therefore providing the most conservative results. As such, a storm duration of 1.5 hours was selected for this study.

2.3 Downstream Boundaries

2.3.1 2D Outflows

A number of stage-discharge boundaries were added to allow water to exit the model 2D domain where significant flow paths meet the model extent. These stage-discharge relationships were calculated automatically by TUFLOW based on gradients determined by taking cross-sections of the LiDAR DTM.

A constant head boundary of 4.93mAOD was set along the model extent where it bounds the River Thames, which is the modelled level for the 1 in 10 year 2005 event at node 2.27 (Grid reference TQ 26951 77325), obtained from the Environment Agency “Tidal Thames Joint Probability Extreme Water Levels 2008”[3] data.

2.3.2 1D Outflows

The 1D network flows out of the model 2D domain at a number of locations. Flow at the downstream extents of the pipe network was assumed to be unimpeded, ensuring water did not back up affecting areas upstream within the area of interest. This was modelled using a weir structure and a low constant head value. This was sensitivity tested by varying the constant head, as well as by removing the weir structure and applying a constant head value equal to the soffit level. The model was not found to be sensitive to this parameter.

A number of pumping stations are present along the southern extent of the model. These pump water from the drainage network into the River Thames. In order to model a worst case scenario, the pumps were assumed to be non-operational, and therefore were not modelled. As the invert levels of the connecting pipes are significantly below the constant head level of 4.93m set along the Thames the connecting network is unable to outfall.

[3]Environment Agency (2008). *Tidal Thames Joint Probability Extreme Water Levels 2008.* Environment Agency.

2.4 Drainage Network Representation

2.4.1 Network Data and Assumptions

The drainage network in Kensington and Chelsea was modelled in 1D and was defined using data collected from the following sources:

- Thames Water data - sewer layer
- Thames Water data - manhole layer
- The Royal Borough of Kensington and Chelsea data - gullies layers
- Transport for London data - gullies layer

The network data provided by Thames Water covered the 2D model domain entirely. Gully data provided by the Royal Borough of Kensington and Chelsea was confined to the borough, and therefore water was not able to enter the network through pits outside of this region. A gully layer was also provided by Network Rail, but as no corresponding network data was supplied, these gullies were not included in the model.

Surface water pipes and manholes, denoted as purpose 'S', and combined pipes and manholes, denoted as purpose 'C' were separated out of the sewer and manhole layers. A large part of the combined network was found to have been mislabelled as "F" or "O" and so these layers were also included in the model.

For all manholes, the type and chamber dimensions were missing. A circular type was assumed for all manholes. An average manhole dimension of 1050mm was applied to all manholes and increased in 300mm increments for manholes connected to pipes of larger diameter, starting from 1200mm.

A large number of pipes were egg shaped; due to difficulty in applying egg-shaped pipes, these were amended to circular type, with diameters taken from the width dimensions provided. This assumption makes pipes smaller than actual and reduces flow velocities for low flows, therefore reducing network capacity. This enforces a conservative representation of network drainage capacity.

The following manual checks were done on the drainage network:

- Pipe downstream invert level is always less than the upstream level;
- Pipe dimensions always increase downstream (towards the main drainage path);
- Pipe gradients do not exceed a 1 in 10 slope;
- Pipe invert levels are greater than or equal to the connecting manholes' invert levels.

In cases where any of the above criteria were not met, the attribute in question was interpolated based on the surrounding network. A number of small pipes feeding into a trunk sewer were found to have a steep gradient, possibly due to downstream invert being interpolated from the invert level of the connecting manhole. In reality, a shallower gradient with a drop at the downstream manhole would be more likely, and such pipes were amended accordingly.

2.4.2 Gullies

The gully layers provided by The Royal Borough of Kensington and Chelsea and Transport for London were used to define the principal means of connecting the 2D (surface) model to the 1D drainage (sub-surface) model. A "pit search distance" command enabled the gullies to automatically connect to the nearest channel end within a radial distance of 100m. Manual checks were done to ensure that gullies connected to the correct part of the network.

The relationship 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 and a profile of "Steep-shallow", corresponding to a steep longitudinal road gradient and shallow cross fall, was applied[4].

Figure 3: Standard Type R Gully[5]

2.5

2.6 Topography

1m resolution LiDAR data provided by the Environment Agency was used to define the topography of the study area. This LiDAR topographic data was reviewed as part of the model build process and constructed into a DTM. The filtering of buildings, particularly those with basements, was crude in places: sharp drops at the edges of buildings led to small mass balance errors and artificially high flood depths. Steep slopes corresponding to road embankments and rail embankments also led to small mass balance errors and artificially high flood depths. Where these were considered to be significant, z-shapes were added to smooth the topography.

Fluvial defences along the River Thames were also reinforced in the model using z-shapes defined using location and elevation data obtained from the Environment Agency's National Flood and Coastal Defence Database.

2.7 Watercourses

The Environment Agency "Detailed River Network" does not show any watercourses within the model extent, and therefore none were included in the model.

[4] Highways Agency (2009). *Design Manual for Roads and Bridges (DRMB),* Vol. 4, Section 2. Department for Transport.

[5] Adapted from Richard Allitt Associates (2011) *Modelling Road Gullies: Paper Presented at the 2011 International Flood and Modelling Conference*

2.8 Model Grid Size

The model was constructed with a 3m 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 3m grid to a 1m grid would significantly increase the model simulation time to days rather than hours.

2.9 Structures

Initially, a base hydraulic model was simulated without structures. Using these initial results as guidance, key structures such as large culverts and road underpasses were identified. These were then added to the hydraulic model as 1D or 2D elements. Height, width and length dimensions were obtained by using aerial mapping and the LiDAR DTM. Elevations were obtained from the DTM. The key structures modelled are listed in Table 1.

Table 1: List of Key Modelled Structures

Name	NGR	Brief Description
1D Structures		
CANAL_1_014	522580,182270	Canal bridge represented as large rectangular box culvert in 1D domain. Bridge deck levels applied to model 2D domain using z-shape.
RAIL_1_014	526012,177202	Rail bridge represented as large rectangular box culvert in 1D domain. Bridge deck level applied to model 2D domain using z-shape.
2D Structures		
Embankment	523625,180731 to 524060,181246	Railway embankment which was filtered out of the LiDAR DTM added using a long z-shape. Road tunnels through the embankment applied as z-shapes lowering this back to bare earth level.

2.10 Building and Road Representation

An innovative modelling methodology was developed and applied in order to better represent building flooding mechanisms in the urban environment of the Royal Borough of Kensington and Chelsea, in which a large proportion of residential properties have basements.

The topographical basis for the 2D model domain is an Environment Agency "bare earth" Digital Elevation Model (DEM), in which buildings, including their basements, have been "filtered out" (removed). An example of this is shown in Figure 4, and a cross-section along the dashed line shown in Figure 5.

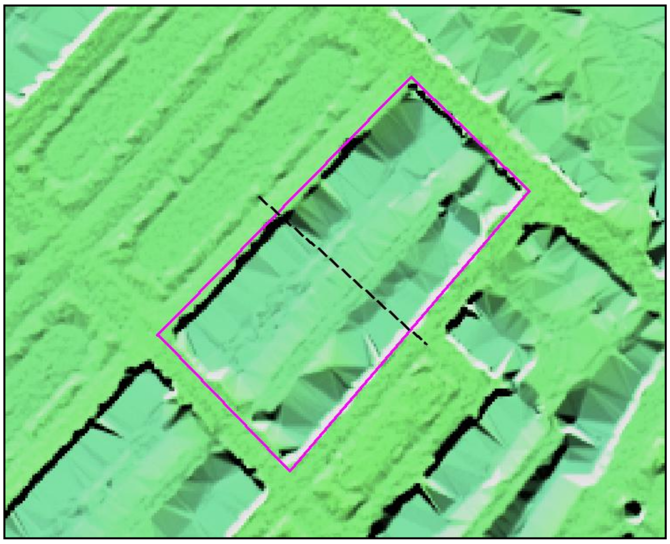

Figure 4: Building Representation in DEM

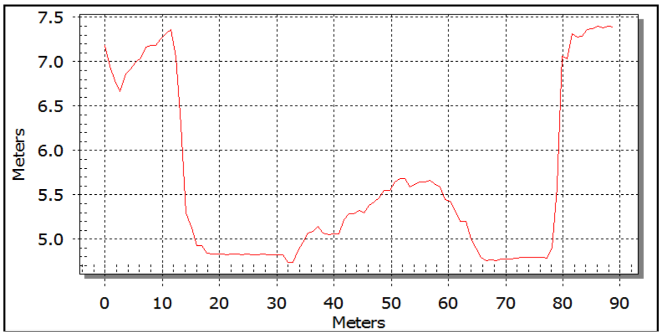

Figure 5: Cross-Section of Building Representation in DEM

The current best-practice method is to apply a building pad that raises the building footprint to the threshold level in combination with a depth varying Manning's roughness coefficient. This method ignores the additional floodwater storage in the basement.

In addition, the standard method of modelling surface water flooding by applying direct rainfall onto the filtered DEM results in unrealistic flood dynamics: rainfall is applied directly into basements and rows of terraced houses act as preferential flow routes or storage areas, significantly overestimating the flood risk to people and properties in these regions. In reality, rain falling onto roofs will generally be rapidly directed into gutters, drainpipes and the surface water drainage system. Surface water flooding will occur if the gutter or drainpipe capacity and/or the receiving sub-surface drainage network capacity is exceeded.

The methodology applied in this modelling study to better represent flooding in urban areas with a large number of basements involves the routing of rainfall from roofs into the subsurface drainage network.

Rather than apply rainfall everywhere, the building footprints (obtained from OS MasterMap) were removed from the rainfall layer, meaning that an areally distributed rainfall was applied to the whole model domain except the buildings. The rainfall that would fall on the buildings was routed directly into the surface water drainage network, using a separate layer which directs the inflow (hyetograph) only to the 2D cells that are connected to a 1D pipe. Using this method, basement flooding can only occur due to surface water that enters as overland flow.

Rooftop drainage is typically designed to accommodate a 1 in 30 year event. For larger events the precipitation falling onto the roof would exceed the gutter/drainpipe capacity and overflow onto the pavements. The modelling approach that was adopted differs in that all water falling on the building is transferred cells containing pits connected to the storm water drainage network, and the flooding mechanism is surcharge of surface water through pits in these locations.

All roads (identified using OS MasterMap) were dropped by 125mm (in line with the EA uFMfSW[6]) such that flow is preferentially routed down the roads.

2.11 Manning's Roughness Values

The Manning's roughness coefficient values contained within Table 2: Manning's RoughnessTable 2 were used throughout the 2D model domain. The various land uses in the 2D component of the model were demarcated by the use of OS MasterMap data provided by the Environment Agency. The "Feature Code" attribute in the data set was used to identify the different land uses and assigned a roughness value. A high Manning's n value (n = 0.5) was applied to the buildings to represent the high resistance that buildings have to flow, ensuring that the buildings form an obstruction to flood water.

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

Table 2: 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

[6] Environment Agency (2012). *Guidance on surface water flood mapping for Lead Local Flooding Authorities, Report version 2.0*. Bristol: Environment Agency.

Feature Code	Descriptive Group	Comment	Manning's Roughness
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

2.12 Infiltration Losses

Infiltration of rainfall into the ground was represented in the model using the Green-Ampt method, in which infiltration losses are applied to permeable surfaces based on the underlying soil textural class. TUFLOW uses the hydraulic properties (hydraulic conductivity, suction and porosity) corresponding to each textural class, as well as 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[7]. These polygons were then allocated a unique code according to textural class. The soil textural classes and corresponding TUFLOW codes applied within Kensington and Chelsea are shown in Table 3 and Figure 6.

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 must 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 which are based on suction, hydraulic conductivity and porosity of soils are not based on UK soils, and textural classifications have been found to be more complex than the simplified hydraulic properties represented in TUFLOW.

Table 3: Soil Textural Class

TUFLOW Soil Code	Description
4	Clay Loam
7	Silt Loam
8	Loam
99	No infiltration

[7][https://www.landis.org.uk/soilscapes/ Accessed: 1st February 2013

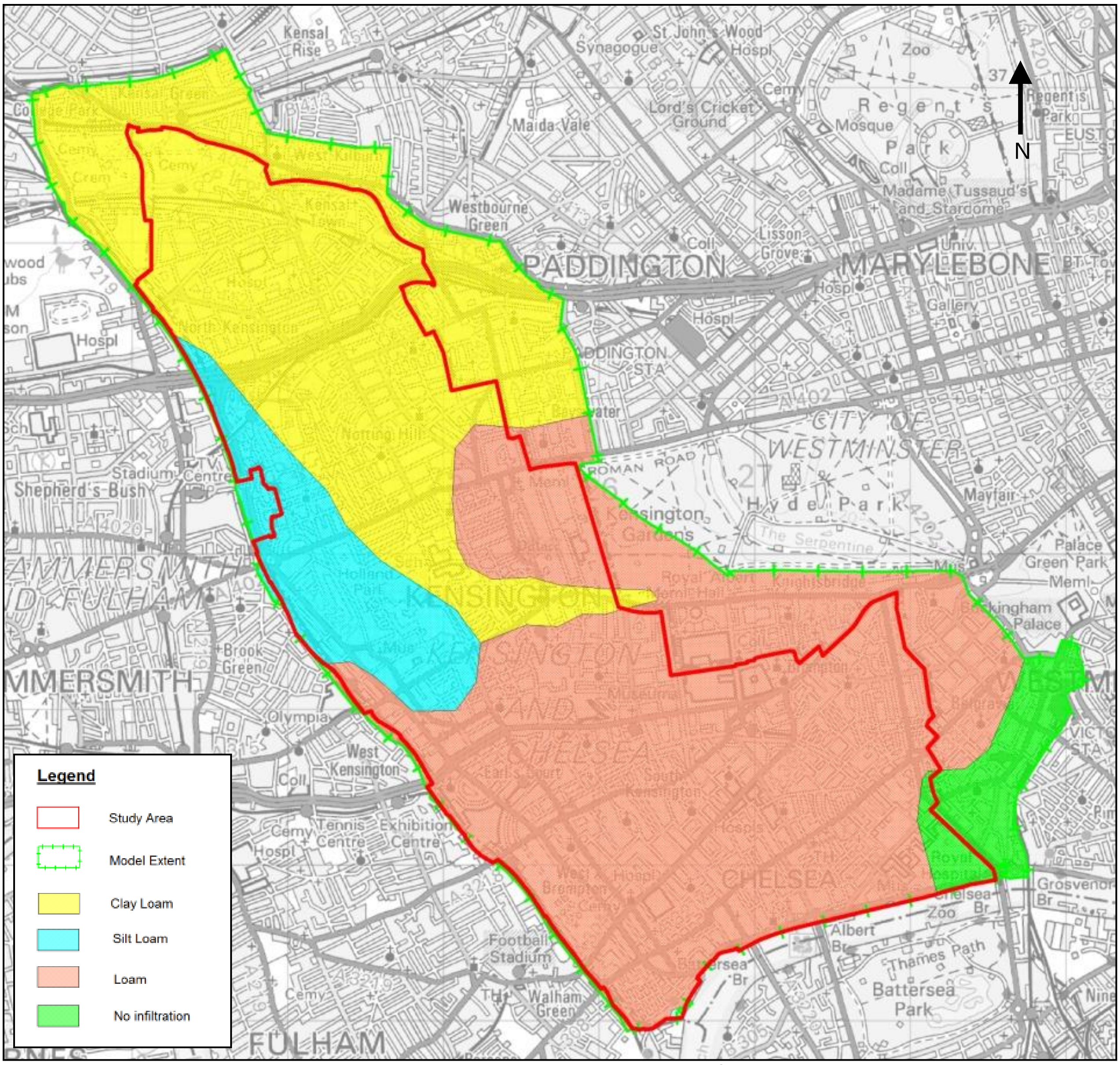

Figure 6: Soil Textural Classes[8]

[8] © Crown copyright and database rights 2013 Ordnance Survey Licence No. LA100019223

3. Model Simulation

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

The model naming convention adopted is detailed below:

RBKC_xxxxR_xxHR_xxx

RBKC: Royal Borough of Kensington and Chelsea
xxxxR: Rainfall Event Probability
xxHR: Duration Event
xxx: Version number

e.g. RBKC_0200R_01.5HR_018 denotes the model run for a 200 year return period storm event of 1.5 hour duration, for version 18.

3.1 Simulation Time

All design events for the Kensington and Chelsea model were simulated for 3 hours. The model results for the final few time steps 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. The 3 hour duration was found to be suitable for the model using this assessment method.

3.2 Time step

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 were deemed suitable for the model grid size and were 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. Figure 9 shows that the cumulative error of the model is within the recommended range of +/-1% throughout the simulation for all assessed rainfall events. Warnings occurred where manholes were not used due to a lack of connecting inlet culvert: these occurred where the manhole was at the upstream end of a section of the pipe network, and were not considered to be of importance to the model.

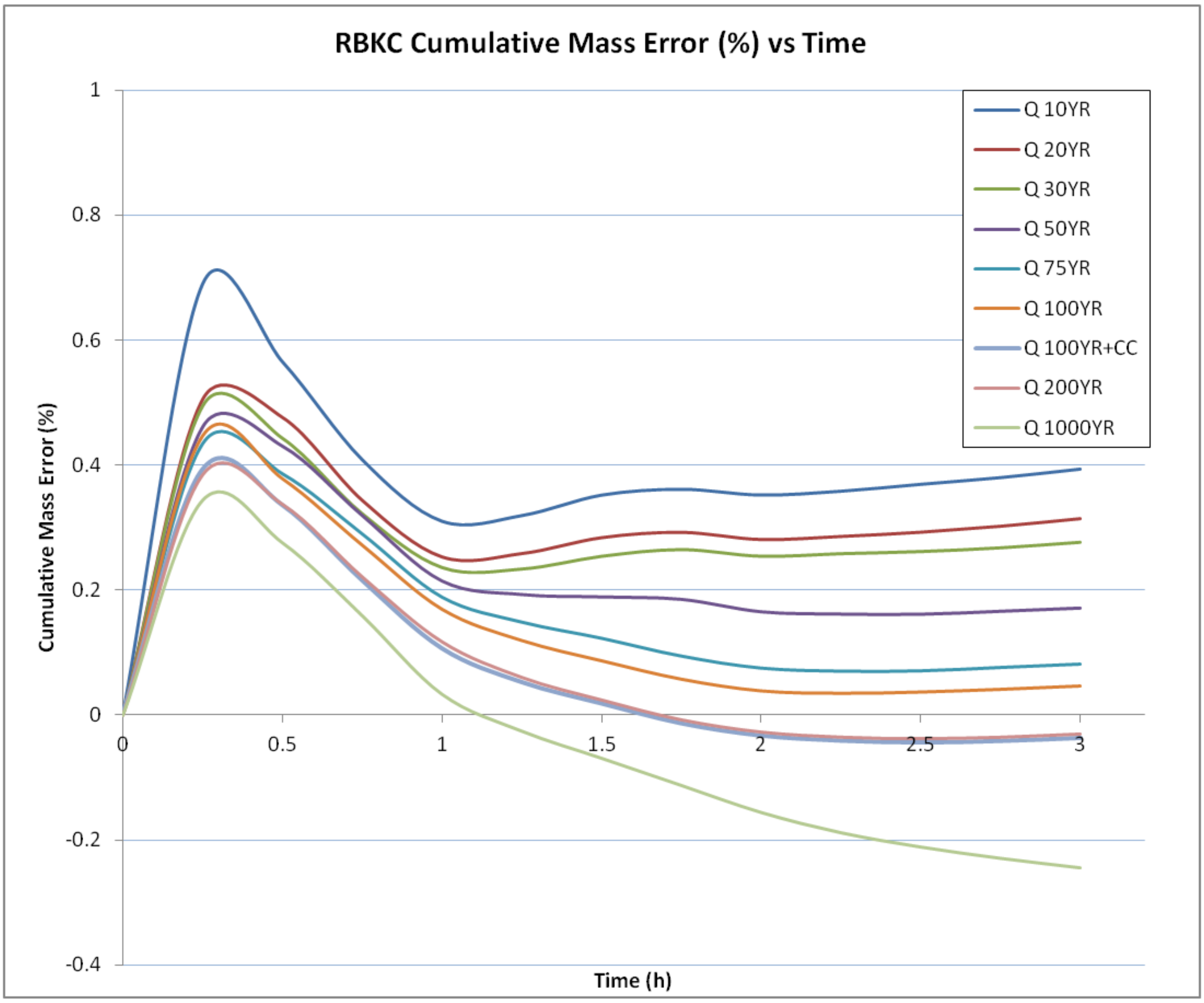

Figure 7: Mass Balance

5. Conclusions and Recommendations

The hydraulic model constructed for The Royal Borough of Kensington and Chelsea Surface Water Management Plan represents a detailed 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 railway drainage network data and a better representation of inflows;
- More detailed study into soil textural classes and the associated infiltration rates for UK soils. There is uncertainty in the soil classification and associated infiltration rates due to the broadscale nature of the data source;
- Inclusion of survey data for critical structures;
- Reduction in model grid size in key areas of risk; and
- The use of better quality or more up to date topographic information particularly in areas of recent development.